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ECOLOGY, ENERGETIC EFFICIENCY AND GREEN ENERGY

EKOLOGIJA, ENERGETSKA EFIKASNOST I ZELENA ENERGIJA

CIRCULAR ECONOMY IN BOSNIA AND HERZEGOVINA: FIRST STEPS IN DEVELOPING WASTE-TO-RESOURCE VALUE CHAINS

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ABSTRACT

This paper explores the development of the circular economy in Bosnia and Herzegovina by analysing the first concrete steps away from a linear, landfill-dependent model and towards more resource-efficient waste and material management. It builds on a comprehensive study of waste management systems, secondary raw materials and investment opportunities. Starting from low recycling rates and the predominance of landfilling, while gradual alignment with European Union policies and regulations is underway, the paper analyses the institutional, infrastructural and market preconditions for the development of circular value chains. Particular emphasis is placed on glass, plastics, waste tyres and construction and demolition waste streams, where specific investment models (e.g. facilities for glass cullet processing, tyre granulation, and mobile C&D waste crushing) and indicative ranges of required capital investments and operating costs are identified. By examining the role of extended producer responsibility schemes, local public utility companies and the private sector, the paper identifies "low-hanging fruit" of the circular economy that can be implemented relatively quickly through a combination of regulatory measures, targeted public support and private investments. Finally, the proposed approach underlines the importance of phased development, from pilot projects and modular facilities to the scaling-up of regional capacities, as a realistic pathway to reducing dependence on landfilling, increasing material circularity and retaining more added value within the domestic economy.

Keywords: Circular economy, waste management, secondary raw materials, extended producer responsibility; waste-to-resource value chains.

INTRODUCTION

The transition from a linear to a circular economy has become an important component of contemporary environmental and industrial policy. Its central premise is to reduce the use of primary resources, prevent avoidable waste generation, and retain the value of products and materials through reuse, recycling, and other forms of recovery [1], [2]. In the European Union, this approach is embedded in the Waste Framework Directive 2008/98/EC, which established the waste hierarchy and set a target for at least 50% by weight of selected household waste materials to be prepared for re-use or recycled by 2020 [3], [4]. The 2020 Circular Economy Action Plan further extended this policy direction by linking waste prevention and material efficiency with product design, industrial competitiveness, and the objectives of the European Green Deal [5], [6].

These issues are particularly relevant in countries where landfilling remains the dominant management option and markets for secondary raw materials are still weak [7], [8], [9]. Bosnia and Herzegovina (BiH) illustrates this situation. The country is progressing towards alignment with European Union requirements while at the same time dealing with infrastructure deficits, fragmented governance, and limited material recovery [7], [10]. European Environment Agency data indicate that municipal waste generation reached 345 kg per capita in 2022, while collection services covered about 74% of the population, with a marked difference between urban and rural areas [11]. According to the Agency for Statistics of Bosnia and Herzegovina (BHAS), approximately 1.1 million tonnes of municipal waste were generated in 2024 (329 kg per capita), of which 976,996 tonnes were collected through public services. Of the collected waste delivered to controlled landfills, 99.90% was permanently disposed of [12]. At the same time, local evidence indicates that improvements in municipal waste management can produce measurable environmental benefits, including reductions in greenhouse-gas emissions, as demonstrated in the case of Prnjavor [13]. Eurostat data suggest an average municipal waste recycling rate of about 9% for BiH over the 2008–2023 period [14].

The accession process provides an additional policy context for these challenges. The European Commission's 2024 Report on Bosnia and Herzegovina assessed the country as being between an early stage and some level of preparation in Chapter 27, Environment and Climate Change, and recorded only limited progress [15]. Weaknesses in institutional coordination are accompanied by pressures on resource use. In 2022, the BiH economy consumed 38.7 million tonnes of natural resources, 6.8% more than in 2015, while domestic extraction of non-metallic minerals increased by 34.2% [16]. A circular material use rate could not yet be calculated because comprehensive waste-treatment data had not previously been available to Eurostat [16]. The OECD's 2025 Economic Convergence Scoreboard places the average waste intensity of the Western Balkans at 20.2 g/USD of GDP, compared with 12.7 g/USD in the European Union. BiH records the lowest value among the six Western Balkan economies, at 17.8 g/USD [17]. This comparatively favourable indicator does not, however, offset the country's weak performance in recycling and material recovery.

Against this background, work undertaken within the EU-funded project “EU Support for Waste Management in the Circular Economy” provides an applied basis for identifying areas in which circular value chains could develop in the near term [18]. Project activities considered construction waste, packaging waste, tyres, waste electrical and electronic equipment, batteries, oils, and end-of-life vehicles, each of which faces a different combination of regulatory, infrastructural, and market constraints. Based on this work, glass, plastics, waste tyres, and construction and demolition (C&D) waste were identified as particularly suitable for early waste-to-resource initiatives because they combine recoverable material value, established treatment technologies, and business models that can be adapted to local conditions [18], [19].

This selection is consistent with the literature on circular value chains. Treatment technology is only one determinant of material recovery; the organisation of collection, reverse logistics, producer responsibility, quality control and demand for recovered outputs weigh just as heavily [7], [8], [20]. Research on extended producer responsibility (EPR) similarly shows that collection and recycling outcomes are strongly influenced by the design of compliance systems, the quality of enforcement, and the distribution of responsibilities among producers, operators, and public

authorities [21], [22], [23], [24]. For plastics, glass, tyres and construction products the implication is that circularity has to be treated as a property of the whole value chain, not of the final waste-management step [8], [19], [25], [26].

The regional and European policy framework also affects the conditions under which these value chains may develop. Through the Sofia Declaration on the Green Agenda for the Western Balkans, endorsed on 10 November 2020, the Western Balkan economies committed to a transition from a linear to a circular economy as one of five pillars of regional green development [27]. Several EU instruments reinforce this direction. The EU Taxonomy includes the transition to a circular economy among its six environmental objectives [28], while the Ecodesign for Sustainable Products Regulation, in force since 18 July 2024, extends requirements related to durability, reparability, and resource efficiency across a broad range of products placed on the EU market [29]. The Carbon Border Adjustment Mechanism (CBAM), which entered its definitive financial phase in January 2026 for sectors including cement, iron and steel, aluminium, fertilisers, electricity, and hydrogen, adds a further competitiveness dimension for carbon-intensive exporters [30], [31]. Circular-economy policy in BiH is thus tied to industrial competitiveness as much as to domestic waste management and EU approximation and access to European markets.

The aim of this paper is to interpret evidence generated through the project in relation to the wider scientific literature and the evolving European policy framework. The analysis focuses on four questions: which structural factors currently constrain circular value chains in BiH; why glass, plastics, waste tyres, and C&D waste offer comparatively realistic entry points; what form of phased development is appropriate under conditions of fragmented governance and uneven market maturity; and how recent EU policy instruments alter the incentives for circular investment and resource recovery in BiH [6], [18].

METHODOLOGY

The paper is based on work undertaken within the EU-funded project “EU Support for Waste Management in the Circular Economy” in Bosnia and Herzegovina [18], during which the authors contributed to activities related to the assessment of waste management systems and circular-economy opportunities. The empirical basis includes evidence generated during project implementation: field visits, consultations with competent institutions, public utility companies, EPR schemes and private operators, together with data collection, technology screening and financial assessment carried out within the project. The present paper uses this material as a case-based evidence base and combines it with selected official statistics and published literature.

A qualitative document-analysis and comparative-synthesis approach was used. Evidence generated through the project was organised around four analytical dimensions: institutional and regulatory conditions, characteristics of priority waste streams, technological and market options for material recovery, and factors affecting investment feasibility [18]. Quantitative values derived from project work were used to indicate the relative scale of individual waste streams and investment opportunities rather than to establish project-level feasibility.

Work in the project passed through six stages, and the same sequence organises the evidence used here [18]. The first stage was a review of policy and regulation, covering the Waste Framework Directive as amended by Directive (EU) 2018/851, the remaining acts of the EU waste package, the Green Agenda for the Western Balkans, and the corresponding gaps in BiH legislation [33], [34]. Stakeholders were then mapped across public authorities, private operators, extended producer responsibility (EPR) schemes, non-governmental organisations, industry and academia. Waste stream analysis followed, dealing with generated quantities, collection arrangements and existing treatment capacity. The financial assessment produced capital and operating cost estimates together with funding gaps and possible financing routes. In the fifth stage the streams were ranked by market potential, technical feasibility, expected impact and institutional readiness. The last stage converted the ranked streams into indicative business models, the policy measures each of them would require, and options for scaling them in phases [18], [35]. Figure 1 shows the sequence.

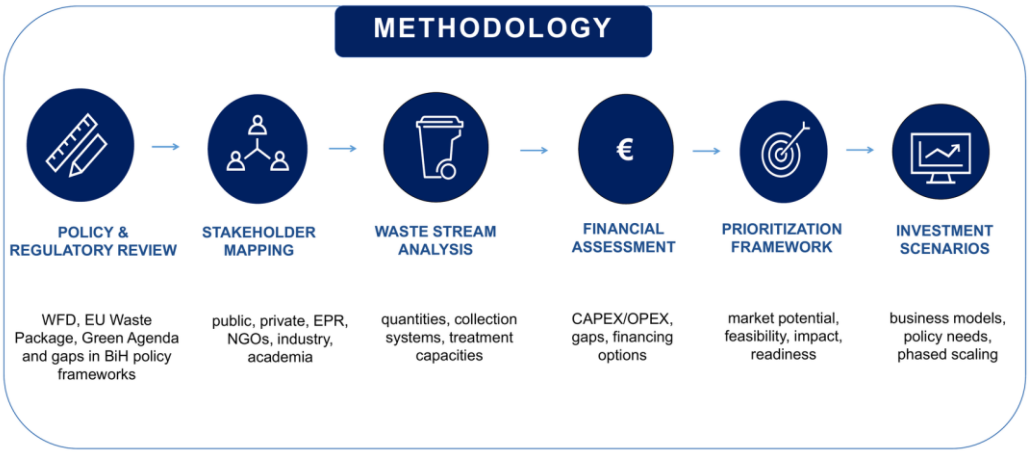

Figure 1. Six-stage analytical workflow applied in the project

The literature review was used to place the BiH findings in a broader analytical context and to support the interpretation of the project results. It covered scientific literature on circular value chains, extended producer responsibility, reverse logistics, waste valorisation and the management of selected waste streams. The analysis also drew on relevant policy documents and official statistical sources, including the BiH Circular Economy White Paper [6], the Sofia Declaration on the Green Agenda for the Western Balkans [27], European Commission enlargement reporting [15], Eurostat and European Environment Agency data on waste and material use [11], [14], [16], the OECD Economic Convergence Scoreboard for the Western Balkans [17], and official BHAS statistics [12].

The analysis comprised four related steps. Evidence generated through project activities was first reviewed with respect to institutional arrangements, data quality, EPR performance, available treatment technologies, and investor constraints [18]. The four priority streams: glass, plastics, waste tyres, and C&D waste were then compared with findings from the scientific literature relevant to material recovery and circular value chains. In a third step, selected quantitative results were checked against national and regional indicators reported by BHAS, Eurostat, the EEA, and the OECD [11], [12], [14], [16], [17]. Finally, the combined evidence was used to formulate a phased development model for BiH, with attention to practical entry points, modular investment, market formation, and alignment with the relevant EU policy framework [4], [5], [27], [28], [29].

The analysis is subject to two main limitations. First, the underlying project work identified substantial data gaps, particularly for packaging, EPR-controlled collection, and the transparency of system costs; some quantitative estimates therefore had to be reconstructed from incomplete reporting [18]. Second, official circular-economy indicators for BiH remain incomplete. The most recent EEA reporting notes that a circular material use rate could not yet be calculated because comprehensive waste-treatment data had only recently become available for Eurostat reporting [16]. For this reason, quantitative and financial values are treated as indicative and are used primarily to compare the relative scale of opportunities and constraints, not as substitutes for detailed project-level feasibility assessments.

RESULTS

Institutional and Market Context for Circular Value Chains in BiH

Evidence generated through the project indicates that the principal constraints on circular-economy development in BiH arise from implementation and coordination rather than from a complete absence of policy or legislation [18]. Responsibilities are distributed across the state, the Federation of Bosnia and Herzegovina (FBiH), Republika Srpska (RS), Brčko District, cantons,

and municipalities, creating uneven conditions for planning, enforcement, and service delivery [10], [18]. The European Commission's 2024 assessment of Chapter 27 is consistent with this picture, recording limited progress and continuing gaps in the national environmental and climate framework [15]. Similar findings are reported in the circular-value-chain literature, where institutional coordination across collection, financing, processing, and end markets is identified as a prerequisite for effective material recovery [7], [23], [36].

Five governance weaknesses emerged from the project work. No circular-economy strategy has been adopted at state level, and there is no mechanism through which environmental, industrial, fiscal and municipal decisions on material flows are coordinated, so such decisions continue to be taken in separate institutional tracks. The regulatory framework is itself divided between the entities and Brčko District, which prevents uniform obligations for producers and operators. Planning at local level is thin: waste management plans have been adopted in only about 30% of municipalities, which leaves much of the country without the institutional basis for separate collection or for municipal contributions to recovery targets. Enforcement, monitoring and reporting are weak throughout. Weak monitoring and reporting also reduce the reliability of the indicators used to support investment decisions [18], [35].

Table 1 presents the main quantitative indicators used to describe the current waste-management and material-use context in BiH, based on BHAS, Eurostat, EEA, and OECD sources [11], [12], [16], [17], [35].

Table 1. Selected waste and material-flow indicators for Bosnia and Herzegovina

Indicator	Value
Municipal waste generated (2024)	≈1.1 Mt (329 kg/cap.)
Waste collected, public service (2024)	976,996 t
Share landfilled, of collected (2024)	99.90%
Population covered, collection (2022)	≈74% (80–90% urban; 40–45% rural)
Waste generated per capita (2022)	345 kg/cap.
Avg. recycling rate (2008–2023)	≈9%
Natural resources consumed (2022)	38.7 Mt (+6.8% vs. 2015)
Non-metallic mineral extraction (2022)	+34.2%
Circular material use rate	Not yet calculable
Waste intensity, WB6 average	20.2 g/USD GDP
Waste intensity, BiH (lowest in WB6)	17.8 g/USD GDP
WEEE collected, formal channels (2023)	≈16%
Packaging captured under EPR (2023)	≈7%
Packaging placed on the market (2023)	256,402 t
Annual OPEX funding gap	EUR 25–35 million

EPR is a particularly important element of this institutional setting. Project analysis indicates that formal packaging systems capture only a limited share of the actual waste stream and that the absence of a consolidated state-level register contributes to under-declaration and free-riding [18]. A World Bank review reached a similar conclusion, noting that although EPR is recognised in both entities, the FBiH and RS systems for packaging and waste electrical and electronic equipment

operate independently, with no cross-entity legal effect, while secondary legislation for waste electrical and electronic equipment was still incomplete in RS [37]. International experience indicates that EPR performs more effectively where fees reflect system costs, reporting is transparent, and compliance obligations are enforceable [21], [24], [36]. Where these conditions are weak, formal producer-responsibility arrangements may generate neither the quantity nor the quality of material needed to support investment in recycling capacity [23], [24].

Capture rates for individual streams show how large this shortfall is. For 2023 the project estimated that formal channels collected roughly 16% of waste electrical and electronic equipment, while EPR arrangements captured only about 7% of the packaging placed on the market, which in that year amounted to 256402 tonnes [18], [35]. The financing picture is comparable. Measured against the recurrent cost of a system able to meet EU-aligned targets, revenues from tariffs, EPR fees and public budgets fall short by an estimated EUR 25–35 million a year [18], [35]. This estimated gap relates to operating expenditure rather than capital investment. A gap of that kind is not closed by donor-financed infrastructure, and whatever recovery capacity is built will have to be run within it.

A related constraint identified through the project is uncertainty over feedstock quantity, quality, and long-term offtake, all of which affect the bankability of circular investments [18]. Waste generation alone does not guarantee a viable recovery system. Investors also require predictable collection, consistent sorting, reliable logistics, and identifiable buyers for recovered materials [7], [8], [20]. Under current BiH conditions, early-stage investments are therefore more plausible where waste streams are sufficiently concentrated, treatment technology is established, and an anchor buyer or clearly defined end market is available [18].

Glass Value Chain

Glass is among the more straightforward near-term opportunities identified through the project analysis. Container glass is technically well understood, and recycled cullet has established industrial uses [18]. Project work identified potential interventions in collection, pre-treatment, cullet preparation, and cooperation with industrial partners within and outside BiH. An important advantage is that the value chain can be developed through regional collection and processing hubs without requiring a domestic integrated remelting facility at the outset [18].

Published research points to the same practical requirements. Recycled glass can be returned to remelting processes or used in selected construction applications, provided contamination is controlled and the required particle characteristics are achieved [19]. Collecting more glass is thus only half of the task. The other half is delivering cullet at a quality that downstream users will accept. For BiH, this places particular importance on source separation, colour sorting, contamination control, and efficient transport arrangements [7], [18], [20].

For a facility producing furnace-ready cullet, the project financial assessment put capital expenditure at EUR 1.5–3 million, a moderate figure when set against the other three streams [18], [35]. Technology complexity is similarly moderate. An export market for cullet is already in place, drawing on demand from container-glass producers in neighbouring countries. It is this combination of a working outlet, mature technology and a manageable capital requirement that makes glass an accessible entry point and not a long-term ambition.

Plastics Value Chain

Plastics offer a larger but more heterogeneous opportunity. Packaging waste is substantial in volume, yet only a limited share is captured through formal household collection and EPR-related channels [18]. Project data indicate that 256,402 tonnes of packaging across the main material categories were placed on the market in 2023, while modelled collection under EPR arrangements amounted to only 18,646 tonnes [18]. The difference points less to a shortage of recyclable material than to the inability of the present system to channel that material into transparent and traceable recovery pathways.

The literature on plastic recycling and EPR helps explain this gap. Effective systems depend on the interaction of fee design, collection architecture, reverse logistics, sorting, and design for

recyclability [8], [21], [26], [36]. In markets that are still developing, investment is often more viable when it begins with a limited number of polymer fractions, such as PET and HDPE, for which specifications, processing technologies, and end markets are comparatively well established [7], [26]. This suggests that a selective approach may be more appropriate for BiH than attempting to process all plastic fractions within a single early-stage system.

The project analysis narrowed this stream to PET and HDPE [18], [35]. Collection for both already runs through EPR arrangements, the sorting and reprocessing technology is proven and can be added in modules, and EU demand for recycled content is strong and still growing, reinforced by the mandatory recycled-content requirements now applying to beverage packaging [32]. Bottle-to-bottle recycling of PET is thus a medium-term prospect for BiH, on condition that separate collection delivers sufficient volume at an acceptable quality.

Waste Tyres Value Chain

Waste tyres are another stream with relatively favourable conditions for early intervention. Project work included baseline estimates, scenario analysis, and financial summaries for tyre collection and treatment, indicating that the stream is sufficiently defined to support targeted investment [18]. Among the options considered, granulation represents a technically established model with identifiable applications for the recovered rubber and other fractions.

Tyres have several practical advantages over mixed municipal waste. The stream is comparatively homogeneous, collection points can be organised through take-back systems, and established outlets include granulated-rubber products, sports surfaces, and tyre-derived fuel [19]. These advantages do not remove the need for effective governance. Reliable take-back obligations, traceable flows, and organised reverse logistics remain essential if treatment facilities are to receive stable quantities of material [8], [36]. In the BiH context, tyres pair mature technology with a collection problem that is manageable, which places them among the more implementation-ready streams examined in the project [18], [20].

Granulation was confirmed in the project work as a technically settled route for this stream, with reasonably stable outlets in sports surfaces, insulation materials and flooring [18], [19], [35]. Financing is a further advantage. Tyre management can be paid for from EPR fees, which removes part of the dependence on municipal budgets and gives operators a steadier revenue base than tariff-financed services provide.

Construction and Demolition (C&D) Waste Value Chain

C&D waste is significant both in quantity and in its potential for local material recovery [18]. Project data indicate that, in the Federation of BiH, 349,780 tonnes from eight special waste categories were collected in 2023, of which construction waste accounted for 229,237 tonnes, the largest share among the categories examined [18]. The project analysis also considered collection and treatment costs, potential material revenues, and processing scenarios for this stream. Its scale makes C&D waste particularly relevant for circular-economy policy, although its management differs from that of packaging or consumer-product waste. Earlier World Bank analysis also pointed to limited centralised waste-treatment infrastructure in FBiH, where only four regional sanitary landfills were operational and served 24 municipalities [38].

The international literature identifies C&D waste as one of the largest material flows with potential for recovery of concrete, bricks, metals, wood, plastics, and glass [25], [26]. The built environment can also provide an important outlet for secondary materials originating from other waste streams [19]. Unlike some recycling chains that depend on distant specialised markets, recovered aggregates can often be used close to the point of generation, reducing transport requirements. Their use nevertheless depends on technical specifications, quality assurance, and procurement rules that recognise recycled materials as acceptable inputs [25], [26].

For BiH, mobile crushing and modular processing are particularly relevant because construction activity is geographically dispersed and centralised treatment capacity is limited [18]. Technology alone, however, will not create a functioning market. Clearer requirements for on-site sorting, separate handling of mineral fractions, quality control, and the use of recycled aggregates

in public works are needed if the resource value of C&D waste is to be captured more consistently [18]. For this stream, standards and procurement practice matter as much as the processing equipment [26].

Of the four streams, C&D waste needs the least capital according to the project financial assessment. Mobile crushing and screening capacity can be bought in stages and moved between sites, so investment need not be concentrated in one fixed plant [18], [35]. Demand for recycled aggregates is local and immediate, and it follows infrastructure works, which makes this the stream most likely to respond to demand created through public procurement.

Comparative Assessment of Priority Value Chains

Table 2 brings together the comparative characteristics of the four chains as they emerged from the project prioritisation framework and financial assessment. The four waste streams differ substantially in capital intensity, technology maturity, downstream market conditions, and the extent to which EPR fees can support operating costs. These differences provide a practical rationale for sequencing interventions rather than applying a uniform investment approach across all four streams. That variation is the practical case for sequencing interventions instead of running one uniform investment programme [18], [35].

Table 2. Comparative characteristics of the four priority value chains

Characteristic	Glass (cullet)	PET / HDPE	Waste tyres	C&D waste
Indicative CAPEX	EUR 1.5–3 million	Moderate; modular	Moderate	Lowest of the four
Technology maturity	Established	Proven, scalable	Proven granulation	Mature; mobile units
Principal market outlet	Export cullet	Bottle-to-bottle; EU recycled content	Sports surfaces, insulation, flooring	Recycled aggregates
EPR financing relevance	Packaging EPR	Packaging EPR	Strong; fee-based	Limited
Main constraint	Cullet quality	Low capture (≈7%)	Take-back enforcement	Sorting and procurement rules

Regional Benchmark: BiH within the Western Balkans

A regional comparison helps place the BiH indicators in context. According to the OECD Convergence Scoreboard, waste intensity across the Western Balkans is about 1.5 times the EU average, while BiH records the lowest value among the six economies, at 17.8 g/USD of GDP [17]. This relatively favourable result contrasts with the country's low recorded municipal recycling rate of about 9% and with the previous absence of sufficiently complete waste-treatment data to calculate a circular material use rate [14], [16]. The contrast suggests that the main circularity deficit lies not simply in the amount of waste generated relative to economic output, but in the weak conversion of waste into documented secondary raw materials. Limited collection infrastructure, incomplete data systems, and underdeveloped end markets remain common constraints across the region and form part of the rationale for the Green Agenda for the Western Balkans [27].

Phased Development Model

Across the four priority streams, a common implication emerges: the initial development of circular value chains in BiH is more likely to succeed through phased and modular investment than through large, fully integrated facilities introduced at an early stage [18]. This approach is consistent with findings generated through the project and with literature emphasising the importance of reliable supply, institutional capacity, and market coordination before major processing capacity is installed [7], [20], [23]. Where data remain uncertain and responsibilities are fragmented, smaller projects can test feedstock availability, operational performance, product quality, and market demand before investment is scaled up.

A practical sequence would begin with clearer reporting requirements, pilot separate-collection schemes, and small or medium processing facilities in the priority streams [18]. Once material flows and product quality are better established, regional partnerships and contract-based supply and offtake arrangements could support larger private investment [8], [18], [36]. More advanced forms of industrial symbiosis and greater domestic use of secondary raw materials would then become realistic as collection systems, compliance mechanisms, and end markets mature [18], [20], [26].

The proposed transition involves a shift from a predominantly linear material flow towards a system in which separate collection feeds sorting and recycling, and recovered secondary raw materials are returned to productive use. Achieving this transition is not primarily a technological challenge. It depends on policy design, targeted investment, innovation, alignment with EU requirements, and the gradual building of chains that link collection points to industrial buyers who can be identified in advance [5], [34]. Figure 2 summarises the shift.

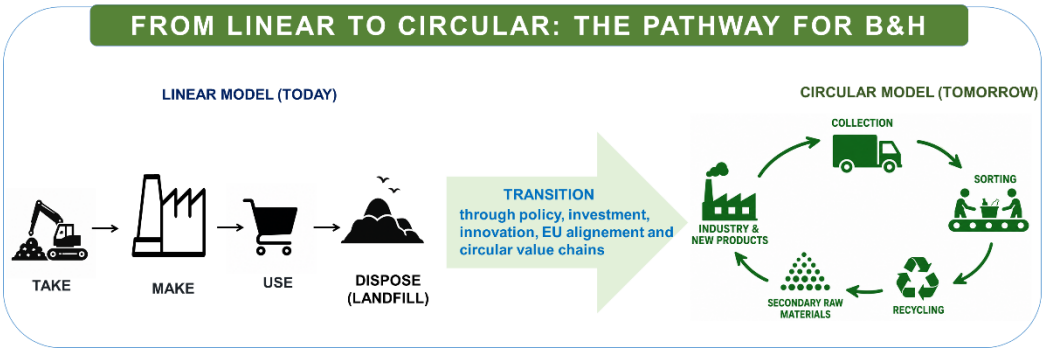

Figure 2. Transition pathway from the linear to the circular model in BiH

DISCUSSION

The results indicate that the principal barriers to circular-economy development in BiH are institutional and market-related rather than technological. Fragmented responsibilities across levels of government, together with entity-based producer-responsibility systems that are not mutually recognised, make it difficult to create uniform conditions for material collection and recovery [18], [36]. The European Commission's assessment of limited progress under Chapter 27 provides a broader policy context for these findings [15]. This interpretation is also consistent with the circular-value-chain and EPR literature, which emphasises coordination across collection, financing, processing, compliance and end markets [7], [23], [36]. Consequently, investment in processing equipment, although necessary, will have limited effect unless accompanied by more consistent rules, comparable data and stronger coordination between FBiH, RS, Brčko District and local authorities.

The quantitative indicators reveal a notable contrast. BiH has the lowest waste intensity per unit of GDP among the Western Balkan economies [17], yet its recorded municipal recycling rate remains close to 9% [14], and a circular material use rate could not previously be calculated because of incomplete treatment data [16]. This suggests a weakness in the middle stages of the value chain: materials are generated and collected, but a large share does not pass through systems that can sort, document, process and return them to productive use. Project analysis points to a similar conclusion from an investment perspective, identifying uncertainty over feedstock volume, quality and offtake as more immediate constraints than the absolute availability of waste [18].

The four priority streams illustrate these constraints in different ways. For glass, the principal issue is the quality and consistency of separately collected cullet rather than the absence of established recycling technology [18], [19]. For plastics, the large difference between estimated packaging placed on the market and the quantity modelled as collected under EPR arrangements

indicates substantial leakage from formal recovery channels [18], while international evidence shows that EPR performance depends strongly on collection architecture, compliance and traceability [21], [24]. Waste tyres are comparatively homogeneous and have mature treatment options, but their viability still depends on enforceable take-back and traceable collection [18], [19]. C&D waste is available in large quantities, yet its use as a secondary resource is constrained by sorting practices, quality standards and procurement rules for recycled aggregates [18], [25], [26]. These differences argue against a single policy instrument for all waste streams and in favour of stream-specific interventions within a common circular-economy framework.

EU policy developments add an economic dimension to these domestic constraints. The Waste Framework Directive and Circular Economy Action Plan continue to shape the direction of waste and resource policy, while the EU Taxonomy and the Ecodesign for Sustainable Products Regulation increasingly affect investment criteria and product requirements [3], [4], [6], [28], [29]. For BiH companies supplying the EU market, the ability to document recycled content, resource efficiency and lower material intensity is likely to become a commercial requirement rather than only an environmental merit. CBAM introduces a different type of pressure by assigning a carbon-related cost to selected imports. Given the exposure of regional cement and electricity exports, greater use of secondary materials and lower-carbon production routes may contribute to maintaining competitiveness, although the scale of this effect will vary by sector and requires further quantitative assessment [30], [31].

The phased model proposed here is best interpreted as a form of investment risk management rather than as a general preference for small projects. Pilot and modular investments can generate information on collection costs, feedstock quality, operating performance and market acceptance, which are among the uncertainties currently limiting bankable circular-economy investments in BiH [18]. If these projects are linked to clearer EPR obligations, transparent reporting and identifiable industrial users, they can provide a basis for later regional scaling [20], [24]. This approach is also compatible with the Sofia Declaration's regional perspective, since some material streams may achieve viable scale more readily through cross-border or regional logistics than within individual domestic markets [27].

Three practical policy priorities follow from the analysis. First, greater compatibility between the EPR and packaging systems in FBiH and RS, supported by more consistent reporting, would improve the transparency and predictability of material flows [18], [37]. Second, public procurement and technical standards can help create demand for recycled aggregates, cullet and granulated rubber where these materials meet defined performance requirements [18], [26]. Third, public and donor finance should support modular and regionally coordinated investments that can be expanded once supply and offtake arrangements have been demonstrated [18], [35]. Future research should monitor the circular material use rate as more complete Eurostat-compatible data become available and quantify, by sector, the extent to which greater use of secondary raw materials could reduce exposure to carbon-related trade costs [16], [30].

Taken together, these findings show that the development of circular value chains in BiH cannot be reduced to investment in individual recycling technologies. Progress depends on a broader set of mutually reinforcing measures: the adoption of circular-economy strategies, effective mechanisms for cross-sector and inter-institutional coordination, stronger EPR systems, access to finance for circular investments, quality standards for recycled materials, continued alignment with EU requirements and systematic waste planning at the local level [18], [35]. The interdependencies between these measures are important. A strategy without an operational coordination mechanism risks remaining declarative; stronger EPR systems will have limited effect if collected materials cannot meet quality requirements or find reliable industrial users; and investment in processing capacity is unlikely to be sustainable where local waste planning, separate collection and predictable material flows remain underdeveloped. Figure 3 summarises these seven areas of intervention and their combined role in creating the institutional, technical and market conditions required for functioning waste-to-resource value chains in BiH.

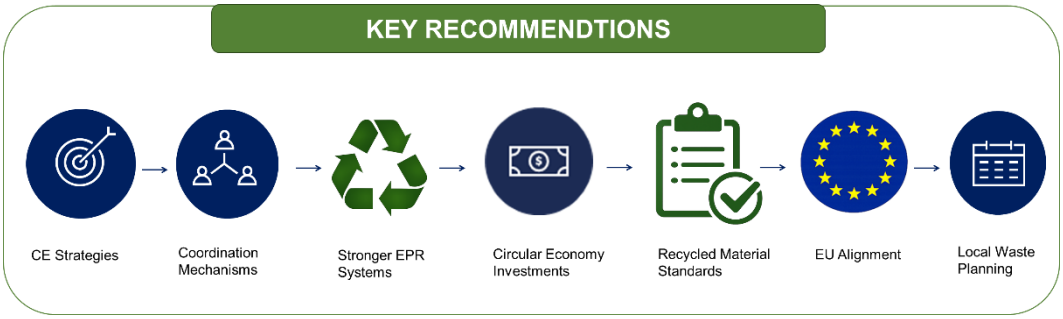

Figure 3. Seven areas of intervention and their interdependencies

CONCLUSION

The analysis identifies glass, plastics, waste tyres and construction and demolition waste as realistic entry points for strengthening circular material flows in Bosnia and Herzegovina. Their potential reflects a combination of recoverable material value, established treatment technologies and identifiable market outlets [18], [19], [26]. At the same time, the findings show that the main barriers to their development are not primarily technological, but arise from fragmented governance, incomplete data, weak collection and EPR systems, uncertain material quality and insufficiently developed markets for secondary raw materials.

Under these conditions, phased and modular development appears more appropriate than immediate investment in large, fully integrated systems. Early projects can establish reliable material-flow data, test collection and processing arrangements, demonstrate product quality and confirm demand before capacity is expanded. Regional logistics, stronger producer-responsibility mechanisms and partnerships with identifiable industrial users can then support subsequent scaling [7], [18], [20].

The transition towards a more circular economy in BiH therefore depends on coordinated improvements in regulation, planning, financing, material standards and market development. Continued alignment with the EU waste and circular-economy framework further strengthens the economic relevance of these reforms by linking resource efficiency and secondary-material use with investment requirements and competitiveness [4], [5], [28], [29], [30], [31]. The four priority waste streams examined in this study can provide practical starting points, but their transformation into functioning waste-to-resource value chains will ultimately depend on the institutional and market conditions that connect waste generation, collection, recovery and productive reuse.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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SUSTAINABLE MOBILITY: THE CASE OF COPENHAGEN

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ABSTRACT

Climate change presents a significant global challenge, with transport contributing substantially to greenhouse gas emissions. This exploratory case study examines cycling-oriented mobility in Copenhagen through the Space, Culture, and Ambition dimensions used in the Copenhagenize Masterclass. Qualitative field observations were undertaken during the programme on 12–14 June 2024 and are contextualised using published municipal indicators. The observations describe separated cycle tracks, supporting facilities, everyday bicycle use, cargo bicycles, and orderly interactions at observed locations. Municipal data provide a separately identified quantitative context rather than measurements from the field visit. Together, these sources suggest that infrastructure provision, everyday cycling practices, and sustained policy support are mutually reinforcing. The study identifies practical planning considerations for other cities while acknowledging that the short observation period and absence of reported count data prevent statistical generalisation or causal evaluation.

Keywords: climate change, sustainable mobility, cycling infrastructure, Copenhagen, urban governance.

INTRODUCTION

Climate change is widely recognised as a critical global challenge, with the transport sector constituting a significant source of greenhouse gas emissions and urban air pollution. The European Green Deal identifies the achievement of climate neutrality by 2050 as contingent upon a fundamental transformation of urban transport and the adoption of sustainable, low-carbon mobility solutions. Among various transport modes, cycling is considered one of the most efficient, environmentally sustainable, and economically viable alternatives for reducing emissions, alleviating traffic congestion, and decreasing energy consumption, while also enhancing public health and overall quality of life [1, 2, 3].

The development of cycling-friendly cities requires more than the construction of bicycle lanes. Recent research indicates that effective cycling policies necessitate an integrated approach that combines high-quality infrastructure, supportive public policies, urban planning, behavioural change initiatives, and sustained political commitment. As a result, cities that have achieved significant increases in cycling rates have typically adopted comprehensive mobility strategies instead of isolated infrastructure projects [4, 5].

International research provides a broader comparative perspective. Pucher and Buehler show that cycling development in the Netherlands, Denmark, and Germany is associated with coordinated infrastructure, traffic calming, bicycle parking, public transport integration, and supportive land-use policies [6]. Their subsequent synthesis places cycling within a wider sustainable transport agenda and emphasises its environmental, health, and space-efficiency advantages [7]. These contributions support examining infrastructure, social practices, and governance together rather than treating cycle lanes as a sufficient intervention.

Studies from Slovenia, Istria, and Graz examine cycling in relation to commuting, tourism, and sustainable urban development [8, 9, 10]. These cases provide regional points of comparison, although their different methods and contexts do not establish the effects of measures in Copenhagen.

Copenhagen offers a useful case for examining how cycling infrastructure, daily travel practices, and public policy interact. Published municipal monitoring provides contextual indicators of cycling use and infrastructure [11]. These indicators must be distinguished by year, geographical coverage, and trip purpose; commuting shares cannot be treated as shares of all journeys.

The Copenhagenize Masterclass combines theoretical instruction with field activities addressing cycling infrastructure, user behaviour, and urban mobility policy. In this study, Space, Culture, and Ambition are used as organising dimensions for a descriptive case analysis, rather than as a validated quantitative index.

This study aims to analyse the principal characteristics of Copenhagen's cycling system using the Copenhagenize methodology and to identify insights to inform the development of sustainable mobility strategies in other European cities, particularly in regions where cycling accounts for a relatively minor share of transport.

MATERIALS AND METHODS

An exploratory, single-city case-study design was adopted. Previous work on Graz provides a comparative conceptual reference [10], while the Copenhagen observations are treated as a distinct, context-specific source of evidence.

The study was conducted during the Copenhagenize Masterclass in Copenhagen, Denmark, from 12 to 14 June 2024. This international educational programme facilitates knowledge transfer on sustainable urban mobility through the Copenhagenize methodology, which evaluates cycling development across three complementary dimensions: Space, Culture, and Ambition.

Field activities included observation of cycling infrastructure, cyclist-count exercises at selected urban intersections, and assessment of bicycle use and supporting facilities. The infrastructure topics considered included cycle track separation, continuity, signage, parking, and traffic organisation. Behavioural topics included the visible diversity of users, cargo bicycle use, responses to traffic signals, and interactions with other road users. The manuscript does not report numerical outputs from the count exercises, site-specific observation durations, or a complete sampling frame. Consequently, those exercises are not used to estimate traffic volumes, gender proportions, or compliance rates.

The Space dimension organised observations on track separation, route connections, and supporting facilities. Culture covered visible bicycle use and road-user interactions. Ambition addressed policy continuity and monitoring using the educational context and documentary evidence. The framework guided descriptive interpretation; it did not provide numerical scores for safety, equity, or social acceptance.

Observations were synthesised descriptively within the three analytical dimensions. No statistical testing or causal modelling was undertaken. The City of Copenhagen's Bicycle Account 2022 was used as a secondary documentary source to contextualise the observations [11]. Its indicators relate primarily to 2021 and 2022 and therefore do not describe conditions measured during the June 2024 visit. Published municipal statistics and the author's field observations are identified separately throughout the results.

RESULTS

Space

At the locations visited, physically separated cycle tracks and clearly allocated cycling space were prominent features. These observations illustrate how street design can reduce direct interaction with motor traffic, although this study did not measure collision risk or perceived safety. The observations concern the visited locations and do not constitute an audit of the entire network.

The infrastructure assessment identified route connections and supporting elements, including bicycle parking, signage, lighting, and dedicated traffic signals. Their practical significance lies in supporting different stages of a journey: reaching a destination, navigating intersections, and parking on arrival. These features suggest that cycling convenience depends on network continuity and supporting facilities together, rather than on isolated track segments.

The allocation of street space to cycling and walking was interpreted as a visible planning priority. However, the field assessment did not quantify modal equity, accessibility for people with disabilities, or differences between neighbourhoods. Such questions require a wider spatial audit and user-based evaluation.

Culture

A continuous flow of cyclists was observed at the intersections visited. This establishes the visible presence of cycling during the observation period, but the absence of reported counts and observation intervals prevents estimation of volumes or citywide modal shares. Everyday bicycle use and the transport of children and goods were prominent descriptive features of the visit; trip purposes were not independently verified through interviews.

Both men and women were observed cycling, and cargo bicycles were visible in family and goods-transport contexts. These observations indicate diversity in bicycle use but do not establish a statistically balanced gender distribution or the frequency of particular user groups. No demographic survey data are available for analysis.

Orderly movement and responses to dedicated traffic signals were noted at the observed locations. Clear markings and spatial separation provided a visible framework for interactions between cyclists and other road users. These findings are descriptive: no standardised conflict assessment or compliance-rate calculation was undertaken. They therefore cannot demonstrate that regulation compliance or safety is uniformly high across Copenhagen.

Ambition

Ambition concerns policy continuity and institutional support, which cannot be established through street observations alone. In this analysis, the governance dimension is therefore interpreted using the Masterclass context and published municipal monitoring [11]. The monitoring publication illustrates how policy objectives can be linked to reported indicators and investment, rather than evaluated solely through visible infrastructure.

The City reported DKK 0.84 billion invested in cycling initiatives over the preceding ten years and a target of 50% of work and education trips by bicycle by 2025 [11]. These are historical expenditure and policy-target figures, respectively; the target is not evidence that the share was achieved. This distinction is essential when interpreting political ambition.

Published municipal indicators

Table 1 provides selected secondary indicators [11]. The 2021 travel shares were affected by COVID-19 restrictions and must not be interpreted as June 2024 measurements. Infrastructure

categories are reported separately, without assuming that they can be summed into a non-overlapping network total.

Table 1. Selected published indicators. Source: City of Copenhagen, Bicycle Account 2022 [11], pp. 6–7 and 14–15. These are secondary data, not results of the 2024 field exercises.

Indicator	Reported value	Reference year
Cycle tracks	388 km	2022
Cycle lanes	33 km	2022
Cycling share of all trips to, from, and in Copenhagen	21%	2021
Cycling share of trips to and from work and education	35%	2021

DISCUSSION

The case suggests that cycling-oriented mobility is best understood through the interaction of infrastructure provision, everyday practices, and institutional support. The field material illustrates these dimensions, while municipal indicators provide a separately sourced quantitative context. Agreement between these evidence types is useful for interpretation, but it does not establish causal relationships or validate the field observations as representative of the city.

The regional studies on Slovenia, Istria, and Graz offer relevant comparisons for commuting, tourism, and planning [8, 9, 10]. The present observations complement these studies by describing the practical visibility of cycling infrastructure and everyday bicycle use in Copenhagen. Differences in study design and local conditions preclude direct estimates of relative policy effectiveness.

The findings are consistent with Pucher and Buehler's account of coordinated cycling policies in the Netherlands, Denmark, and Germany [6]. Their analysis suggests that network provision works alongside parking, traffic calming, public transport integration, and compact development. Copenhagen's observed facilities illustrate some of these elements, but their individual contributions were not measured here. The broader sustainable transport perspective [7] also supports evaluating cycling alongside other urban modes rather than in isolation.

For cities with lower cycling participation, the case suggests assessing missing network links, intersection design, destination parking, and connections to public transport together. These are planning considerations rather than tested prescriptions. Their suitability depends on local trip distances, topography, settlement patterns, resources, and user needs. A locally adapted assessment should precede investment decisions and include people who currently do not cycle.

The main limitations are the three-day observation period, selection of locations within an educational programme, absence of reported count results, and lack of a standardised sampling protocol. Gender balance, compliance, and safety cannot be quantified from this material. Secondary indicators refer to earlier years and include pandemic-related travel changes. No emissions reductions, health effects, or policy impacts were directly measured. Future work should report locations, observation intervals, weather, cyclist counts, and a transparent coding procedure, and repeat observations across seasons. User surveys and before-and-after evaluations would help assess whether interventions improve accessibility and increase cycling.

CONCLUSIONS

This exploratory case study organises observations from the Copenhagenize Masterclass around Space, Culture, and Ambition. The principal descriptive findings concern separated cycling space, supporting facilities, diverse everyday bicycle use, and the relevance of policy monitoring. Published municipal indicators add quantitative context while remaining distinct from the June 2024 observations.

The case supports considering infrastructure, user practices, and governance together when developing sustainable mobility strategies. It does not establish the causal effects of individual measures, quantify environmental benefits, or demonstrate that the Copenhagen approach can be transferred unchanged to other cities.

For Slovenia and other European contexts, the framework can structure an initial diagnostic assessment. Its practical value should be tested through locally collected data, explicit indicators, and monitoring of implemented measures.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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VERMICOMPOSTING OF RABBIT MANURE FOR SUSTAINABLE ORGANIC WASTE MANAGMENT AND ENVIRONMENTAL QUALITY IMPROVEMENT

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ABSTRACT

This paper analyzes a model of sustainable organic waste management through the utilization of rabbit manure via vermicomposting. Rabbit manure, consisting of solid and liquid excreta combined with bedding materials (straw, sawdust), is not directly applied to agroecosystems but is biologically transformed using California red worms (*Eisenia fetida*). Given the high annual manure output (approximately 90 kg per animal), this approach represents an efficient valorization strategy. During vermicomposting, organic matter is decomposed and converted into stable humus with significantly increased macroelement content compared to conventional farmyard manure, including nitrogen, phosphorus, and potassium. The process is conducted under controlled conditions in wooden containers with continuous addition of fresh manure. The resulting vermicompost is applied in the production of fruit, vegetables, and ornamental plants without the use of synthetic fertilizers. The results indicate that this system enables nutrient cycling within the household, reduces waste generation, and improves soil fertility while simultaneously supporting the production of healthy feed for rabbits. The described approach represents a practical model of sustainable agricultural practice applicable in small-scale production systems.

Keywords: vermicomposting, *Eisenia fetida*, rabbit manure, organic waste management, soil fertility, environmental quality.

INTRODUCTION

The intensification of agricultural production has led to an increase in the amount of organic residues originating from livestock production systems, posing a challenge for sustainable resource management and environmental protection. Contemporary agricultural production concepts are increasingly based on the principles of the circular economy, in which organic by-products are regarded not as waste, but as valuable resources that can be reintroduced into the production cycle through appropriate treatment and management practices [1].

Inadequate management of animal-derived organic matter can result in nutrient losses, the generation of unpleasant odors, greenhouse gas emissions, and the potential contamination of soil and water resources. Consequently, modern agricultural production systems increasingly employ biological treatment processes that stabilize organic matter and convert it into products with greater agronomic value.

Vermicomposting is a biotechnological process that stabilizes organic matter through the activity of specialized epigeic earthworm species and the associated microbial community [2,12]. During this process, organic material is fragmented, decomposed, and transformed into stable humic compounds. Unlike conventional composting, vermicomposting relies on the active participation of epigeic earthworm species that inhabit organic matter-rich surface soil layers and play a key role in its transformation [2].

Eisenia fetida is one of the most widely used earthworm species in vermicomposting systems due to its high tolerance to a wide range of organic substrates, rapid reproduction, and efficiency in the transformation of organic matter [3,13,17]. In addition to its direct role in the decomposition process, the activity of this species also influences the development of microbial communities, which play a crucial role in the stabilization of organic matter.

Recent studies indicate that vermicomposting is a complex biological system in which interactions between earthworms and microorganisms determine the course of substrate transformation. Microbial communities associated with *Eisenia fetida* contribute to changes in the composition of organic matter and the formation of a more stable end product [4], [5], [14].

Rabbit manure is a specific organic material consisting of a mixture of feces and bedding used in rabbit production facilities. Owing to its organic matter content and nutrient composition, it represents a potentially valuable substrate for biological transformation. Recent studies have also demonstrated that rabbit manure represents a suitable substrate for vermicomposting because it undergoes rapid biological stabilization and produces a nutrient-rich organic fertilizer [12].

Molina *et al*. [6] demonstrated that rabbit manure can be successfully processed through vermicomposting using *Eisenia fetida*, resulting in the stabilization of organic matter and the production of a material with potential agricultural applications.

The application of vermicompost can improve the physical, chemical, and biological properties of soil, increase soil organic matter content, and enhance nutrient use efficiency in crop production [7,15].

In small-scale agricultural systems, particularly on family farms where livestock and crop production are closely integrated, vermicomposting represents a practical model of a closed-loop nutrient cycling system. In this way, organic matter generated from rabbit production can be transformed into a valuable input for crop production.

The aim of this study was to demonstrate the potential for sustainable management of rabbit manure through vermicomposting at the Dimitrijević family farm in the village of Barje Čiflik, near Pirot, Serbia, and to examine the significance of this process within the context of circular agriculture, environmental protection, and the efficient utilization of organic resources.

Legal Framework for Sustainable Organic Matter Management and Rabbit Welfare

Sustainable management of organic matter generated in agricultural production constitutes an integral part of the broader framework for environmental protection and the rational use of natural resources. In the Republic of Serbia, this area is regulated by legislation that establishes the

principles of environmental protection, waste management, soil conservation, and the responsible treatment of animals.

The Law on Environmental Protection of the Republic of Serbia (2004), [8], establishes the fundamental principles of environmental protection, including pollution prevention, the conservation of natural resources, and the implementation of practices that promote sustainable development. In this context, the utilization of rabbit manure through the vermicomposting process represents an example of transforming organic material into a product with beneficial applications rather than allowing it to become an environmental burden.

The Law on Waste Management of the Republic of Serbia (2025), [9], defines the principles of waste prevention, reuse, and material recovery whenever feasible. Although organic matter generated from agricultural production has a specific legal status compared with municipal waste, the principles of sustainable resource management and the prevention of adverse environmental impacts provide an important basis for the application of processes such as vermicomposting.

In addition to the sustainable management of organic matter, the sustainability of agricultural production systems also requires the provision of appropriate conditions for animal welfare. The Law on Animal Welfare of the Republic of Serbia (2009), [10], stipulates the obligation to ensure appropriate housing conditions, safeguard animal health, provide adequate nutrition and accommodation, and implement management practices that prevent unnecessary suffering.

In rabbit production, animal welfare is closely associated with housing hygiene, bedding quality, ventilation, moisture control, and the regular removal of organic waste. Proper manure management is an integral component of good agricultural practice, as it contributes to maintaining hygienic conditions and reducing potential risks to both animal health and the environment.

Accordingly, the vermicomposting of rabbit manure can be regarded as an integrated approach that links animal welfare, the sustainable management of organic resources, and environmental protection through a closed-loop nutrient cycle.

METHODOLOGY SECTION

Research Site and Characteristics of the Production System

The study was conducted at the Dimitrijević family farm in the village of Barje Čiflik near Pirot, Serbia, where rabbit production and the management of organic material generated during the rearing process are carried out. The farm's production system includes the New Zealand White rabbit and the English Spot rabbit breeds.

The subject of this research was a practical model for the utilization of rabbit manure as an organic substrate for the vermicomposting process, with the aim of assessing its potential transformation into a more stable organic material suitable for application in crop production.

The organic matter management system was based on the integration of livestock and crop production through a closed nutrient cycle:

rabbit production → manure generation → vermicomposting → production of organic fertilizer → crop production

This approach to organic resource management is consistent with the principles of circular agriculture, in which by-products from one production activity are utilized as resources in another. In this way, more efficient nutrient utilization is achieved, the need for removing organic material from the production system is reduced, and a more sustainable approach to farm management is promoted.

Generation and Collection of Rabbit Manure

The organic material used in the vermicomposting process originated from rabbit production at the Dimitrijević family farm, which had 11 animal housing cages during the observation period.

The housing facilities and cages were cleaned once or twice a week, ensuring the maintenance of appropriate hygienic conditions and reducing the accumulation of moisture and harmful gases, particularly ammonia, which at elevated concentrations can negatively affect rabbit health and welfare.

During cleaning, special attention was given to corners and hard-to-reach areas within the facility where organic material could accumulate. Disinfection of the housing facility was carried out periodically, in accordance with the requirements of the production system.

The rabbit manure used in the vermicomposting process consisted of a mixture of solid and liquid excreta combined with bedding material composed of straw and sawdust.

The material was collected after cage cleaning, whereby the housing system with wooden slatted flooring enabled more efficient collection of organic material and its subsequent transfer for further processing.

Figures 1 and 2 document the generation of organic waste, which represents the initial substrate for the biological transformation process. They illustrate the rabbit housing system and the facility hygiene maintenance procedures that precede the collection and further processing of organic matter.



Figure 1. Female rabbit before cage cleaning (source: Lj. Dimitrijević, 2025)



Figure 2. Female rabbit after cleaning the wooden slatted floor cage (source: Lj. Dimitrijević, 2025)

Vermicomposting Process

Rabbit manure supplemented with bedding material was used as the initial substrate for the vermicomposting process. Californian red worms of the species *Eisenia fetida* were introduced into the prepared organic material. Continuous feeding of fresh organic material during vermicomposting was performed in accordance with recommendations for maintaining stable earthworm activity under small-scale production conditions [17]. This species is frequently used in vermicomposting systems due to its high efficiency in the transformation of various organic substrates [2].

The vermicomposting process was carried out at the Dimitrijević family farm using wooden boxes measuring 1 × 2 m, which were suitable for the storage and processing of the generated manure.

Figure 3 shows four wooden boxes containing the initial organic substrate, which served as the basis for the transformation process.

During the process, conditions favorable for earthworm and microbial activity were maintained, primarily appropriate substrate moisture and temperature. Maintaining suitable environmental conditions represents one of the key factors determining the success of vermicomposting, as the activity of *Eisenia fetida* depends on the characteristics of the environment in which the process takes place.

Fresh rabbit manure was added gradually in smaller quantities, as recommended for continuous vermicomposting systems [17], enabling the continuous progression of the process and the gradual transformation of organic matter.

During vermicomposting, interactions between earthworms and microorganisms occur, resulting in the physical fragmentation, decomposition, and transformation of organic material into a more stable organic product enriched with humic compounds.



Figure 3. Wooden boxes containing rabbit manure *(source: Lj. Dimitrijević, 2025)*

It is important to note that laboratory analyses of the physical, chemical, and microbiological properties of the obtained vermicompost were not conducted within the scope of this study. Therefore, the evaluation of the significance of the process is based on direct observation of the production system and comparison with the findings of previous scientific studies.

Application of the Obtained Vermicompost

The obtained vermicompost was used in crop production at the Dimitrijević family farm as an organic fertilizer intended to improve soil quality and support plant nutrition.

The application of vermicompost enables the return of nutrients originating from rabbit production back into the soil system. In this way, a closed cycle of organic matter is achieved:

rabbit production → generation of organic material → vermicomposting → production of organic fertilizer → crop production

The use of vermicompost contributes to increasing soil organic matter content, improving soil structure, and creating more favorable conditions for plant development, which is consistent with previous research findings on the role of vermicompost in sustainable agriculture [7].

The application of the obtained product within the same farm represents the final stage of a closed production cycle, in which organic material generated from livestock production is reintroduced into crop production.



Figure 4. Greenhouse at the Dimitrijević family farm where vermicompost produced from rabbit manure is applied (source: Lj. Dimitrijević, 2025)

Data Analysis and Approach to Results Interpretation

The results of this study are based on a descriptive analysis of the practically implemented model of organic material management at the Dimitrijević family farm and a comparison with available findings from previous scientific studies in the field of vermicomposting.

The following data sources were used within this study:

- direct observation of the production system;
- documentation of the process through photographs
- data on rabbit housing methods and organic material management;
- description of the vermicomposting procedure at the farm;
- comparison with the results of previous scientific studies.

Literature data were used to interpret the significance of the vermicomposting process, the characteristics of *Eisenia fetida*, the role of microbial communities, the properties of vermicompost, and its application in sustainable agriculture.

The obtained results represent a description of the practical implementation of a sustainable organic material management model under the conditions of a small family farm rather than an experimental laboratory study involving quantitative measurements.

RESULTS AND DISCUSSION

Practical Application of Rabbit Manure Vermicomposting at the Dimitrijević Family Farm

Based on the presented production model at the Dimitrijević family farm in the village of Barje Čiflik near Pirot, the possibility of practical valorization of rabbit manure through the vermicomposting process was confirmed. Organic material generated as a by-product of rabbit production was not considered waste requiring disposal, but rather a resource that can be reintroduced into the production cycle through appropriate treatment.

In the observed system, rabbit manure, consisting of excreta and bedding material (straw and sawdust), was used as the initial substrate for the development of the vermicomposting process with the application of *Eisenia fetida*. During the process, biological transformation of organic matter occurs [12], resulting in the formation of a more stable organic material intended for use in crop production.

The presented model demonstrates the possibility of establishing a closed nutrient cycle within a small family farm:

rabbit production → manure generation → vermicomposting using *Eisenia fetida* → organic fertilizer → crop production

In this way, livestock and crop production are integrated, whereby nutrients originating from the livestock production system are returned to the soil system. This approach is consistent with the principles of circular agriculture, in which organic by-products are utilized as resources, thereby reducing the need for their disposal and increasing the efficiency of available material utilization.

The photographs presented in this study (Figures 1–4) document the course of the process, from the generation of manure in rabbit housing facilities, through its collection and processing in wooden boxes, to the application of the obtained vermicompost in the farm's greenhouse.

The model implemented at the Dimitrijević family farm represents an example of a small integrated production system (Figure 5), in which organic matter is transformed and returned to the production cycle. Such systems are particularly important for small agricultural holdings because they enable the rational use of locally available resources through the application of simple biotechnological processes.

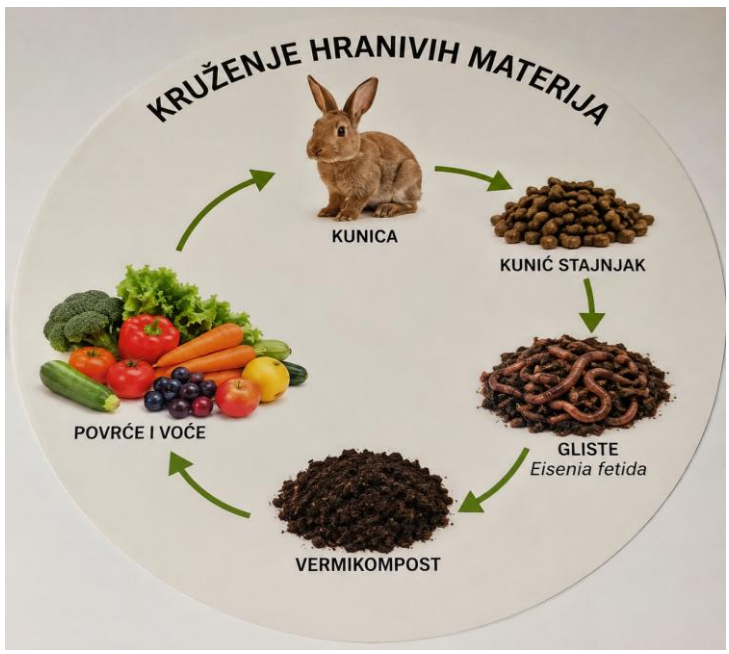

Figure 5. Nutrient Cycling
(Legend: Nutrient Cycling - Female Rabbit; Rabbit Manure; Earthworms; Vermicompost; Fruit and Vegetables)

Transformation of Organic Waste and the Role of *Eisenia fetida*

The vermicomposting process represents a complex biological system in which the combined activity of earthworms and microorganisms leads to the physical fragmentation, decomposition, and stabilization of organic matter.

The species *Eisenia fetida* is one of the most commonly used species in vermicomposting systems due to its ability to adapt to various organic substrates, high reproductive capacity, and efficiency in organic matter transformation [2], [3].

The activity of this species is not limited to the direct consumption of organic material but also involves changes in the microbial community of the substrate. Earthworms and

microorganisms participate in interconnected processes, whereby earthworms fragment the material and create more favorable conditions for the development of microorganisms responsible for the further decomposition of organic compounds. Species-specific interactions between *Eisenia fetida* and microbial communities have been shown to accelerate the decomposition of organic matter and influence the succession of microbial populations during vermicomposting [14].

Recent studies confirm the importance of microbial changes during vermicomposting. Srivastava *et al*. [5] demonstrated that vermicomposting involves the succession of bacterial communities, i.e., changes in the composition and function of microbial populations associated with organic matter transformation. Furthermore, Budroni *et al*. [4] highlighted the importance of microbiota associated with vermicomposting systems in the stabilization processes of organic material.

Under the conditions of the Dimitrijević family farm, the application of *Eisenia fetida* represents a biological treatment approach through which organic material generated from rabbit production is converted into a more stable product suitable for use in crop production.

Specific Characteristics of Using Rabbit Manure as a Substrate

Rabbit manure represents a valuable organic by-product of livestock production due to its content of organic matter and plant nutrients. Its composition, which includes excreta and bedding materials, enables its utilization as a potentially suitable substrate for biological transformation processes.

Direct application of fresh organic materials to soil may be limited by their instability and possible adverse effects if they are not appropriately treated. Vermicomposting enables the controlled transformation of organic matter and the formation of a more stable product with more favorable properties for application in crop production.

Molina *et al*. [6] demonstrated that rabbit manure can be successfully used in the vermicomposting process with the application of *Eisenia fetida*, resulting in the stabilization of organic matter and the formation of a product with greater potential for agricultural use.

During the process, easily available organic compounds are decomposed, while more complex organic structures are transformed into more stable humic compounds. Vermicomposting also increases the concentration and availability of essential plant nutrients, particularly nitrogen, phosphorus and potassium, compared with untreated livestock manure [12]. The formation of humus plays an important role in improving soil properties, as it can contribute to:

- Increased soil water retention capacity;
- Improved binding of nutrients;
- Enhancement of soil structure;
- Creation of more favorable conditions for the development of plant root systems.

In this way, vermicomposting of rabbit manure represents a process through which an organic by-product is transformed into a product with greater agronomic value.

Significance of Vermicompost for Soil and Crop Production

The vermicompost obtained at the Dimitrijević family farm is used in greenhouse crop production as an organic fertilizer. Its application represents the final stage of a closed production cycle, in which material originating from rabbit production is returned to the soil system.

According to Lazcano and Domínguez [7], the application of vermicompost can positively influence the physical, chemical, and biological properties of soil by increasing organic matter content and stimulating soil biological activity.

Atiyeh *et al*. [11] reported that vermicomposts can contribute to improving conditions for plant growth, with the effect depending on vermicompost characteristics, plant species, and the method of application.

Within small-scale production systems, the use of vermicompost is particularly significant because it enables the utilization of materials generated on the farm itself and reduces dependence on external production inputs.

Contribution to Circular Agriculture and Environmental Protection

The model implemented at the Dimitrijević family farm represents a practical example of circular agriculture, as it enables the reintegration of organic matter into the production process.

Unlike a linear system:

production → organic waste → disposal

a circular system is established:

rabbit production → manure → vermicompost → crop production → return of nutrients to the agroecosystem

Bernal *et al*. [1] emphasize the importance of proper management of animal-derived organic materials in order to reduce nutrient losses and enhance the sustainability of agricultural systems.

In accordance with the principles established by the Law on Environmental Protection of the Republic of Serbia (2004), [8], and the Law on Waste Management of the Republic of Serbia (2025), [9], organic materials generated within production processes should be considered from the perspective of their potential for reuse and valorization whenever this is technically and environmentally justified.

In this regard, vermicomposting of rabbit manure represents a process that contributes to more responsible management of organic materials by enabling their transformation into a useful product rather than their inappropriate disposal.

Such a system is particularly important for small family farms, where the integration of livestock and crop production can lead to more efficient resource utilization and a reduction in the amount of material leaving the production system. Comprehensive reviews indicate that vermicomposting represents one of the most efficient biological approaches for converting different types of agricultural organic waste into high-quality organic fertilizers while supporting circular agriculture principles [16].

Environmental Aspects of Rabbit Manure Vermicomposting and Its Contribution to Environmental Protection

The management of organic materials originating from livestock production represents an important aspect of environmental protection, particularly in small-scale production systems where the proper storage, treatment, and utilization of manure directly influence production area hygiene and the conservation of natural resources.

Inadequate manure management can result in nutrient losses, the generation of unpleasant odors, and potential impacts on soil and water resources. Therefore, processes that stabilize organic matter and enable its reuse within production systems represent an important component of sustainable resource management.

Vermicomposting of rabbit manure represents an environmentally acceptable method for organic material transformation, as it enables the conversion of unstable organic matter into a more stable organic product. In this way, nutrients remain within the production system and can be reused through crop production.

The application of the obtained vermicompost on the same farm contributes to closing the material cycle and is consistent with the principles of the circular economy. This approach can contribute to reducing the need for mineral fertilizer application, increasing soil organic matter content, and preserving its physical, chemical, and biological properties.

From the perspective of the legislative framework of the Republic of Serbia, this approach to organic material management is associated with the principles of pollution prevention, rational use

of natural resources, and responsible waste management, as defined by the Law on Environmental Protection (2004), [8], and the Law on Waste Management (2025), [9].

At the same time, manure management is also connected with rabbit welfare, as maintaining hygienic conditions in housing facilities, regular removal of organic material, and control of factors such as moisture and the concentration of harmful gases represent important elements of good production practice. In accordance with the Law on Animal Welfare of the Republic of Serbia (2009), [10], ensuring appropriate housing conditions represents a fundamental prerequisite for maintaining animal health and welfare.

The example of the Dimitrijević family farm demonstrates that vermicomposting is not merely a technique for producing organic fertilizer, but rather an integrated approach that connects environmental protection, responsible management of organic resources, rabbit welfare, and sustainable crop production.

CONCLUSION

Vermicomposting of rabbit manure represents a sustainable biotechnological process through which an organic by-product of livestock production is transformed into a more stable organic material suitable for reuse within the agricultural system. The example of the Dimitrijević family farm confirms the possibility of establishing a closed nutrient cycle, thereby integrating livestock and crop production in accordance with the principles of circular agriculture.

The particular value of the presented model lies in its simplicity and adaptability to the conditions of small-scale farms, where significant contributions to resource conservation and soil quality improvement can be achieved with minimal technical requirements. Thus, vermicomposting is demonstrated as a process that simultaneously connects animal welfare, rational management of organic materials, and environmental protection.

A limitation of this study is the fact that laboratory analyses of the physical, chemical, and microbiological properties of the obtained vermicompost were not conducted. Future studies should include detailed analyses of nutrient content, the carbon-to-nitrogen ratio (C:N), microbial activity, vermicompost maturity, and comparisons with recently developed continuous-flow vermicomposting systems [17].

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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BEES AS ENVIRONMENTAL BIOINDICATORS: THE ASSESSMENT OF POLLUTION AND ECOLOGICAL RISK

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ABSTRACT

Honey bees (*Apis mellifera*) are reliable bioindicators of environmental quality due to their role as pollinators, their wide foraging range, and their continuous interaction with various components of the ecosystem. The aim of this paper is to examine the importance of honey bees as bioindicators by analysing the mechanisms of pollutant accumulation and their application in ecological risk assessment. During the collection of nectar, pollen, water, and plant resins, honey bees come into contact with pollutants originating from air, water, and soil, including heavy metals, pesticides, and microplastic particles, which can subsequently be detected in their tissues and bee products. In addition to chemical analyses, changes in the behaviour, physiological condition, and mortality of bee colonies represent important indicators of environmental contamination. Particular attention is given to pesticides, especially neonicotinoids, owing to their pronounced toxic and sublethal effects. Although research on the presence of microplastics in bee products is still evolving, current findings indicate their potential value in biomonitoring. Overall, honey bees represent an effective and cost-efficient tool for environmental biomonitoring, with considerable importance for ecological risk assessment and biodiversity conservation.

Keywords: bees, bioindicators, biomonitoring, environment, ecological risk.

INTRODUCTION

Honey bees play a vital role in maintaining the environment, biodiversity, and ecosystem functioning. Their importance extends beyond the production of food products to include a wide range of substances used in the pharmaceutical, cosmetic, and industrial sectors. Pollination by honey bees is a key ecological process in natural ecosystems, contributing to both the quality and yield of agricultural crops. In many countries, pollination is provided as an organised, contract-based service between crop producers and beekeepers. It also plays a crucial role in maintaining ecological balance and biological diversity. A large proportion of crops intended for human consumption depend, to varying degrees, on insect pollination, with honey bees serving as the primary pollinators. It has been estimated that approximately four million flowers must be visited to produce one kilogram of honey, while a single honey bee visits around 7,000 flowers per day [1]. Consequently, honey bees come into daily contact with extensive areas of soil, water, and vegetation, making them reliable bioindicators of environmental pollution [1]. A single bee colony can effectively „monitor" an area extending several kilometres from the hive, enabling relatively accurate assessments of local environmental contamination. Furthermore, honey bees respond rapidly to changes in environmental conditions, and alterations in colony size, behaviour, or mortality may be associated with increased levels of pollution. This review presents the findings of studies investigating honey bees and bee products as tools for environmental biomonitoring.

METHODOLOGY

The paper employs a review-based approach encompassing an analysis of the biological and ecological characteristics of the honey bee (*Apis mellifera*), including its taxonomic classification, developmental biology, and the organization of the honey bee colony. Particular emphasis is placed on the role of honey bees in the ecosystem and their interactions with plants, water, soil and air, thereby enabling an integrated assessment of environmental quality.

Taxonomy and Species Diversity

Bees (Apiformes) comprise approximately 20,000 species worldwide [2]. They inhabit all continents except Antarctica. The western honey bee, *Apis mellifera Linnaeus* (1758) belongs to the subfamily *Apinae* within the family *Apidae* [3].

The biological classification of the European honey bee (*Apis mellifera, L*), as described by Linnaeus, is presented in Table 1.

Table1 Taxonomic classification of the species *Apis mellifera L.* (translated and adapted from [4]).

CLASS	
Regnum (Kingdom)	*Animalia*
Phylum (Type)	*Arthropoda*
Subphylum (Subtype)	*Mandibulata (Hexapoda)*
Classis (Class)	*Insecta*
Subclassis (Subclass)	*Pterygota*
Ordo (Order)	*Hymenoptera*
Subordo (Suborder)	*Apocrita*
Infraordo (Group)	*Aculeata*
Superfamilia (Superfamily)	*Apoidea*
Familia (Family)	*Apidae (bumblebees and honey bees)*
Subfamilia (Subfamily)	*Apinae (honey bees)*
Tribus (Tribe)	*Apini*
Genus	*Apis*
Species	*Apis mellifera Linnaeus (1758)*

Apis mellifera carnica (Pollmann, 1879) –The Carniolan honey bee is a subspecies of *Apis mellifera*. Due to its efficiency in nectar foraging and honey production, it is currently one of the most widespread subspecies of the honey bee in Europe and beyond. Its body is covered with fine hairs and is well adapted to a variety of climatic conditions. In particular, it is adapted to survive long and cold winters [5].

The Biology of the Species

Honey bee belongs to the group of holometabolous insects. This means that all members of a bee colony must pass through specific developmental stages during their life cycle (egg, larva, pupa, and adult), as shown in Figure 1.

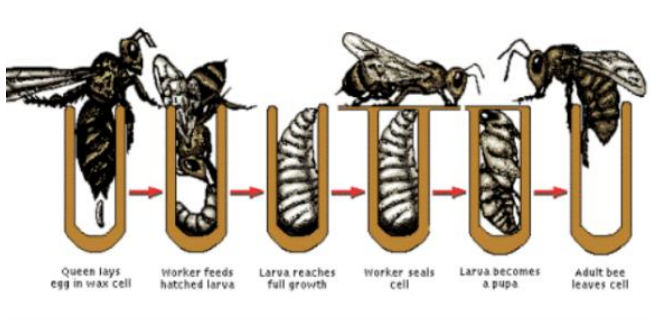

Figure 1 Holometabolous Development of the Honey Bee [6]

The complete development of the honey bee includes embryonic and post-embryonic periods. During embryonic development, which lasts three days, changes occur within the egg membranes. These processes result in the transformation of a single egg cell into a multicellular larva. After these transformations, the larva hatches by breaking through the egg membrane and enters the brood cell, marking the beginning of post-embryonic development. Post-embryonic development includes all subsequent developmental stages that take place outside the egg membranes.

The Structure and Organisation of the Honey Bee Colony

The honey bee is adapted to a social way of life. This colony consists of a single queen, two to three thousand drones (during the foraging season), and several tens of thousands of worker bees (Figure 2).

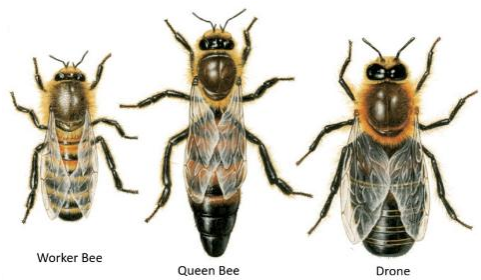

Figure 2 Worker Bee, Queen Bee and Drone (translated and adapted from [7])

The bee colony consists of both male and female members. The female members include the queen and worker bees, while the male members are drones. The queen is the only reproductively active female in the hive. She has the ability to secrete specific chemical substances (pheromones)

that influence the development and behaviour of worker bees. In this way, the queen ensures the coordinated and integrated development of the bee colony.

Drones are the male members of the bee colony whose primary role is to fertilise the queen. The presence of drones in the hive stimulates worker activity and increases honey production. They also contribute to the thermoregulation of the hive, while drone brood serves as a reserve source of water and proteins. After mating with the queen, drones die.

Worker bees are the permanent and most numerous members of the bee colony, performing all functions within the colony except reproduction. In the first days after emergence, workers clean the cells and maintain hive hygiene, acting as hygienists. After this period, they take on the role of nurse bees, feeding the larvae and the queen. As they age, they begin to secrete wax and participate in comb construction, as well as in the processing of nectar into honey. In later life stages, they become hive guards. The oldest workers assume the role of foragers. They leave the hive and collect nectar, pollen, water, and propolis. During these activities, they can travel long distances and thereby contribute to plant pollination, which is of crucial importance for ecosystems and agriculture [8].

Honey bees possess a specific anatomical structure that becomes particularly important during the collection of nectar and pollen in nature. Bees have a specially adapted tibia and the first tarsal segment of the hind legs. The outer side of the tibia is concave, surrounded by a fringe of hairs. This structure is used by the bee to store pollen and is therefore referred to as the pollen basket (corbicula). On the upper part of the first tarsal segment, there is a spur-like projection used by the bee to press and pack the collected pollen into the tibia [9]. Without such specialised anatomical adaptations, bees would collect significantly less food, which would directly result in weaker brood development and a reduced population size of the bee colony.

The Role of Bees in the Ecosystem

The honey bee is the most economically important insect and, among other roles, serves as a pollinator of agricultural crops. As such, honey bees are crucial for maintaining biological diversity [10]. As pollinators, bees increase the yield of agricultural crops and also contribute to their quality. Through pollination of crops, bees improve their characteristics, including fruit shape and size, as well as acidity and sugar concentration.

In some parts of the world, such as the United States, the provision of commercial pollination services for agricultural crops is widely practiced. This service is considered economically profitable and is based on contractual agreements between crop owners and beekeepers. These contracts include information on the flowering stage of cultivated crops as well as any potentially wild vegetation within or surrounding the plantation; the average number of frames with bees and brood per colony at the beginning of the pollination service; the grower's commitment not to use pesticides that may be harmful to bees during their presence in the crop area; and an obligation to promptly inform beekeepers if pesticide application becomes necessary, along with other relevant provisions that ensure the protection of the rights and responsibilities of both contracting parties [8]. In Serbia, contract-based crop pollination is also practiced and is typically based on cooperation between larger companies and beekeeping associations.

Pollen of entomophilous plants (insect-pollinated plants) is heavier and stickier compared to pollen of anemophilous plants (wind-pollinated plants). According to Spürgin [11], approximately four honey bee colonies per hectare are required for efficient pollination. The attractiveness of cultivated plant flowers to honey bees depends on flower shape, size, colour, and scent; the flowering duration of the plant species; the distance of bee colonies from nectar sources; the availability of water sources; climatic conditions; colony strength; and the presence of wild and nectar-producing weed species [8]. In addition, bees contribute to the collection and production of honey, wax, propolis, pollen, royal jelly, and bee venom. All of these bee products are valuable natural resources in human nutrition and related applications [9]. As pollinating insects, bees play a significant role in the survival of rare plant species, and a healthy bee colony benefits many other organisms within the ecosystem [11].

Approximately one quarter of a honey bee colony, or about 10,000 worker bees, is involved in crop pollination. Each foraging bee performs an average of 12–15 flights per day. During a single foraging trip, in order to collect nectar, a bee must visit around 100 apple blossoms (*Malus domestica*) or approximately 80 pear blossoms (*Pyrus communis*) to fill its honey stomach and secure sufficient reserves for its return to the hive [12]. On a daily basis, a single honey bee colony visits an average of 13,500,000 flowers. This finding highlights the crucial and irreplaceable role of honey bees in maintaining biological diversity, as well as their importance as biological indicators of environmental conditions. The specific anatomical structure of *Apis mellifera* not only enables efficient pollen collection but is also directly linked to their function as bioindicators of environmental quality. Due to the presence of pollen baskets (corbiculae) and dense body hairs, bees come into contact with a large number of plants and environmental particles during each flight. In doing so, they collect not only pollen and nectar but also various pollutants (e.g. pesticides, heavy metals, dust particles) that may be present on plants or in the air. Honey bees can therefore be considered "free" self-sampling organisms. They provide beekeepers with samples that can be used to determine numerous indicators of environmental conditions [13].
These characteristics indicate that honey bees represent a unique biological system for monitoring environmental quality. Unlike conventional sampling of individual ecosystem components, bees simultaneously come into contact with air, water, soil, and plants during their daily activities, thereby enabling an integrated assessment of the presence of various pollutants within a given area. Due to this lifestyle, bee-based biomonitoring represents an efficient, cost-effective, and scientifically reliable approach for assessing environmental quality.

RESULTS

Pollution Indicators

Honey bees are considered among the most suitable insects for detecting environmental pollution and assessing its adverse effects. They are sensitive to various biocides, such as pesticides. They are referred to as a "first-order indicator species" since their disappearance signals a serious disturbance of ecological conditions. Any change in the natural environment may be reflected in bees through altered or increased mortality rates. Traces of environmental pollution may be present in bees, their brood, and bee products [12], [14]. Foraging bees are in direct contact with pollutants from water and air, and indirectly through plants and contaminants originating from soil (Figure 3). Pollutants that enter the hive via nectar, pollen, propolis, and water accumulate in bee products (collectors), as well as in larvae and adult bees (accumulators) [15].

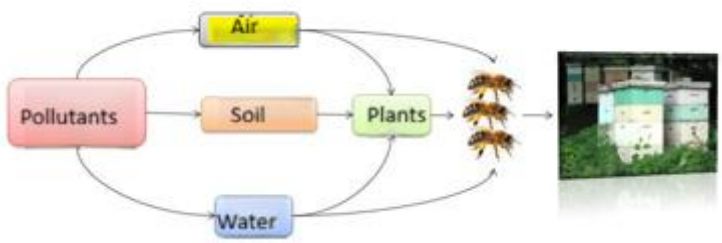

Figure 3 The Impact of the Environment on the Bee Colony (translated and adapted from [16])

Advantages of Honey Bees as Bioindicators

The advantages of honey bees as bioindicators are reflected in their large foraging range, daily contact with air, soil, water, and plants, as well as their ability to accumulate various pollutants in their bodies and bee products. In addition, sampling of bees and their products is relatively simple and cost-effective, enabling continuous biomonitoring of different types of ecosystems.

Heavy Metals

Heavy metals are classified among the most significant potentially harmful pollutants. Honey bees are exposed to heavy metals through contaminated air, water, soil, and food sources. The presence of heavy metals can affect physiological and metabolic processes in living organisms. Heavy metals are non-degradable and are therefore permanently present in the environment, entering biological cycles. For honey bees, the most important heavy metals are those that are most commonly found in the environment and exhibit strong toxic effects even at low concentrations. Due to their high toxicity to living organisms and wide environmental distribution, the most significant include cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni), as well as bioelements such as copper (Cu), iron (Fe), zinc (Zn), manganese (Mn), cobalt (Co), and selenium (Se). These bioelements in small concentrations are essential for various biochemical and physiological processes, but may become harmful at higher concentrations [16].

The results of previous studies indicate that the concentrations of heavy metals in bee bodies and their products reliably reflect the level of local environmental contamination. Due to their bioaccumulation capacity and constant contact with various components of the ecosystem, honey bees enable the assessment of the spatial distribution of pollution and the identification of potential sources of heavy metal emissions.

Pesticides

Honey bees come into contact with pesticides during the collection of nectar, pollen, and water from treated plants, which can lead to acute or chronic poisoning. In addition to direct toxic effects, pesticides may also cause sublethal effects. These sublethal effects may manifest as reduced immunity and increased susceptibility to diseases and parasites. Bees that come into direct contact with certain insecticides may die at the site of exposure or upon returning to the hive. The number of dead bees in front of the hive is considered one of the most reliable indicators for suspecting pesticide poisoning.

One of the early studies on the effects of pesticides on honey bees was conducted in northern Italy between 1983 and 1986 as part of a monitoring project. The study included apiaries located in areas with varying levels of agricultural intensity and chemical pressure. During the research, dead bees from sites with increased mortality were analysed. In 76% of the cases, the presence of a chemical agent responsible for bee mortality was identified [12].

In Brazil, during 2003 and 2004, honey samples from apiaries located near the ecological reserve in Bauru were found to contain 48 different pesticides. The detected pesticides belonged to various chemical groups, including organochlorine, organophosphate, organonitrogen, and pyrethroid compounds [17]. These results indicated the widespread presence of pesticides in the environment and their incorporation into bee products.

With the increasing use of pesticides from the neonicotinoid group for seed treatment of agricultural crops, a significant rise in the occurrence of neonicotinoid residues has been observed in pollen, water, soil, and bees. Bees exposed to sublethal doses of neonicotinoids lose their orientation ability and sense of taste, which affects their feeding behaviour. Consequently, their overwintering capacity is reduced, leading to increased colony mortality [18]. Since neonicotinoids are used worldwide, their residues can be found in food products such as fruit, vegetables, cereals, honey, and baby food, and they also persist in the environment.

Available findings indicate that honey bees can be used not only for the detection of acute poisoning events but also for monitoring long-term exposure to pesticides. The analysis of dead bees, honey, pollen, and wax enables the assessment of the level of chemical load in agroecosystems. Based on the presented studies, it can be concluded that honey bees represent an extremely sensitive biological system for the early detection of pesticide presence in agroecosystems.

Microplastics

Microplastic particles (MPs) are defined as polymer particles containing plasticizers and having a diameter of less than 5 mm. Microplastics are present in various environmental compartments, including air, soil, and water [19].

Microplastics are classified into two subgroups, primary and secondary microplastics. Primary microplastics are manufactured directly as microscopic materials and are intended for use in consumer products such as cosmetics, detergents, cleaning agents, and abrasive blasting media. Secondary microplastics originate from the degradation of plastic materials in the atmosphere or aquatic environments under the influence of natural ageing processes and weathering conditions. Examples of secondary microplastics include particles generated by the wear of tyres and road surfaces, as well as sludge from municipal wastewater treatment [20], [21]. It is generally considered that the majority of environmental microplastics consist of secondary microplastics [22], [23]. Microplastic particles that enter the atmosphere have negative impacts on both aquatic and terrestrial organisms, including honey bees [24].

Studies have shown that polystyrene microplastics (PS-MPs) can reduce bacterial diversity in the gut of the western honey bee, induce changes in the gut microbiome, and alter the expression of genes associated with oxidative damage, detoxification, and immune responses [25]. Bee mortality induced by microplastic particles is significantly increased when the gut microbiome is disrupted due to tetracycline exposure [25].

Environmental factors such as weather conditions, solar radiation, pH, exposure duration, and the hydrophobicity of persistent organic pollutants (POPs) can influence the adsorption kinetics of pollutants onto microplastics [26]. For instance, polyethylene (PE) microplastics may serve as important carriers of pesticides in agricultural soils [27], thereby further enhancing pesticide exposure effects in honey bees.

Accumulation of pollutants in bees, either on their bodies or within them, as well as in bee products such as honey, pollen, and wax, enables their use as indicators of environmental quality [28], [29], [30]. The presence of microplastics in honey and pollen not only indicates environmental risk but may also have potential consequences for both bee and human health.

Although the application of honey bees in microplastic monitoring is still in the developmental stage, current findings highlight the significant potential of this approach. At the same time, differences in sampling methods and laboratory analyses indicate the need for standardized protocols to ensure comparability of results across studies.

Overall, the results of numerous studies confirm that honey bees can serve as reliable bioindicators of different types of pollution. Their capacity to accumulate contaminants, together with changes in the behaviour, physiology, and vitality of bee colonies, enables the assessment of ecological risk and the early detection of changes in environmental quality.

Legislative Framework in Serbia

The Food Safety Law regulates the conditions for the production and trade of food with the aim of protecting consumer health. Within this legal framework, honey as a bee product is subject to monitoring for the presence of contaminants, including pesticides and heavy metals. Although bees are not formally recognised as environmental bioindicators in a legal sense, the analysis of their products enables indirect monitoring of environmental pollution in ecosystems, thereby linking food safety systems with ecotoxicological research [31]. The Plant Protection Products Act, harmonised with EU regulations (in particular Regulation (EC) No 1107/2009), does not formally recognise bees as a specific legal category of organisms; however, they are explicitly included in risk assessment procedures as sensitive non-target organisms [32].

Additional elements of the regulatory framework include the Environmental Protection Law and the Chemicals Law, which govern the control of pollutants and hazardous substances in the environment, including air, water, and soil [33], [34]. These regulations provide a general basis for monitoring and managing the chemical load of ecosystems, in which bees play an important role as indicators of environmental contamination.

Although current legislation does not formally recognise honey bees as bioindicators, their application in scientific research and biomonitoring programmes may represent a significant complement to existing environmental monitoring systems.

CONCLUSION

The results of the analysed studies confirm that honey bees represent a reliable and highly versatile bioindicator of various forms of environmental pollution. Their use enables the simultaneous assessment of the chemical load of ecosystems and the monitoring of biological responses of organisms to the presence of contaminants, making them a valuable tool in modern biomonitoring programmes. Although the potential applications of honey bees in biomonitoring are well documented, further improvement of standardised sampling methods and laboratory analyses is necessary to ensure comparability of results across different studies. The integration of bee-based biomonitoring into environmental monitoring programmes may enhance early detection of pollution and enable more effective planning of ecosystem protection measures. Given their multiple ecological and economic roles, the inclusion of honey bees in routine environmental monitoring programmes could significantly contribute to biodiversity conservation, improved food safety, and more efficient protection of natural resources.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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BIOCHAR APPLICATION IN MANURE MANAGEMENT: ENVIRONMENTAL IMPACTS, GAS EMISSIONS, AND NUTRIENT RETENTION

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ABSTRACT

Manure management in intensive livestock production represents a major environmental challenge due to gas emissions, nutrient losses, and potential air and water pollution. Biochar is a carbon-rich material produced through biomass pyrolysis under limited oxygen conditions. It is used as an amendment in manure management systems due to its porous structure and ability to adsorb ammonia and other compounds present in manure. This paper reviews the available scientific literature on biochar application in manure management, with the aim of summarizing its effects on environmental impact, gas emissions, and nutrient retention. The literature most commonly indicates that biochar application may reduce ammonia and greenhouse gas emissions and improve nutrient retention in manure. However, these effects are not consistent and depend on biochar physicochemical properties, manure type, and application conditions. The reviewed findings highlight biochar as a potentially useful amendment that can contribute to reducing environmental burdens and improving the sustainability of manure management systems.

Keywords: biochar, manure, gas emissions, environmental impact, nutrient retention, sustainability.

INTRODUCTION

Intensive livestock production generates large quantities of manure, which represents a valuable organic resource for agricultural use. At the same time, inadequate manure management can lead to various adverse environmental impacts. During manure storage, treatment, and land application, emissions of ammonia (NH_3), methane (CH_4), and nitrous oxide (N_2O) occur, along with nutrient losses, affecting the quality of air, soil, and water, while also reducing the agronomic value of manure as a fertilizer [1], [2].

Manure management is no longer considered solely from the perspective of greenhouse gas emissions, but also in the context of the presence of emerging pollutants. Antibiotic residues, *antibiotic resistance genes* (ARGs), microplastics, and other organic pollutants can be introduced into the soil through manure application, posing potential risks to agroecosystems and human health. Consequently, management strategies are being developed to simultaneously reduce gaseous emissions, conserve nutrients, and limit the spread of these contaminants [3].

One approach that has attracted considerable attention in recent years is the application of biochar in manure management systems. Biochar is produced through the pyrolysis of biomass under oxygen-limited conditions and is characterized by a well-developed porous structure, a high specific surface area, a high cation exchange capacity (CEC), and the ability to adsorb a wide range of organic and inorganic compounds. These properties enable the retention of ammonium ions and other nutrients, reduce nutrient losses, and influence the microbial processes occurring during manure storage [4], [5], [6].

The results of previous studies indicate that the application of biochar can contribute to reducing emissions of ammonia, methane, and nitrous oxide, while simultaneously enhancing nutrient retention and improving the quality of manure as an organic fertilizer. However, the magnitude of these effects varies considerably among studies, primarily due to differences in biomass feedstock, biochar production conditions, manure type, application rate, and storage practices. Therefore, the effectiveness of biochar cannot be considered independently of the conditions under which it is applied [3], [7], [8].

The aim of this paper is to review and analyse the relevant scientific literature in order to evaluate the potential of biochar application in manure management, with particular emphasis on its effects on ammonia and greenhouse gas emissions, nutrient retention, and its potential to reduce the dissemination of emerging pollutants. Particular attention is given to the factors determining the effectiveness of biochar and the limitations associated with its application in modern livestock production systems.

METHODOLOGY

This paper is structured as a review study based on an analysis of the available scientific literature on the application of biochar in manure management systems in intensive livestock production. The review focuses on studies investigating the effects of biochar on emissions of ammonia, methane, and nitrous oxide, nutrient retention, and the factors influencing the effectiveness of its application.

The literature was collected through searches of the Scopus, Web of Science, and Google Scholar databases using combinations of the following keywords: *biochar, manure management, ammonia emissions, greenhouse gas emissions, nutrient retention*, and *livestock manure*. Priority was given to review articles and original research papers published in international peer-reviewed journals, encompassing a range of biochar types, manure types, and application conditions.

The analysis included the studies which:

- examined the application of biochar in manure management systems,
- evaluated its effects on NH_3, CH_4, and N_2O emissions or on nutrient retention,
- enabled comparison of different biochar characteristics and application conditions, and
- were peer-reviewed scientific articles or reviews.

Special attention was given to recent studies examining the role of biochar in the retention of emerging pollutants, including antibiotics, antibiotic resistance genes (ARGs), and microplastics.

The literature analysis was conducted through a qualitative comparison of individual study results, identifying similarities and differences in the effects of biochar application on gas emissions, nutrient retention, and other indicators relevant to sustainable manure management. Particular emphasis was placed on factors influencing biochar effectiveness, including biomass feedstock, pyrolysis temperature, physicochemical properties of biochar, manure type, and storage conditions.

The methodological approach applied in this study is presented in Figure 1.

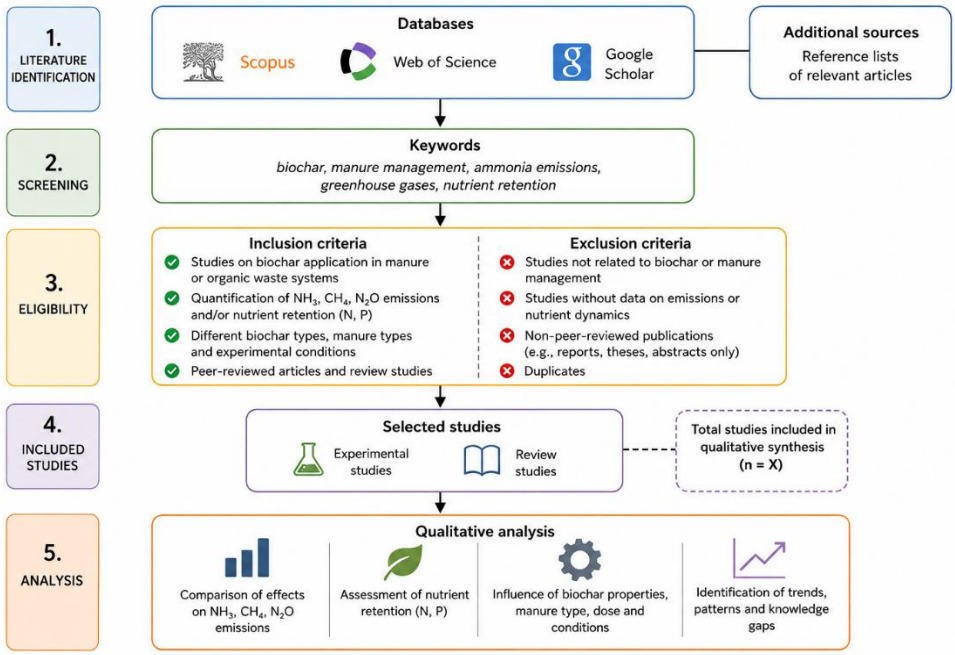

Figure 1 Methodology Flowchart (developed by the author and visually rendered with AI tools)

RESULTS AND DISCUSSION

The results of the literature review are organized according to the most significant areas of biochar application in manure management. Particular attention is given to the properties of biochar that determine its effectiveness, its impact on ammonia and greenhouse gas emissions, nutrient retention, and the limitations of its application. A conceptual representation of these processes is shown in Figure 2.

Properties of biochar relevant to manure management

The effectiveness of biochar in manure management systems largely depends on its physicochemical properties. These are influenced by the type of biomass, production conditions — particularly pyrolysis temperature — as well as any post-treatment processes. Changes in these parameters affect porosity, specific surface area, pH, cation exchange capacity (CEC), functional group content, and carbon stability, which in turn determine its ability to retain nutrients and adsorb compounds present in manure [4], [5], [6].

The most important property of biochar is its well-developed porous structure, which provides a large specific surface area for the adsorption of ammonium ions (NH_4^+), ammonia

(NH_3), water, and dissolved organic compounds. Due to its high cation exchange capacity (CEC), it contributes to the retention of nutrients and reduces their losses during manure storage [4], [6], [9].

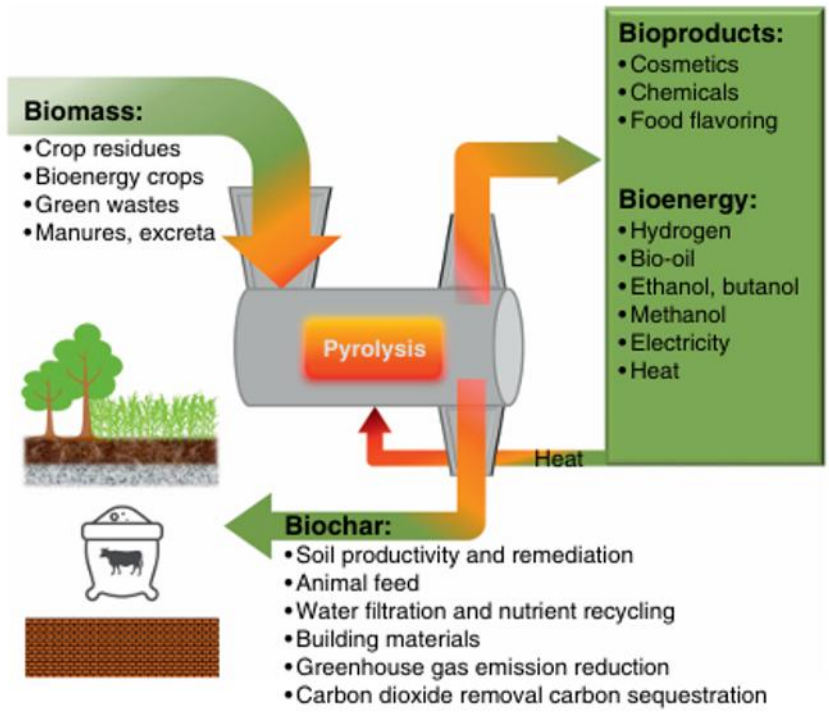

Figure 2 Structure and Flow of the Biochar System [4]

Pyrolysis temperature significantly influences its properties. Biochar produced at higher temperatures exhibits a larger specific surface area, more pronounced porosity, and greater carbon stability, whereas materials obtained at lower temperatures contain a higher number of oxygen-containing functional groups, which may enhance the binding of certain organic compounds. Therefore, the selection of biochar should be aligned with the intended application and the characteristics of the manure [4], [6].

The effectiveness of its application is also influenced by manure characteristics, including dry matter content, pH, carbon-to-nitrogen ratio, and storage conditions. These differences affect adsorption and microbial processes, which is why the effects of biochar vary across different livestock production systems [1], [3].

Effect of biochar on ammonia emissions

Ammonia (NH_3) emissions represent one of the most significant challenges in manure management, as they contribute to soil acidification, eutrophication of aquatic ecosystems, and nitrogen losses, thereby reducing the agronomic value of manure. Consequently, the development of technologies that enable nitrogen retention is considered a priority in sustainable livestock production [1].

The reduction of ammonia emissions following biochar application is primarily attributed to its adsorption properties. Due to its well-developed porous structure, large specific surface area, and high cation exchange capacity, biochar binds ammonium ions (NH_4^+), reduces their transformation into gaseous ammonia, and limits ammonia volatilization. At the same time, it

improves water retention and creates more favourable conditions for microbial processes that contribute to nitrogen conservation in manure [4], [10].

The results of the analysed studies confirm that the addition of biochar can significantly reduce ammonia emissions; however, the observed effects are not consistent. They are influenced by biochar properties, manure characteristics, and storage conditions, including temperature, moisture content, pH, and storage method. Therefore, results from laboratory studies cannot always be directly transferred to production conditions, highlighting the need for further research under real livestock farming conditions [3], [10], [11].

By retaining a larger proportion of nitrogen in manure, nitrogen losses during storage are reduced, thereby increasing its utilisation efficiency after application to agricultural soils. In this way, biochar can contribute to more efficient nitrogen management and more rational use of manure in crop production [3], [12].

Effect of biochar on greenhouse gas emissions

In addition to ammonia, methane (CH_4) and nitrous oxide (N_2O) emissions represent significant environmental concerns during manure storage and treatment. Their formation results from microbial processes influenced by organic matter content, oxygen availability, temperature, moisture, and the chemical composition of manure [1], [13].

Unlike ammonia, the impact of biochar on CH_4 and N_2O emissions is based on more complex mechanisms. The addition of biochar can improve manure aeration, alter the availability of carbon and nitrogen, affect moisture content, and create conditions that modify the activity of microorganisms responsible for methanogenesis, nitrification, and denitrification. At the same time, the adsorption of dissolved organic compounds and mineral forms of nitrogen may influence the intensity of biochemical processes leading to the formation of these gases [7], [8].

Research findings generally indicate a reduction in methane emissions following biochar application, with the observed effects depending on its properties, manure characteristics, and storage conditions. The most pronounced reductions have been recorded in systems where biochar improved aeration and reduced conditions favourable for methanogenic microorganisms. However, some studies have not found statistically significant changes, indicating that the effects of biochar application are not uniform across all production conditions [8], [14].

Similar trends have been observed for nitrous oxide emissions. In most studies, a reduction has been reported, which is associated with changes in mineral nitrogen availability and in the conditions governing nitrification and denitrification processes. Nevertheless, the magnitude of the observed effect varies among studies, confirming that N_2O emissions are simultaneously influenced by biochar properties, manure characteristics, and storage conditions [7], [8].

Recent review studies indicate that biochar has significant potential to reduce greenhouse gas emissions; however, its effectiveness depends on application conditions. Therefore, further long-term research and methodological standardisation are needed to more reliably assess the effects of different types of biochar in manure management systems [3].

Retention of nutrients and improvement of manure quality

One of the important effects of biochar application in manure management is the preservation of nutrients during storage. Losses of nitrogen, phosphorus, and potassium reduce the value of manure as an organic fertiliser and at the same time increase the risk of air, soil, and water pollution. Due to its well-developed porous structure, large specific surface area, and high cation exchange capacity (CEC), biochar contributes to nutrient retention and reduces their losses [4], [9].

The most pronounced effects have been observed for nitrogen, where losses are reduced through the binding of ammonium ions (NH_4^+) and the limitation of their transformation into gaseous ammonia. In this way, a greater proportion of nitrogen is retained in manure until its application to agricultural soils, enabling more efficient utilisation of this nutrient in crop production [12], [15].

Studies show that biochar can also contribute to the retention of phosphorus and potassium, although the magnitude of this effect depends on its properties, manure type, and storage conditions. As a result, findings are not fully consistent; however, they indicate that biochar application can reduce the losses of these nutrients and increase their availability after manure is applied to soil [15], [16].

By preserving nutrients during storage, their potential for use in crop production is increased, while at the same time environmental losses are reduced. In this way, biochar can contribute to more sustainable resource use and more efficient manure management [3], [16].

In addition to its effects on nutrient preservation, increasing attention in recent years has been given to the ability of biochar to adsorb contaminants present in manure. Existing research shows that biochar can bind antibiotic residues, antibiotic resistance genes (ARGs), and other organic compounds, thereby reducing their transfer into soil following manure application. Although current findings indicate significant potential of biochar in this area, further research is needed to better understand adsorption mechanisms and to assess the long-term stability of bound contaminants under different application conditions [1].

Limitations of biochar application and future research directions

Although numerous studies indicate the positive effects of biochar on reducing ammonia and greenhouse gas emissions, as well as on nutrient retention in manure, its effectiveness is not uniform. Differences in biomass feedstock, pyrolysis conditions, physicochemical properties of biochar, manure type and composition, applied dosage, and storage conditions all influence the observed outcomes, which is why results from different studies are not always directly comparable [3], [4], [6].

A key limitation of most available research is the lack of standardised methodologies and the predominant reliance on laboratory and controlled experimental conditions. Long-term studies under real livestock production conditions remain insufficient, making it difficult to formulate reliable practical recommendations [3], [8].

Future research should focus on understanding the mechanisms through which biochar influences microbial processes responsible for gas emissions and nutrient transformations, as well as assessing its long-term stability and safety after soil application. Of particular research importance is also the investigation of its role in the adsorption of antibiotics, antibiotic resistance genes (ARGs), and other contaminants, as well as their behaviour in soil systems [3].

Further development of biochar production technologies and improved control of its properties may contribute to more reliable application in manure management. The integration of biochar with other measures for reducing emissions and conserving nutrients represents a promising direction for the development of sustainable livestock production systems in line with the principles of circular economy and environmental protection [4], [8].

CONCLUSION

Biochar represents an effective tool for improving manure management in livestock production systems. The literature review shows that its application can reduce emissions of ammonia, methane, and nitrous oxide, while simultaneously enhancing the retention of nitrogen and other nutrients in manure.

The effects of biochar application are not consistent under all conditions. Differences in feedstock, biochar production methods, manure properties, and storage conditions influence the magnitude of the observed results, limiting their direct comparability.

In addition to its effects on emissions and nutrient retention, biochar shows potential for binding antibiotics, resistance genes, and other organic contaminants, thereby reducing the risk of their transfer into soil.

Future research should focus on examining these effects under real production conditions and across different manure types in order to develop more reliable practical recommendations.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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TYRES WEAR, HARMFUL EFFECT ON HUMAN AND MEASUREMENTS FOR IT REDUCTION: A REVIEW

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ABSTRACT

The tires are the acting organs of the vehicle by which it achieves its movement. During the vehicle movement/drive it comes to the friction between the tires and road, which causes the tires wear. The particles formed due to the tires wear, are harmful for human and its environment. In the paper is conducted the review of existing literature, where firstly are presented factors which contribute to the tires wear. After, it is given the representation, how these particles enter into human organism, and how this further influence on human health. Further are presented measurements for wear reduction. On the basis of the comprehensive analysis of the observed papers from the subject field, have come to the very useful conclusions as well as propositions to what should give attention during the future researches, as well as during the development of new tires, in order to reduce their wear.

Keywords: particles, tires wear, environment, human health.

INTRODUSTION

Tire wear particles are particles with a diameter of ≤5 mm. During the rolling of tires on the road surface, tire wear occurs due to the action of shear forces [1]. According to available data, air pollution ranked as the second leading risk factor in terms of the total number of deaths in 2023 [2], whereas in 2019 it was ranked fourth [3]. Considering only airborne particles, according to the

World Health Organization (WHO), they were responsible for 239,000 premature deaths in the EU during 2022 [4]. Tire abrasion is the main source of microplastics in the environment [5]. Airborne particles are a mixture of solid and liquid particles that differ in size (Figure 1), chemical composition, shape, solubility, surface properties, and origin [6]. Airborne particles can be classified according to their size as follows [7], [8]:

- Coarse particles – which are less than10 μm and are classified as PM_{10},
- Fine particles – which are less than 2,5 μm and are classified as $PM_{2,5}$, and
- Ultrafine particles – particles which are less than 0,1 μm and are classified as $PM_{0,1}$.

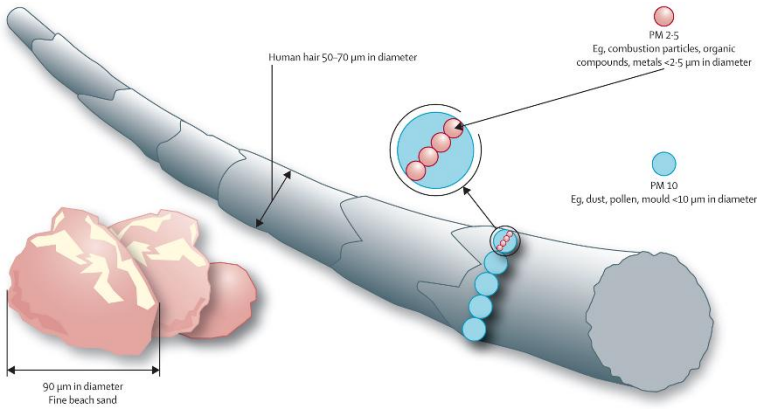

Figure 1. *The illustrative comparison of the particles size in respect to the human hair* [9]

Figure 2 presents statistical data on the amount of PM10 originating from several different sources. Since it is expected that electric vehicles will account for a larger share of road traffic by 2035, particles originating from combustion processes will decrease, while the emission of particles originating from tires will increase. The reason for this increase is the greater mass of electric vehicles due to their batteries. Until recently, the maximum permissible emissions originating from tires were not defined by standards. However, this has now been regulated under the Euro 7 standard [10].



Figure 2. Amount of PM10 in EU27 for years 2015., 2025. и 2035. Which originate from road, vehicle exhaust gasses, brakes and tires and total tires wear [4]

The impact of particles on humans is a highly relevant topic. Particles generated as a result of tire wear attract significant attention from researchers around the world. The main questions raised, which this research aims to answer, are:

- How are tire wear particles generated?
- Which factors contribute to tire wear?
- How do tire wear particles affect human health?
- What measures can be taken to reduce tire wear?

The introductory section explains the process of tire wear formation, thereby providing an answer to the first question. Section three addresses the factors contributing to tire wear, which corresponds to the second question. An overview of how particles generated by tire wear affect human health is presented in the fourth section. This is followed by a section discussing measures for reducing tire wear, thereby answering the fourth question. Finally, the conclusions derived from this research are presented.

RESEARCH METHODOLOGY

The research methodology was carried out through several phases. The study is based on a review of available research conducted by authors in the relevant field, as well as available statistical data. The research phases implemented in this paper are as follows:

1. Familiarization with the process of tire wear generation, possible particle sizes, and available statistical data;
2. Identification of factors which contribute to the tire wear generation;
3. Analysis of their effects on humans;
4. Proposed measures for reduction; and
5. General conclusions derived from the conducted research.

FACTORS WHICH CONTRIBUTE TO THE TIRES WEAR

Factors which contribute to the tires wear are next [11]:

- Tire characteristics:
  - The silica content in the tread compound affects the increased emission of fine particles, while the amount of coarse particles is lower [12];
  - Studded winter tires emit a larger quantity of particles [13];
  - If the tire pressure is higher than recommended, the pressure exerted on the road surface increases, contributing to increased tire wear [14], [15]. In cases where tire pressure is lower than specified by the manufacturer, greater and uneven tire wear will occur [16];
  - With an increase in tire tread temperature, the size of tire wear particles increases, whereas at lower temperatures, the particle size is smaller [17];
  - When the road surface is wet, friction is reduced and tire wear is lower [17], and
  - TWR (Treadwear Rating) affects the degree of wear. Two tires from the same manufacturer with different ratings showed that the tire with the lower rating experienced greater tread mass loss [18];

- Road surface characteristics:
  - Greater road surface irregularities lead to a larger quantity of coarse tire wear particles [17];
  - The greater the roughness of the road surface, similar to sandpaper, the greater the tire wear [19];
  - The presence of sand on the road contributes to increased tire wear, and
  - Road pavement texture also affects tire wear [20];

- Vehicle operation:
  - Increasing speed limits on roads has led to increased tire wear [21], [22], [23];
  - Longer traveling time at high speeds lead to abnormal tire wear [24];
  - Vehicle movement from a stationary position accompanied by wheel slip leads to higher emissions of tire wear particles [25];
  - Long-term braking [26], [27];
  - Sudden braking in accident or emergency situations [28], and
  - Vehicle movement while cornering [26];

- Vehicle characteristics
  - Increasing vehicle mass results in greater emissions of tire wear products [29], [30];
  - Improper wheel dynamic performance, under the influence of stiff suspension systems and axles, contributes to increased tire wear [31];
  - Increasing the toe angle by 1° to 1.5° can cause tire wear to increase by 3 to 10 times [32], and
  - The amount of tire wear is also influenced by the vehicle category [33].

HARMFUL EFFECT ON HUMAN

Tire wear particles can enter the human body in three ways: through food intake, consumption of contaminated water, or inhalation [34], [35], [36]. The most common way in which tire particles enter the human body is through the consumption of contaminated food or water, after which they enter the bloodstream and negatively affect human health [37]. When particles enter the body together with food, they also adversely affect the digestive organs, particularly intestinal digestion and absorption [38]. Research on how tire particles affect human health when inhaled is still limited. The only effects observed by researchers are DNA damage and inflammatory effects [39]. This prompted some researchers to conduct studies on mice. When mice inhaled air contaminated with tire particles, it was observed that it caused respiratory dysfunction and pulmonary fibrosis [40]. In addition, disorders of lipid metabolism were also reported [41]. Since research on the effects of inhaled tire particles on human health is still limited, comprehensive conclusions cannot yet be drawn. However, based on a study reviewing 400 scientific papers, it was determined that tire particles cause oxidative stress and inflammation [42].

MEASURES FOR THE REDUCTION

There are several different measures and recommendations for reducing tire wear, including:

- Installation of tire pressure sensors that promptly inform the driver when tire inflation is required [43];
- Tire pressure should be checked every 14 days or before longer journeys in order to minimize tire wear [44], [45];
- The use of tunnels [46] positioned near the wheel and intended for capturing particles (Figure 3);
- The application of tires which contain ISAF N234 [47];
- Adding nanoprene to a tread mix containing silica [48] in the tread compound to improve wear resistance, as well as the addition of nano-silica and carbon black [49] [50];
- Selection of road construction materials, specifically the use of low-noise pavements [51], [21];
- Replacing signalized intersections with roundabouts [52];
- The application of self-driving cars [34], and
- Wheel alignment adjustment [53].

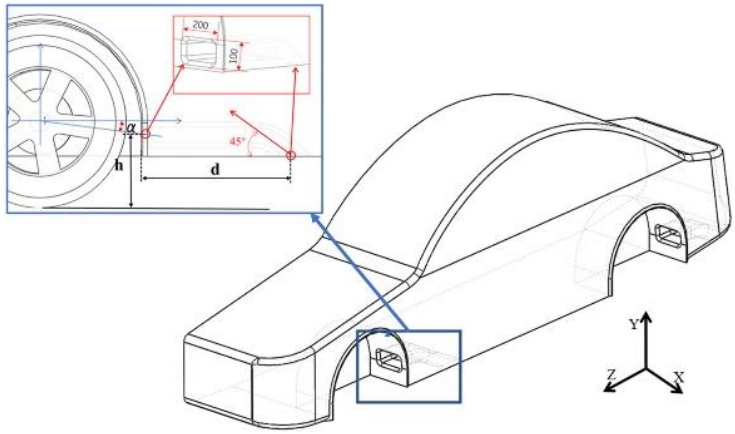

Figure 3 Tunnel on a vehicle for capturing particles generated by tire wear [46]

CONCLUSION

The emission of harmful substances originating from vehicles is currently attracting significant public attention. During vehicle operation, emissions are generated not only from the combustion process occurring in the internal combustion engine, but also from tire and brake wear. The focus of this paper is placed on tire wear because it contains microplastics and other harmful components that may adversely affect human health. Based on the literature review, the following conclusions were drawn:

- The main source of microplastics in the environment is tire wear.
- The degree of tire wear depends on tire characteristics, road surface characteristics, vehicle characteristics, and vehicle operating conditions.
- Tire wear products most commonly enter the human body through the consumption of contaminated food.
- Research on how tire particles affect human health when inhaled is still limited.
- Tire wear reduction can be achieved through regular tire pressure checks and maintaining pressure within prescribed limits, the application of tire pressure sensors, reconstruction of road infrastructure, and similar measures

The presented conclusions provide highly important information for ensuring key elements related to ecology, impacts on humans and the environment, and aspects that should receive particular attention in future research.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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DIGITAL FASHION COMMUNICATION: CONSUMER PERCEPTIONS OF ONLINE CAMPAIGNS AND INFLUENCER IMPACT

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ABSTRACT

This paper examines the role of the digital environment in shaping communication between fashion brands and consumers, with a particular focus on digital marketing campaigns and influencer impact. The study explores respondents' attitudes toward fashion brands' digital presence, the frequency and patterns of following brand activities on digital platforms, and the perceived effectiveness of online campaigns. Special attention is given to the role of influencers in shaping consumer attitudes, purchase decisions, and overall behavior. The findings indicate that digital platforms represent a crucial communication channel for fashion brands, while influencer marketing significantly contributes to consumer engagement and trust. The paper highlights key trends relevant for both academic research and marketing practice in the fashion industry.

Keywords: Digital marketing communication, Fashion brands, Influencer marketing, Consumer behavior.

INTRODUCTION

The rapid expansion of digital technologies has fundamentally transformed fashion consumption patterns, with online channels becoming an increasingly important part of the consumer decision-making process. According to statistical data, global revenue in the fashion e-commerce market continues to grow, driven by increased smartphone adoption, social media influence, and changing consumer preferences toward convenient digital shopping experiences [1]. Furthermore, social media platforms have become critical sources of fashion inspiration and product discovery, with a substantial proportion of consumers reporting that they use social networks to explore trends, evaluate brands, and inform purchase decisions [2]. This high level of connectivity has made digital marketing campaigns central to brand visibility, allowing fashion

companies to deliver personalized, cost-effective, and timely messaging [3]. As a growing share of consumer touchpoints move online, understanding how audiences perceive and respond to these digital communication strategies has become essential for both academic inquiry and industry practice in various fields [4], [5].

Within this evolving digital landscape, social media influencers have emerged as powerful intermediaries between fashion brands and consumers, particularly on platforms such as Instagram, TikTok, and YouTube [6]. These influencers function as contemporary opinion leaders who shape trends, build brand attitudes, and guide purchasing decisions [7]. Research suggests that consumer trust in an influencer's credibility, expertise, and authenticity strongly affects how favorably a brand or campaign is perceived [8]. Similarly, the characteristics of digital influencers, including relatability, perceived expertise, and content usefulness, have been shown to meaningfully influence purchase intention toward fashion products [9]. Despite this expanding body of research, questions remain about how consumers process and evaluate online campaigns compared to traditional advertising, and about the specific mechanisms through which influencer-driven content translates into brand engagement and purchase behavior [10].

This growing reliance on influencer-mediated communication raises important questions about consumer trust, authenticity, and the broader effectiveness of digital fashion campaigns. While earlier studies established the general importance of digital channels and social media influencers in shaping public perception [11], more recent research has examined how factors such as perceived credibility and trustworthiness of digital sources and online engagement interact to shape consumer attitudes toward fashion brands specifically [12], [13], [14]. However, a systematic understanding of how these dynamics combine digital campaign design, influencer credibility, and consumer perception, within the fashion sector in developing countries remains limited. This paper therefore aims to examine consumer perceptions of digital fashion communication, with particular attention to how online campaigns and influencer marketing jointly shape brand attitudes and purchasing behavior in the contemporary digital marketplace.

LITERATURE REVIEW

Digital fashion communication and consumer engagement

The transformation of the fashion industry through digital technologies has fundamentally changed the way brands communicate with consumers, build relationships, and influence purchasing decisions [15]. Unlike traditional fashion communication, which relied predominantly on mass media, fashion shows, print advertising, and celebrity endorsements, contemporary digital fashion communication is characterized by continuous interaction, personalized content, and multi-directional communication across digital platforms. Social media networks, brand websites, mobile applications, and influencer-generated content have become essential components of fashion brands' communication strategies, enabling companies to engage consumers throughout the entire customer journey, from awareness and information search to purchase and post-purchase evaluation [16].

Research on digital fashion communication draws primarily on several theoretical perspectives that explain how consumers process, evaluate, and respond to digital brand messages. One of the most influential frameworks is source credibility theory, originally developed by Ohanian [17], which suggests that the effectiveness of persuasive communication depends largely on three perceived characteristics of the communicator: expertise, trustworthiness, and attractiveness. Within the context of fashion marketing, this framework has been widely applied to explain why consumers respond differently to recommendations from influencers, celebrities, and other digital opinion leaders [18], [19]. Influencers who are perceived as knowledgeable about fashion trends, authentic in their communication style, and personally trustworthy are more likely to shape consumers' attitudes toward brands and products.

A complementary perspective is provided by parasocial interaction theory, which explains the development of perceived interpersonal relationships between audiences and media personalities despite the absence of direct reciprocal interaction. In digital environments, influencers frequently

share personal experiences, lifestyle content, and everyday activities, creating a sense of familiarity and closeness among followers. This perceived relationship can strengthen the persuasive power of influencer recommendations, as consumers may interpret such recommendations as advice from a trusted social connection rather than as conventional advertising content [20], [21], [22]. In the fashion context, where identity expression, lifestyle association, and symbolic meanings play an important role in consumption, parasocial relationships can significantly contribute to consumers' emotional attachment to brands promoted by influencers.

Social media platforms and influencer-based fashion communication

Social media platforms represent one of the most influential channels through which fashion brands communicate with contemporary consumers. Platforms characterized by visual content, such as Instagram and TikTok, have become particularly relevant for fashion marketing because they allow brands and influencers to present products through storytelling, lifestyle imagery, short-form videos, and interactive formats [23], [24], [25]. Through these platforms, consumers are no longer passive recipients of promotional messages but active participants who can comment, share, review, and co-create brand-related content.

As influencer marketing has become increasingly integrated into fashion communication strategies, researchers have devoted growing attention to the challenge of maintaining authenticity in commercial collaborations. Unlike traditional advertising, influencer marketing relies heavily on the perception that recommendations represent genuine opinions and personal experiences. However, the increasing commercialization of influencer activities creates potential tension between commercial objectives and audience expectations of authenticity [26]. A substantial body of research has examined how influencer characteristics affect the effectiveness of digital fashion campaigns. For example, De Veirman et al. [8] demonstrated that a larger follower base does not necessarily guarantee greater advertising effectiveness, as follower numbers interact with other factors, including perceived product fit and audience perceptions of authenticity. Consequently, research has increasingly focused on micro- and nano-influencers, who often have smaller but more engaged communities. Their perceived accessibility and relatability may enhance trust and strengthen consumers' willingness to consider their recommendations [27], [28].

This issue is particularly relevant in fashion marketing, where purchasing decisions are frequently influenced by symbolic and emotional factors rather than purely functional product attributes. While macro-influencers may provide greater visibility and brand awareness, smaller influencers may generate stronger engagement due to their perceived similarity with followers. However, the relationship between reach and credibility remains complex. Some studies indicate that expertise and perceived authority are particularly important in higher-involvement purchase situations, whereas relatability and emotional connection may have stronger effects on everyday fashion consumption decisions [29], [30], [31].

Audrezet et al. [26] argue that influencers continuously negotiate between self-brand construction and maintaining audience trust, particularly as sponsored partnerships become more visible. The disclosure of paid collaborations may increase transparency but can also reduce perceived spontaneity if consumers interpret the content as primarily motivated by financial incentives. Similarly, research examining Instagram-based endorsements indicates that audiences are highly sensitive to authenticity signals and may respond negatively when influencer content appears excessively promotional or inconsistent with the influencer's established identity [32].

These findings expand traditional credibility-based approaches by suggesting that trust should not be understood as a stable characteristic of influencers. Instead, trust represents a dynamic consumer evaluation that changes depending on the context of the campaign, perceived alignment between influencer and brand, transparency of communication, and the consistency of the influencer's online identity. In the fashion industry, where brand image and personal identity are closely interconnected, authenticity represents a particularly important determinant of communication effectiveness.

Perceived risk and consumer decision-making in digital fashion environments

Another important research stream examines the role of perceived risk in consumers' responses to digital fashion communication. Online fashion purchases involve uncertainty related to product quality, fit, appearance, and brand reliability [33], [34]. Therefore, digital communication strategies that reduce uncertainty and increase consumer confidence may significantly influence purchase intentions.

Cabeza-Ramírez et al. [35] found that uncertainty associated with influencer recommendations may reduce consumers' willingness to purchase unless supported by transparent and credible communication. This supports the argument that trust operates as a risk-reduction mechanism: when consumers perceive influencers as reliable sources of information, the perceived psychological and functional risks associated with online purchasing are reduced ([36], [37]).

Nevertheless, recent studies suggest that consumer responses cannot be explained solely by influencer credibility. Some research indicates that perceived behavioral control and consumers' own ability to evaluate digital information may represent equally important determinants of attitudes toward influencer-generated content. In other words, consumers do not simply accept recommendations based on the characteristics of the communicator; they also assess their own knowledge, confidence, and ability to make independent purchasing decisions ([14], [30]). This perspective highlights the active role of consumers in interpreting and evaluating digital fashion communication.

Consumer differences in responses to digital fashion communication

Research also indicates that the effectiveness of digital fashion communication varies across consumer segments. Demographic characteristics, particularly age and income, influence how consumers perceive and respond to online campaigns and influencer recommendations. Cabeza-Ramírez et al. [38] found differences between Generation X and Millennials regarding trust formation and product involvement, suggesting that consumers from different generations apply different criteria when evaluating digital marketing messages.

Similarly, previous studies indicate that socioeconomic characteristics, including income level, influence how consumers respond to digital marketing strategies. Higher-income consumers tend to demonstrate greater interest in symbolic, experiential, and prestige-oriented brand communication, including luxury fashion content, where brand image and exclusivity represent important sources of value [39], [40], [41]. In contrast, consumers with lower purchasing power are generally more sensitive to price-related benefits and promotional incentives, making discounts, special offers, and value-oriented messages more influential in purchase decisions. These findings emphasize the importance of segmentation and suggest that digital fashion communication strategies should be adapted to specific consumer profiles rather than developed according to a universal approach.

Despite extensive research on influencer marketing, several gaps remain. Existing studies frequently examine isolated elements of digital communication, such as influencer credibility or purchase intention, while fewer studies adopt a broader perspective that integrates consumers' perceptions of online campaigns, social media engagement, influencer influence, brand responsiveness, and digital purchasing behavior. Furthermore, research focusing on emerging markets and diverse consumer groups remains relatively limited. Therefore, examining how consumers perceive different dimensions of digital fashion communication provides valuable insights into the evolving relationship between fashion brands and consumers in digital environments.

EMPIRICAL RESEARCH

Methodology

The survey was conducted in Belgrade, Serbia, in 2025 and distributed online via e-mail and social media platforms. Respondents were recruited using convenience sampling, with participation being voluntary and anonymous. The research employed a structured questionnaire

consisting of four sections and including single-choice and Likert-scale questions designed to measure respondents' engagement with digital fashion communication, perceptions of digital marketing campaigns, interactions with fashion brand content on social media, and the perceived influence of social media influencers on purchasing decisions and brand attitudes.

The collected data were analyzed using descriptive statistical methods to provide a comprehensive overview of the observed response patterns. Descriptive statistics, including frequencies, percentages, and measures of central tendency were employed to summarize respondents' characteristics and their attitudes toward different aspects of digital fashion communication. This approach enabled the identification of prevailing trends and consumer preferences while providing insight into the role of digital communication in shaping perceptions of fashion brands.

Emphasis was placed on examining respondents' perceptions of digital marketing campaigns, the frequency and way they follow fashion brands across digital platforms, and the influence of social media influencers on consumers' attitudes, purchase intentions, and decision-making processes. The analysis also explored the extent to which digital communication channels contribute to consumer engagement and brand perception within the contemporary fashion industry.

Sample structure

A total of 100 respondents participated in the study, of whom 63% were female and 37% were male. Regarding the age distribution, the largest proportion of respondents (38%) belonged to the 31-40 age group, followed by those aged 41-50, who accounted for 29% of the sample. Respondents aged 18-30 represented 20% of the sample, while participants older than 50 years accounted for the remaining 13%.

In terms of educational attainment, the largest share of respondents (37%) had completed secondary education. Furthermore, 29% held a bachelor's degree, 22% had completed college-level or vocational higher education, and 12% possessed a master's or doctoral degree.

With respect to employment status, 44% of respondents were employed, while 42% were students. The remaining respondents consisted primarily of unemployed individuals and retirees, each representing 7% of the sample.

RESULTS

Consumers' use of digital channels for fashion information and shopping

The findings indicate a strong consumer orientation toward digital channels when searching for information about fashion products and making purchase decisions. A substantial majority of respondents (77%) completely agreed that they increasingly rely on digital methods when purchasing fashion products, while an additional 18% agreed. Only 5% expressed a neutral opinion, and none disagreed with the statement. These findings suggest that digital channels have become the primary environment through which consumers interact with fashion brands.

Similarly, respondents overwhelmingly reported using digital communication channels when seeking information about fashion products. As many as 82% completely agreed with this statement, while 10% somewhat agreed. Only 6% expressed a neutral opinion, and 2% somewhat disagreed. These results further confirm the dominant role of digital communication in consumers' information search behavior.

Among the available digital channels, social media emerged as the most frequently used source of fashion-related information. Respondents unanimously agreed that social networking platforms represent their primary source of information when exploring fashion products. This finding highlights the central role of social media in contemporary fashion communication and supports previous research emphasizing the growing importance of visually oriented platforms in consumer-brand interactions.

By contrast, fashion brand websites were found to play a secondary role. While 40% of respondents agreed that they use official brand websites when searching for information (38% somewhat agreed and 2% completely agreed), 30% remained neutral. Moreover, 30% reported

limited reliance on brand websites, with 10% somewhat disagreeing and 20% completely disagreeing that websites represent their primary source of information. These findings suggest that although official websites continue to serve as an important information source, consumers are considerably more inclined to obtain fashion-related content through social media platforms.

Overall, the results demonstrate that digital marketing communication has become an integral component of consumers' interactions with fashion brands. Social media platforms, particularly visually oriented networks such as Instagram and TikTok, appear to dominate consumers' information-seeking behavior, whereas official brand websites serve a complementary role in the digital customer journey.

The influence of fashion influencers on consumer decision-making

The second part of the analysis examined the extent to which fashion influencers affect consumers' attitudes and purchasing behavior. One-third of respondents (33%) completely agreed that they enjoy purchasing fashion brands recommended by influencers, indicating a considerable level of influencer impact. However, respondents' opinions were relatively divided. While 22% somewhat agreed with the statement, 20% expressed a neutral opinion. Conversely, 20% somewhat disagreed, and 5% completely disagreed, suggesting that influencer recommendations are persuasive for a substantial segment of consumers but are not universally accepted.

Despite the influence of recommendations on purchase intentions, respondents demonstrated relatively low levels of direct interaction with influencers. A majority (60%) indicated that they do not frequently ask influencers for advice or additional information about fashion brands they intend to purchase. Twenty percent expressed a neutral opinion, while only 15% completely agreed that they regularly contact influencers regarding their experiences with fashion brands. An additional 5% somewhat disagreed with the statement.

These findings indicate that although influencers play an important role in shaping consumers' perceptions and purchase intentions, their influence is primarily passive. Consumers are more likely to observe influencer-generated content and rely on recommendations than to actively engage in two-way communication by requesting personalized advice. This suggests that influencers primarily function as opinion leaders and content creators whose recommendations contribute to brand awareness and purchase consideration rather than serving as direct advisors during the purchase decision process.

The findings indicate that negative influencer endorsements have a particularly strong effect on consumers' purchase intentions. As many as 82% of respondents completely agreed that they would avoid purchasing a fashion product if an influencer expressed a negative opinion about the brand. An additional 10% somewhat agreed with the statement, while 6% remained neutral and only 2% somewhat disagreed. These results suggest that negative electronic word-of-mouth (eWOM) disseminated through influencers may have a stronger influence on consumer decision-making than positive recommendations.

Respondents also demonstrated a high level of engagement with influencer-generated promotional activities. Specifically, 90% reported that they frequently participate in contests and giveaways organized by influencers on social media in collaboration with fashion brands, whereas only 10% indicated that they do not engage in such activities. This finding reflects consumers' willingness to interact with branded content when it incorporates entertaining or rewarding elements.

Consumer preferences for digital brand communication

The results further explored consumers' preferences regarding different forms of digital communication employed by fashion brands. Email marketing appears to have a relatively limited influence on respondents. Only 25% completely agreed that they appreciate receiving promotional offers from fashion brands via email, whereas the majority (70%) expressed a neutral opinion and 5% completely disagreed. These findings indicate that email remains a supplementary communication channel rather than consumers' preferred means of interacting with fashion brands.

In contrast, mobile applications play a much more prominent role in consumers' shopping behavior. An overwhelming majority of respondents (95%) reported having mobile applications of their preferred fashion brands installed on their smartphones and using them to purchase products. Only 5% indicated otherwise (3% completely disagreed and 2% somewhat disagreed). This finding highlights the increasing importance of mobile commerce and dedicated brand applications in the digital fashion ecosystem.

Respondents also reported a high level of engagement with user-generated content. Nearly all participants (99%) indicated that they frequently read comments and opinions about fashion brands in the digital environment, demonstrating the importance of online consumer reviews and peer-generated content in shaping brand perceptions and purchase decisions.

The influence of brands' digital presence was also examined. When asked whether the absence of an active online marketing campaign discourages them from purchasing a fashion brand, respondents expressed relatively mixed opinions. While 20% completely agreed and 10% somewhat agreed that a lack of digital communication reduces their likelihood of purchasing a brand, the majority (60%) reported a neutral attitude. Only 10% disagreed with the statement (5% somewhat disagreed and 5% completely disagreed). These findings suggest that although digital visibility contributes to brand evaluation, it is not the sole determinant of consumers' purchasing decisions. Furthermore, all respondents agreed that they particularly appreciate fashion brands that respond promptly to customer inquiries submitted through digital communication channels. This unanimous response underscores the importance of responsiveness and two-way communication in establishing positive consumer-brand relationships within the digital environment.

Finally, respondents overwhelmingly recognized the importance of digital marketing campaigns in stimulating purchasing behavior. Most participants agreed that an active and well-designed digital campaign can positively influence consumers' purchase intentions. Collectively, the findings suggest that online shopping has become an integral part of contemporary consumer behavior. Respondents emphasized the convenience, speed, and broader product assortment available through online channels compared with traditional brick-and-mortar stores, reinforcing the strategic importance of digital communication in the fashion industry.

DISCUSSION

The findings provide further evidence of the increasingly central role of digital communication in consumers' interactions with fashion brands. The overwhelming majority of respondents reported relying on digital channels when searching for fashion information and making purchasing decisions, while social media emerged as the primary source of fashion-related information. This finding is consistent with previous research emphasizing the transformation of fashion communication through digital technologies and the growing importance of social media throughout the consumer decision-making process [15], [16], [24], [25]. The particularly strong role of social media observed in this study also supports the view that visually oriented platforms such as Instagram and TikTok have become important spaces for fashion discovery, brand evaluation, and consumer engagement [42], [43]. At the same time, the relatively limited reliance on official brand websites suggests that consumers increasingly encounter and evaluate fashion brands through social media and user-generated content, rather than relying exclusively on brand-controlled communication. This observation is consistent with previous research showing that both firm-created and user-generated social media content can shape fashion consumers' brand perceptions and purchase intentions [44], [48].

The results concerning influencer marketing largely support previous research on the persuasive role of digital opinion leaders, while also indicating that influencer influence is not uniform across consumers. More than half of respondents agreed that they enjoy purchasing fashion brands recommended by influencers, which is consistent with studies demonstrating the relationship between influencer characteristics, credibility, trust, and purchase intention [6], [7], [9], [12]. However, the relatively high proportion of neutral and negative responses indicates that influencer recommendations do not automatically translate into consumer acceptance. This finding is in line with De Veirman et al. [8], who argue that influencer reach alone does not guarantee

advertising effectiveness, and with more recent research emphasizing the importance of relatability, expertise, authenticity, and consumer involvement [29], [30], [31]. The finding that most respondents do not actively contact influencers for additional information further suggests that influencer communication operates primarily through exposure to content and recommendations rather than through direct interpersonal interaction. Thus, influencers appear to function predominantly as opinion leaders whose content contributes to awareness, evaluation, and purchase consideration.

One of the most notable findings is the substantially stronger effect of negative influencer communication. The fact that 82% of respondents completely agreed that they would avoid purchasing a fashion product if an influencer expressed a negative opinion about the brand suggests that negative electronic word-of-mouth may be particularly consequential in the fashion context. This result complements previous research showing that trust and credibility are central to the effectiveness of influencer communication [7], [12], while also supporting research indicating that perceived risk can substantially affect consumers' responses to influencer recommendations [35]. When an influencer is perceived as a credible source, negative information may increase consumers' perceptions of potential product or brand risk and consequently discourage purchase. This finding also reinforces literature's emphasis on authenticity: when consumers perceive influencers as credible and relatable, their evaluations, whether positive or negative, may carry greater persuasive weight [26], [32].

The findings regarding consumer engagement further extend the literature by demonstrating that consumers respond particularly strongly to interactive and user-generated forms of digital communication. The high participation rate in influencer contests and giveaways and the fact that almost all respondents reported reading online comments and opinions about fashion brands indicate that consumers actively use peer-generated content when evaluating brands. These findings are consistent with research suggesting that social media has transformed consumers from passive recipients of promotional messages into active participants in brand communication [24], [25]. Similarly, the unanimous preference for prompt responses to customer inquiries highlights the importance of responsiveness and two-way communication. This finding supports the broader understanding of digital communication as a relational rather than exclusively promotional activity.

Finally, the relatively limited influence of email marketing and the very high use of mobile fashion applications indicate that consumers' preferred communication channels are increasingly shaped by convenience, immediacy, and integration with everyday digital practices. Interestingly, although respondents recognized the importance of active digital campaigns, the majority remained neutral regarding whether the absence of such campaigns would directly discourage them from purchasing a brand. This suggests that digital visibility is important for brand awareness and evaluation [46], [47], [48] but should not be interpreted as the sole determinant of purchase behavior. Overall, the findings support the existing literature while adding empirical evidence from consumers in Serbia, an emerging market context that remains comparatively underrepresented in research on digital fashion communication. The study therefore contributes by demonstrating that effective digital fashion communication depends not only on visibility, but also on credibility, authenticity, interaction, responsiveness, and consumer-generated information.

CONCLUSION

The findings of this study confirm the growing importance of digital environments in shaping consumer perceptions, attitudes, and purchasing behavior in the fashion industry. The results indicate that digital channels have become a dominant source of information and interaction between consumers and fashion brands, with majority of respondents strongly agreeing that they increasingly rely on digital methods when searching for and purchasing fashion products. Furthermore, the findings highlight the significant role of influencers in the consumer decision-making process, particularly in relation to brand evaluation. The fact that most respondents stated that they would avoid purchasing a fashion product if an influencer expressed a negative opinion

about the brand demonstrates the persuasive power of digital opinion leaders and the relevance of electronic word-of-mouth in contemporary fashion communication.

Despite providing valuable insights into consumer responses to digital fashion communication, this study has several limitations, primarily related to the sample size, sampling approach, and the use of descriptive statistical analysis, which limits the possibility of establishing causal relationships. Nevertheless, the results offer important practical implications for fashion brands by emphasizing the need to develop authentic, interactive, and consumer-oriented digital communication strategies. Effective use of social media platforms, influencer collaborations, and personalized digital content can contribute to stronger consumer engagement, improved brand perception, and the development of long-term relationships between fashion brands and their audiences. Future research should further explore these relationships using larger samples and advanced analytical methods to better understand the factors that determine the effectiveness of digital fashion communication.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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MONETARNA POLITIKA EU - STANJE I PERSPEKTIVA

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APSTRAKT

Monetarna politika Evropske unije predstavlja jedan od ključnih instrumenata za ostvarivanje makroekonomske stabilnosti, održivog ekonomskog rasta i očuvanja stabilnosti cijena u zemljama članicama eurozone. U radu se analizira institucionalni okvir monetarne politike Evropske unije sa posebnim osvrtom na ulogu Evropske centralne banke, njene ciljeve, instrumente i mehanizme djelovanja. Posebna pažnja posvećena je izazovima sa kojima se monetarna politika suočila tokom posljednjih godina, uključujući posljedice globalne finansijske krize, pandemije COVID-19, inflatorne pritiske izazvane poremećajima u lancima snabdijevanja i geopolitičkim nestabilnostima. Cilj istraživanja je sagledavanje trenutnog stanja monetarne politike Evropske unije, ocjena njene efikasnosti u ostvarivanju postavljenih ciljeva te identifikovanje ključnih perspektiva budućeg razvoja. U radu se primjenjuju metode deskriptivne i komparativne analize, kao i analiza relevantnih statističkih pokazatelja i zvaničnih dokumenata Evropske centralne banke.

Ključne riječi: monetarna politika, Evropska unija, Evropska centralna banka, eurozona, inflacija, finansijska stabilnost,

UVOD

Evropska monetarna unija (EMU) predstavlja jedan od najznačajnijih projekata ekonomskog ujedinjenja u historiji, gdje zemlje članice Europske unije nepovratno odriču se dijela svog monetarnog suvereniteta i prihvaćaju zajedničku valutu – euro, čime se stvara jedinstveno valutno područje koje trenutno obuhvata 20 od 27 članica EU. EMU je osnovana na načelima ekonomske i monetarne integracije, sa centralnom monetarnom političom koju vodi Evropska centralna banka (ECB), dok fiskalne politike ostaju u nadležnosti pojedinačnih država, što stvara institucijski "neravnoteže" koji predstavlja ključni izazov za dugoročnu stabilnost. Od implementacije Sporazuma iz Mastrihta 1992. godine, EMU je prošla kroz brojne testove otpornosti – globalnu finansijsku krizu 2007-2009, finansijsku krizu u europodručju 2010-2012, pandemiju COVID-19 i

inflacioni šok 2022. – koji su istovremeno otkrili institucionalne nedostatke i pokazali sposobnost unije da se prilagodi i reformira, pri čemu budući uspjeh EMU-a zavisi od sposobnosti dubljeg fiskalnog integrisanja, strukturnih reformi i bolje koordinacije ekonomskih politika među članicama.

MATERIJAL I METODE RADA

U ovom radu primijenjena je metoda teorijske i empirijske analize monetarne politike Evropske centralne banke (ECB) u okviru Evropske monetarne unije (EMU). Istraživanje se zasniva na analizi relevantne domaće i međunarodne naučne literature, stručnih publikacija, izvještaja Evropske centralne banke, Eurostata i OECD-a, kao i na rezultatima istraživanja objavljenim u međunarodnim naučnim časopisima.

U teorijskom dijelu rada korištena je deskriptivna metoda radi prikaza razvoja Evropske monetarne unije, nastanka Evropskog monetarnog sistema i institucionalnog okvira djelovanja ECB-a. Metoda analize sadržaja primijenjena je za proučavanje naučnih radova koji se odnose na transmisijski mehanizam monetarne politike, efekte konvencionalnih i nekonvencionalnih instrumenata monetarne politike te ulogu ECB-a u kriznim periodima.

Empirijski dio istraživanja zasniva se na komparativnoj analizi stopa inflacije u državama članicama Evropske monetarne unije i državama članicama Evropske unije koje nisu dio eurozone u periodu od 2020. do 2025. godine. Podaci su prikupljeni iz baza Eurostata, Evropske centralne banke i OECD-a. Korištene su metode statističke analize, komparacije i interpretacije podataka kako bi se utvrdile razlike u inflatornim kretanjima između posmatranih grupa zemalja i procijenili efekti monetarne politike ECB-a na stabilnost cijena.

Prilikom obrade rezultata korišten je analitičko-sintetički pristup kojim su povezani teorijski nalazi iz literature sa empirijskim pokazateljima inflacije i monetarnih mjera ECB-a tokom finansijske, dužničke i pandemijske krize. Na taj način omogućeno je sveobuhvatno sagledavanje efikasnosti monetarne politike Evropske centralne banke u različitim ekonomskim okolnostima.

EVROPSKA MONETARNA UNIJA (EMU)

Evropska monetarna unija (EMU) predstavlja jedan od najznačajnijih oblika ekonomske integracije u savremenoj istoriji. Njeno uspostavljanje podrazumijevalo je da države članice trajno prenesu dio svog monetarnog suvereniteta na institucije Evropske unije i prihvate zajedničku valutu – euro. Realizacija EMU odvijala se kroz tri međusobno povezane faze.

Prva faza obuhvatala je izmjene Rimskog ugovora radi stvaranja institucionalnih i pravnih pretpostavki za uspostavljanje Evropske monetarne unije, završetak jedinstvenog tržišta i uključivanje svih država članica Evropske ekonomske zajednice u Evropski monetarni sistem. Poseban naglasak stavljen je na koordinaciju monetarne i fiskalne politike država članica. Ova etapa uspješno je okončana krajem 1993. godine.

Druga faza započela je 1. januara 1994. godine. U tom periodu ostvarena je visok nivo usklađenosti makroekonomskih politika država članica, a osnovan je Evropski monetarni institut sa sjedištem u Frankfurtu, čiji je zadatak bio da pripremi uslove za formiranje Evropske centralne banke. Iako je proces integracije intenziviran, monetarne odluke su se još uvijek donosile na nacionalnom nivou.

Treća faza označila je konačno uspostavljanje monetarne unije. Nadležnosti nacionalnih centralnih banaka prenesene su na Evropsku centralnu banku, a radi vođenja jedinstvene monetarne politike uvedena je zajednička valuta. Iako je prvobitno bilo planirano da ovaj proces bude završen 1. januara 1997. godine, različiti nivoi ekonomskog razvoja, nacionalni razvojni prioriteti, kao i razlike u stabilnosti privreda država članica odgodili su početak funkcionisanja EMU.

Dodatni podsticaj monetarnoj integraciji Zapadne Evrope dat je na sastanku u Mastrihtu u decembru 1991. godine, kada je postavljen cilj stvaranja ekonomske, monetarne i političke unije.

U skladu sa Sporazumom iz Mastrihta, početkom 1999. godine započela je završna faza procesa uvođenjem nove zajedničke valute – eura. Time su države članice odustale od samostalnog vođenja monetarne politike i prenijele odgovornost za monetarno upravljanje na zajedničke

evropske institucije. Istovremeno, euro je postao osnovna obračunska jedinica u međunarodnim transakcijama unutar monetarne unije.

Kriterijumi konvergencije definisani u Mastrihtu djelimično su zasnovani na teoriji optimalnog valutnog područja i cost-benefit analizi formiranja jedinstvene valutne zone kao temelja Evropske monetarne unije [1] (Bukowski, 2006, 1). Kako bi stekle pravo pristupanja jedinstvenom monetarnom sistemu, države članice morale su tokom 1997. i 1998. godine ispuniti pet osnovnih kriterijuma:

- Budžetski deficit nije smio prelaziti 3% bruto domaćeg proizvoda;
- Udio javnog duga u bruto domaćem proizvodu nije smio biti veći od 60%, osim ukoliko se taj odnos kontinuirano smanjuje i približava zadatoj granici zadovoljavajućom dinamikom;
- Prosječna stopa inflacije nije smjela biti viša za više od 1,5 procentnih poena u odnosu na prosjek tri države članice sa najnižom inflacijom;
- Dugoročne kamatne stope nisu smjele premašiti više od 2 procentna poena prosjek tri zemlje sa najnižim dugoročnim kamatnim stopama;
- Nacionalna valuta morala je najmanje dvije godine prije pristupanja monetarnoj uniji održavati stabilan kurs u okviru dozvoljenih odstupanja od ± 2,25% u odnosu na centralni kurs.

Među navedenim kriterijumima posebno mjesto zauzima stabilnost cijena, koja predstavlja ključni uslov za pristupanje eurozoni novih država članica [2] (Moinescu, 2012, 1). Ovakav pristup proizlazi iz Ugovora iz Mastrihta iz 1992. godine, kojim je stabilnost cijena definisana kao primarni cilj Evropske centralne banke. Tek nakon ostvarivanja ovog cilja, ECB može pružati podršku širim ekonomskim politikama Evropske unije [3; str. 7] (Hein, & Turger, 2005, 7).

Evropska monetarna unija zasniva se na usklađenom vođenju ekonomske i monetarne politike država članica, uz poštovanje strogih fiskalnih pravila koja se odnose na budžetski deficit i javni dug. Evropska centralna banka odgovorna je za sprovođenje monetarne politike sa osnovnim ciljem očuvanja stabilnosti cijena i održavanja inflacije na nivou blizu 2%, dok institucije Evropske unije, uključujući Vijeće Evropske unije i Evropski parlament, vrše nadzor i koordinaciju ekonomskih politika država članica.

REZULTATI I DISKUSIJA

Rezultati istraživanja pokazuju da je monetarna politika Evropske centralne banke imala značajnu ulogu u očuvanju makroekonomske i finansijske stabilnosti eurozone tokom različitih kriznih perioda. Analiza relevantne naučne literature potvrđuje da su promjene referentnih kamatnih stopa, programi dugoročnog refinansiranja banaka i programi kupovine aktive predstavljali ključne instrumente kojima je ECB djelovala na inflaciju, kreditnu aktivnost i ekonomski rast.

Monetarna politika Evropske centralne banke prvenstveno se sprovodi putem upravljanja referentnim kamatnim stopama. Prilagođavanjem visine ključnih kamatnih stopa ECB utiče na cijenu finansiranja poslovnih banaka, koje potom te promjene prenose na privredu i stanovništvo kroz uslove kreditiranja i štednje. Istraživanje Angelonija i Ehrmanna (2003) pokazuje da je nakon uspostavljanja Ekonomske i monetarne unije mehanizam transmisije monetarne politike postao ujednačeniji među državama članicama [4]. Posebno je izražena veća usklađenost bankarskog i kamatnog kanala transmisije, pri čemu jedinstvena monetarna politika proizvodi sličnije efekte u ekonomijama eurozone, što doprinosi efikasnijem ostvarivanju ciljeva ECB-a.

Pored standardnih instrumenata monetarne politike, globalna finansijska kriza iz 2008. godine, kao i kasnija dužnička kriza u eurozoni, nametnule su potrebu za primjenom nekonvencionalnih mjera. Nakon što su referentne kamatne stope dostigle izuzetno nizak nivo, ECB je uvela niz dodatnih instrumenata, uključujući programe dugoročnog refinansiranja banaka, negativne kamatne stope na depozite i programe otkupa finansijske aktive, poznate pod nazivom kvantitativno popuštanje (Quantitative Easing – QE). Prema Driffillu (2016), ove mjere značajno su doprinijele smanjenju prinosa na dugoročne državne obveznice i poboljšanju uslova finansiranja

širom eurozone [5]. Istovremeno, povećana je likvidnost finansijskog sistema, što je podstaklo rast kreditne aktivnosti.

Rezultati istraživanja Feldkirchera i Hubera (2018) ukazuju da nekonvencionalne mjere ECB-a pozitivno djeluju na ekonomski rast i inflaciju u većini država eurozone [6]. Međutim, efekti nisu jednako izraženi u svim zemljama, prvenstveno zbog razlika u razvijenosti finansijskih tržišta i stabilnosti bankarskog sektora. Države sa manje razvijenim ili slabije kapitalizovanim bankarskim sistemom uglavnom ostvaruju skromnije koristi od ekspanzivne monetarne politike u poređenju sa finansijski stabilnijim ekonomijama.

Slične zaključke iznosi i Georgiadis (2015), koji naglašava da efekti zajedničke monetarne politike nisu potpuno jednaki u svim članicama eurozone [7]. Struktura nacionalnih privreda, nivo zaduženosti i osjetljivost pojedinih ekonomskih sektora na promjene kamatnih stopa utiču na različite reakcije država na iste monetarne mjere ECB-a. Ovakvi nalazi potvrđuju složenost sprovođenja jedinstvene monetarne politike u okviru monetarne unije koju čine zemlje različitog stepena ekonomskog razvoja i različitih strukturnih karakteristika.

Važnost monetarne politike ECB-a posebno je došla do izražaja nakon pandemije COVID-19 i energetskih šokova izazvanih geopolitičkim krizama, kada je inflacija dostigla visok nivo u eurozoni. Kao odgovor na rast cijena, ECB je od 2022. godine započela ciklus postepenog povećavanja kamatnih stopa s ciljem suzbijanja inflatornih pritisaka. Prema analizama Lanea (2024), restriktivna monetarna politika djeluje kroz smanjenje agregatne tražnje, usporavanje kreditne aktivnosti i stabilizaciju inflacionih očekivanja, čime se stvaraju uslovi za postepeni povratak inflacije prema ciljanoj stopi od 2% [8].

Savremena naučna literatura dodatno potvrđuje značaj efikasnog funkcionisanja transmisijskog mehanizma monetarne politike. Prema istraživanju Mandlera, Scharnagla i Volza (2022), iako među državama eurozone i dalje postoje određene strukturne razlike, zajednička monetarna politika Evropske centralne banke u velikoj mjeri uspijeva da utiče na najvažnije makroekonomske pokazatelje, uključujući inflaciju, proizvodnju i zaposlenost [9]. Njihovi nalazi ukazuju da je monetarna politika ECB-a postala jedan od ključnih instrumenata za očuvanje makroekonomske stabilnosti u okviru monetarne unije.

Na osnovu dosadašnjih iskustava može se zaključiti da monetarna politika Evropske centralne banke predstavlja centralni element ekonomskog upravljanja u eurozoni. Korišćenjem konvencionalnih instrumenata, kao što su kamatne stope, ali i nekonvencionalnih mjera razvijenih tokom kriznih perioda, ECB nastoji da očuva stabilnost cijena, zaštiti vrijednost eura i doprinese ukupnoj ekonomskoj stabilnosti. Iako intenzitet efekata monetarne politike nije identičan u svim državama članicama, brojna istraživanja potvrđuju njenu važnu ulogu u ublažavanju ekonomskih poremećaja i podršci privrednom oporavku.

Uloga Evropske centralne banke posebno dolazi do izražaja u periodima ekonomskih i finansijskih nestabilnosti, kada je očuvanje monetarne i finansijske stabilnosti od presudnog značaja za funkcionisanje eurozone. Posljednjih godina države Evropske unije suočile su se sa snažnim inflatornim pritiscima nastalim kao posljedica pandemije COVID-19, poremećaja u globalnim lancima snabdijevanja, rasta cijena energenata i geopolitičkih tenzija. Navedeni faktori doveli su do rekordnih stopa inflacije u eurozoni od njenog osnivanja, što je zahtijevalo odlučne intervencije Evropske centralne banke.

Kako bi odgovorila na izazove koje su donijele različite krize, ECB je razvila i primijenila širok spektar monetarnih instrumenata, uključujući kako tradicionalne tako i nekonvencionalne mjere. Cilj ovih aktivnosti bio je ublažavanje negativnih posljedica na privredni rast, zaposlenost i stabilnost finansijskog sistema. Dosadašnja iskustva pokazala su da je pravovremena reakcija centralne banke od ključne važnosti za očuvanje povjerenja investitora i stabilno funkcionisanje monetarne unije.

Među najvažnijim nekonvencionalnim instrumentima izdvajaju se programi kupovine državnih i korporativnih obveznica, negativne kamatne stope na depozite i dugoročne operacije refinansiranja banaka. Feldkircher i Huber (2018) ističu da su navedene mjere doprinijele rastu privredne aktivnosti i povećanju inflacije u većini država eurozone, iako su njihovi efekti bili različitog intenziteta među članicama [6]. Njihovo istraživanje pokazuje da su ove mjere bile

naročito značajne tokom dužničke krize, kada je djelotvornost tradicionalnih kanala monetarne transmisije bila ograničena.

Posebno mjesto među nekonvencionalnim instrumentima zauzima program kvantitativnog popuštanja (Quantitative Easing – QE), koji je Evropska centralna banka pokrenula 2015. godine. Kroz otkup velikih količina finansijske aktive ECB je nastojala povećati likvidnost tržišta, sniziti dugoročne kamatne stope i podstaći investicionu aktivnost. Pažický (2018) zaključuje da je ovaj program doprinio rastu inflacije, smanjenju troškova finansiranja i ubrzanju ekonomskog oporavka eurozone nakon finansijske i dužničke krize [10]. Istovremeno, kvantitativno popuštanje pomoglo je u sprečavanju deflatornih kretanja koja su predstavljala ozbiljan rizik za ekonomski rast.

Pandemija COVID-19 otvorila je novo poglavlje u vođenju monetarne politike ECB-a. Nagli pad ekonomske aktivnosti i zatvaranje velikog broja privrednih sektora zahtijevali su hitnu intervenciju centralne banke. Kao odgovor na nastalu situaciju, ECB je pokrenula Pandemijski program hitne kupovine aktive (Pandemic Emergency Purchase Programme – PEPP), čija je ukupna vrijednost premašila 1,8 biliona eura. Benigno i saradnici (2022) navode da je ovaj program doprinio stabilizaciji finansijskih tržišta, očuvanju kreditnih tokova i podršci ekonomskom oporavku država članica eurozone [11]. Prema njihovom mišljenju, riječ je o jednoj od najobuhvatnijih monetarnih intervencija u istoriji Evropske monetarne unije.

Pored toga, brojna istraživanja ukazuju da uspješnost monetarne politike u velikoj mjeri zavisi od nivoa ekonomske neizvjesnosti. Hauzenberger, Pfarrhofer i Stelzer (2020) zaključuju da tradicionalni instrumenti monetarne politike ostvaruju slabije rezultate u uslovima povećane neizvjesnosti, dok nekonvencionalne mjere, poput kvantitativnog popuštanja, pokazuju veću efikasnost [12]. Njihovi nalazi potvrđuju da je prilagođavanje instrumenata monetarne politike specifičnim okolnostima svake krize jedan od ključnih preduslova za uspješnu stabilizaciju ekonomskih tokova i očuvanje makroekonomske ravnoteže.

Inflacija predstavlja jedan od ključnih izazova makroekonomske politike Evropske unije, pri čemu je očuvanje stabilnosti cijena osnovni cilj monetarne politike Evropske centralne banke. Nakon dužeg perioda obilježenog veoma niskom inflacijom, pa čak i pojavom deflatornih pritisaka, eurozona se tokom 2021. i 2022. godine suočila sa naglim rastom cijena. Prema istraživanju Huber, Onorante i Pfarrhofer (2022), značajnu ulogu u formiranju inflacionih kretanja imala su očekivanja potrošača i preduzeća, dok su rast cijena energenata i povećani troškovi proizvodnje predstavljali glavne pokretače inflacije [13].

Tokom 2023. i 2024. godine zabilježeno je postepeno slabljenje inflacionih pritisaka, što je rezultat kombinovanog djelovanja restriktivne monetarne politike ECB-a, stabilizacije energetskih tržišta i normalizacije globalnih lanaca snabdijevanja. Evropska centralna banka ističe da su dugoročna inflaciona očekivanja ostala relativno stabilna i usklađena sa srednjoročnim ciljem inflacije od 2%, što predstavlja važan preduslov za uspješnu kontrolu cjenovnih kretanja.

Nalazi OECD-a (2025) potvrđuju da se proces dezinflacije u državama Evropske unije odvija postepeno, iako i dalje postoje određeni rizici koji mogu uticati na dinamiku inflacije [14]. Kretanje cijena energenata, promjene u međunarodnoj trgovini, kao i rast zarada ostaju važni faktori koji oblikuju inflaciona očekivanja i stvarna cjenovna kretanja. Prema projekcijama OECD-a, prosječna stopa inflacije u eurozoni trebalo bi da iznosi približno 2,2% tokom 2025. godine, dok se za 2026. godinu očekuje njeno približavanje nivou od 2,0%, što ukazuje na postepeni povratak stabilnijim uslovima nakon perioda snažnih inflatornih poremećaja.

Ipak, uprkos evidentnim pozitivnim trendovima, inflacija u Evropskoj uniji i dalje ostaje pod uticajem brojnih neizvjesnosti. Geopolitičke tenzije, nestabilnost energetskih tržišta, promjene u globalnim trgovinskim tokovima i rast troškova rada mogu dovesti do ponovnog jačanja inflatornih pritisaka. Zbog toga Evropska centralna banka kontinuirano prati inflaciona očekivanja i prilagođava instrumente monetarne politike kako bi očuvala stabilnost cijena i makroekonomsku ravnotežu.

Može se zaključiti da je Evropska unija nakon perioda izrazito visoke inflacije ušla u fazu postepenog smirivanja cjenovnih pritisaka i stabilizacije inflacionih kretanja. Međutim, održavanje inflacije na ciljnom nivou i dalje će predstavljati jedan od najvažnijih zadataka ekonomske i monetarne politike u narednom periodu, posebno imajući u vidu prisutne globalne i regionalne rizike.

U nastavku rada prikazan je pregled prosječnih godišnjih stopa inflacije mjerenih harmonizovanim indeksom potrošačkih cijena (HICP) za države Evropske monetarne unije u periodu od 2020. do 2025. godine. Podaci za 2025. godinu predstavljaju procjene i prosječne vrijednosti zasnovane na raspoloživim informacijama Evropske centralne banke i Eurostata [15].

Iz tabele 1 je vidljivo da je najveći inflatorni talas zabilježen tokom 2022. godine, kada je prosječna inflacija u eurozoni premašila 8%, prvenstveno zbog energetske krize i poremećaja u lancima snabdijevanja. Baltičke zemlje (Estonija, Litvanija i Letonija) zabilježile su najviše stope inflacije, dok su Francuska i Malta imale relativno niže stope. Tokom 2024. i 2025. godine inflacija se postepeno vratila prema ciljanoj stopi ECB-a od 2%, zahvaljujući restriktivnoj monetarnoj politici i stabilizaciji cijena energenata.

Tabela 1: Stopa inflacije u zemljama članicama EMU

Zemlja	2020	2021	2022	2023	2024	2025*
Austrija	1,4	2,8	8,6	7,8	3,0	3,6
Belgija	0,4	3,2	10,3	2,3	4,3	2,6
Hrvatska	0,1	2,7	10,7	8,4	4,0	4,6
Kipar	-0,6	2,3	8,1	3,9	2,2	0,0
Estonija	-0,6	4,5	19,4	9,4	3,5	6,2
Finska	0,4	2,2	7,2	4,4	1,6	1,6
Francuska	0,5	2,1	5,9	5,7	2,3	0,8
Njemačka	0,4	3,2	8,7	6,1	2,5	2,2
Grčka	-1,3	0,6	9,3	4,2	3,0	2,5
Irska	-0,3	2,4	8,1	5,2	2,1	1,5
Italija	-0,1	1,9	8,7	6,0	1,1	1,6
Letonija	0,1	3,2	17,2	9,0	1,4	3,9
Litvanija	1,1	4,7	18,9	8,7	1,0	3,4
Luksemburg	0,0	2,7	8,2	2,9	2,3	2,2
Malta	0,8	0,7	6,1	5,6	2,4	2,2
Nizozemska	1,1	2,8	11,6	4,1	3,2	2,0
Portugal	-0,1	0,9	8,1	5,3	2,7	2,5
Slovačka	2,0	2,8	12,1	11,0	3,2	4,5
Slovenija	-0,1	2,0	9,3	7,4	2,0	2,0
Španija	-0,3	3,0	8,3	3,5	2,9	2,7
Prosjek EMU	0,3	2,6	8,4	5,4	2,4	2,9

Podaci iz tabele 2 pokazuju da su zemlje Evropske unije koje nisu članice Evropske monetarne unije uglavnom bilježile više stope inflacije od prosjeka eurozone. Najizraženiji inflatorni pritisci zabilježeni su tokom 2022. i 2023. godine, kada su Mađarska, Češka, Poljska i Rumunija ostvarile dvocifrene stope inflacije. Najveću inflaciju imala je Mađarska sa 15,3% u 2022. i 17,5% u 2023. godini, dok je Danska tokom cijelog perioda zadržala relativno niže stope inflacije. Inflatorni rast bio je posljedica energetske krize, poremećaja u lancima snabdijevanja, rasta cijena hrane i ekspanzivnih fiskalnih mjera nakon pandemije COVID-19 [15]. Tokom 2024. godine vidljivo je značajno smanjenje inflacije u svim posmatranim državama, dok podaci za 2025. godinu ukazuju na djelimično ponovno jačanje inflatornih pritisaka u pojedinim zemljama, posebno u Rumuniji i Bugarskoj.

Tabela 2: Prosječne godišnje stope inflacije (HICP, %) u državama članicama EU koje nisu bile članice Evropske monetarne unije (eurozone) u periodu 2020–2025

Zemlja	2020	2021	2022	2023	2024	2025
Bugarska	1,2	3,3	13,0	8,6	2,6	6,3
Češka	3,3	4,5	14,8	12,1	2,7	4,2
Danska	0,4	1,9	8,5	3,4	1,3	4,1
Mađarska	3,4	5,2	15,3	17,5	3,7	4,5
Poljska	3,7	5,2	13,2	10,9	3,7	5,3
Rumunija	2,3	4,1	12,0	9,7	5,8	6,8
Švedska	0,7	2,7	8,1	5,9	2,0	3,8
Prosjek	2,1	3,8	12,1	9,7	3,1	5,0

Empirijska analiza inflatornih kretanja pokazuje da je period od 2021. do 2023. godine obilježen izrazito snažnim rastom cijena u svim državama Evropske unije. Prosječna stopa inflacije u eurozoni dostigla je vrhunac od 8,4% tokom 2022. godine, dok su pojedine države, naročito baltičke zemlje, zabilježile inflaciju veću od 18%. Istovremeno, države članice Evropske unije koje nisu dio eurozone ostvarile su još veće stope inflacije, pri čemu su Mađarska, Češka, Poljska i Rumunija bilježile dvocifrene vrijednosti inflacije tokom više uzastopnih godina.

Dobijeni rezultati ukazuju da je zajednička monetarna politika ECB-a doprinijela relativno većoj stabilnosti cijena u odnosu na zemlje koje vode samostalnu monetarnu politiku. Međutim, analiza takođe pokazuje da efekti monetarne politike nisu bili jednaki u svim državama članicama eurozone. Razlike u strukturi privrede, nivou zaduženosti, razvijenosti finansijskih tržišta i snazi bankarskog sektora uticale su na različitu efikasnost transmisije monetarne politike.

Diskusija rezultata potvrđuje nalaze brojnih autora da su nekonvencionalne mjere ECB-a, posebno kvantitativno popuštanje i pandemijski program kupovine aktive, značajno doprinijele ublažavanju posljedica finansijske, dužničke i pandemijske krize. Istovremeno, rezultati ukazuju da buduća efikasnost monetarne politike zavisi od daljeg jačanja fiskalne koordinacije i institucionalne integracije unutar Evropske monetarne unije. Stoga se može zaključiti da monetarna politika ECB-a ostaje jedan od najvažnijih instrumenata stabilizacije ekonomskih kretanja u Evropskoj uniji, ali da njena uspješnost u velikoj mjeri zavisi od ekonomskih karakteristika pojedinačnih država članica.

Prema Laneu (2006), uspostavljanje Evropske monetarne unije značajno je doprinijelo jačanju ekonomske integracije među državama članicama [16]. Međutim, autor upozorava da potencijalni izazov za stabilnost monetarne unije predstavljaju ozbiljni ekonomski poremećaji ili finansijske krize koje mogu pogoditi pojedinačne članice. Takve situacije, prema njegovom mišljenju, predstavljaju svojevrsni „test političke održivosti eura“. Lane takođe naglašava da inflacioni diferencijali među državama eurozone, kao i pojava asimetričnih ekonomskih šokova, ostaju trajni izazovi za sprovođenje jedinstvene monetarne politike Evropske centralne banke (ECB).

Jedan od najvažnijih izazova budućeg razvoja Evropske monetarne unije odnosi se na nedovoljnu fiskalnu konvergenciju među državama članicama. Iako je monetarna integracija dostigla visok nivo razvoja, još uvijek ne postoje potpuno razvijeni fiskalni mehanizmi i institucije koje bi omogućile dugoročno održivu konvergenciju ekonomija unutar eurozone (SUERF/OeNB, 2019) [17]. U tom kontekstu, Cohen i Wyplosz (1989) ističu da je osnovno pitanje pristupanja valutnoj uniji procjena da li koristi od smanjenja transakcionih troškova, eliminacije neizvjesnosti deviznih kurseva i postizanja stabilnijih inflacionih performansi mogu nadoknaditi gubitak samostalnosti u vođenju monetarne politike [18].

Nakon iskustava stečenih tokom pandemije COVID-19, sve više se razmatra mogućnost trajnije fiskalne integracije unutar eurozone. Riet (2020) smatra da države članice imaju priliku da

razviju trajniji fiskalni okvir koji bi djelovao komplementarno monetarnoj politici [19]. Takav okvir mogao bi uključivati uspostavljanje centralnog fiskalnog kapaciteta, kao i zajedničkog sigurnog finansijskog instrumenta (sovereign asset) namijenjenog cijeloj eurozoni.

Dalji razvoj Evropske monetarne unije u velikoj mjeri zavisi od spremnosti država članica da produbе fiskalnu integraciju i sprovedu neophodne strukturne reforme. Iskustva prethodnih kriza pokazala su da je jača fiskalna povezanost važan preduslov za dugoročnu stabilnost monetarne unije. Istovremeno, postalo je jasno da članstvo u eurozoni podrazumijeva veći stepen prenosa nacionalnog suvereniteta na zajedničke evropske institucije nego što se prvobitno očekivalo.

Može se zaključiti da su dugoročne perspektive Evropske monetarne unije i dalje pozitivne, ali da njihov uspjeh zavisi od daljeg unapređenja fiskalne integracije, sprovođenja strukturnih reformi i efikasnije koordinacije ekonomskih politika među državama članicama. Samo kroz jačanje ovih elemenata moguće je osigurati stabilnost i održivost monetarne unije u uslovima budućih ekonomskih i finansijskih izazova.

ZAKLJUČAK

Evropska monetarna unija predstavlja jedan od najznačajnijih oblika ekonomske integracije u savremenom svijetu, dok Evropska centralna banka ima centralnu ulogu u očuvanju monetarne i finansijske stabilnosti eurozone. Analiza razvoja EMU-a, instrumenata monetarne politike ECB-a i inflatornih kretanja pokazuje da je zajednička monetarna politika doprinijela stabilnosti cijena, jačanju finansijskog sistema i smanjenju ekonomskih posljedica brojnih kriza sa kojima se Evropska unija suočavala tokom posljednjih decenija.

Rezultati istraživanja potvrđuju da su konvencionalni i nekonvencionalni instrumenti monetarne politike imali značajnu ulogu u ublažavanju posljedica globalne finansijske krize, evropske dužničke krize i pandemije COVID-19. Posebno se ističe značaj programa kupovine aktive, dugoročnih operacija refinansiranja i drugih vanrednih mjera koje su omogućile očuvanje likvidnosti finansijskog sistema i podršku privrednom oporavku.

Analiza inflatornih kretanja pokazala je da su zemlje eurozone tokom posmatranog perioda ostvarivale relativno stabilnija cjenovna kretanja u odnosu na države Evropske unije koje nisu članice Evropske monetarne unije. Ipak, prisutne razlike među državama članicama potvrđuju da jedinstvena monetarna politika djeluje u različitim ekonomskim okruženjima, što predstavlja jedan od najvećih izazova za ECB.

Može se zaključiti da će budući uspjeh Evropske monetarne unije zavisiti od sposobnosti daljeg unapređenja institucionalnog okvira, jačanja fiskalne koordinacije i prilagođavanja monetarne politike novim ekonomskim izazovima. U uslovima povećane globalne neizvjesnosti, geopolitičkih rizika i mogućih novih inflatornih pritisaka, ECB će i dalje imati ključnu ulogu u očuvanju stabilnosti cijena i održivog ekonomskog razvoja Evropske unije.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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EU MONETARY POLICY – CURRENT STATE AND PERSPECTIVES

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ABSTRACT

The monetary policy of the European Union is one of the key instruments for achieving macroeconomic stability, sustainable economic growth, and maintaining price stability within the euro area member states. This paper analyzes the institutional framework of the European Union's monetary policy, with particular emphasis on the role of the European Central Bank, its objectives, instruments, and operational mechanisms. Special attention is given to the challenges that monetary policy has faced in recent years, including the consequences of the global financial crisis, the COVID-19 pandemic, inflationary pressures caused by disruptions in supply chains, and geopolitical uncertainties. The aim of the research is to examine the current state of the European Union's monetary policy, assess its effectiveness in achieving its established objectives, and identify the key perspectives for its future development. The study applies descriptive and comparative analysis methods, as well as an analysis of relevant statistical indicators and official documents of the European Central Bank.

Keywords: Monetary policy, European Union, European Central Bank, euro area, inflation, financial stability.

THE IMPACT OF INDUSTRIAL ROBOTICS ON PRODUCTIVITY AND THE LABOR MARKET

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ABSTRACT

The development of industrial robotics and automation is significantly transforming the organization of production processes and business operations in modern companies. The use of robots in manufacturing contributes to higher efficiency, precision, and productivity, while also leading to changes in the labor market.

This paper analyzes the impact of industrial robotics on enterprise productivity and the changes in employment structure resulting from automation. Special attention is given to the economic effects of robot implementation, as well as the challenges related to adapting the workforce to new technological conditions. The focus is on shifts in demand for certain occupations, the need for additional employee training, and the emergence of new jobs connected to digital technologies.

The research is based on analytical, descriptive, and comparative methods, along with a review of domestic and international literature. The results indicate that industrial robotics contributes to the growth of productivity and the competitiveness of companies, but at the same time requires continuous investment in knowledge development and adaptation of the labor market to modern technological changes.

Keywords: Industrial robotics, automation, productivity, labor market, digitalization, employment.

INTRODUCTION

Despite the growing number of studies dealing with industrial robotics, automation and their effects on enterprises and employees, there is still a need to connect the economic and labor market aspects of this technological development. A considerable part of the existing literature focuses on the effects of automation on productivity, production efficiency and business performance, while another part examines changes in employment, the disappearance of certain routine jobs and the emergence of new occupations [1], [2], [3], [4]. Considering these aspects separately may provide only a partial understanding of the broader effects of industrial robotics.

The originality of the paper does not lie in the collection of new empirical data, but in the systematization, comparison and interpretation of existing findings from relevant literature. Particular attention is given to the connection between productivity growth and changes in employment structure, as well as to the role of employee education and professional development in the process of technological adaptation. This approach makes it possible to identify common findings across different studies and to point out the importance of considering technological development together with the development of human resources [5], [6].

An additional contribution of the paper is the inclusion of both domestic and international literature in the analysis. The use of sources from Bosnia and Herzegovina and Serbia, together with relevant international publications, enables a broader consideration of the research problem and provides a basis for comparing the characteristics of the regional environment with wider international trends. Such an approach is particularly important because the effects of industrial robotics may differ depending on the level of technological development, industrial structure and economic conditions of individual countries [4], [7].

The basic research question of the paper is:

"How does the application of industrial robotics affect the productivity of companies and how does automation change the employment structure in the modern business environment?"

In accordance with the research question, the main aim of the paper is to analyze the economic and organizational effects of industrial robotics, with particular emphasis on productivity growth, changes in labor market requirements and the development of new employee competencies. The paper also aims to identify the main benefits and challenges associated with the implementation of industrial robotics and to explain how changes in technology influence the structure of jobs and the skills required from employees.

A further aim is to determine whether the effects of automation should be understood only through the reduction of certain jobs or more broadly through changes in the structure of employment and the emergence of new professional opportunities. In this context, special attention is given to the importance of continuous education, professional development and adaptation of employees to technological changes.

The relevance of the topic stems from the fact that industrial robotics has become an important element of modern technological and economic development [8], [7]. Companies increasingly use automation to improve production efficiency, reduce costs, increase product quality and maintain competitiveness in changing market conditions. At the same time, technological development changes the requirements placed on employees and creates a growing need for knowledge related to digital technologies, programming, automated systems, data analysis and the management of modern production processes.

For this reason, understanding the relationship between industrial robotics, enterprise productivity and employment structure is important not only for companies, but also for employees and educational institutions. The successful introduction of new technologies depends on the ability of organizations and workers to adapt to changing conditions. Therefore, the analysis presented in this paper is aimed at providing a clearer understanding of the economic benefits of robotization, the changes occurring in the labor market and the importance of developing competencies required in the modern technological environment.

The contribution of this paper is reflected in the systematic synthesis and comparative interpretation of findings from domestic and international literature concerning the economic and labor market effects of industrial robotics.

Rather than presenting primary empirical results, the paper integrates existing evidence on productivity, production efficiency, competitiveness, employment restructuring and the development of employee competencies.

Particular attention is given to the relationship between productivity gains resulting from robotization and the simultaneous transformation of employment structures and skill requirements. In this regard, the paper provides an integrated perspective on industrial robotics by connecting technological and economic effects with the human resource and labor market dimensions of technological change [5], [6].

METHODOLOGY

The subject of this research is the analysis of the impact of industrial robotics on enterprise productivity and changes in the employment structure that occur as a result of the automation of production and business processes [9], [10], [11]. Since the topic includes technological, economic and organizational aspects, the research applies a combined methodological approach based on descriptive, analytical and comparative methods.

The research was conducted as a theoretical-analytical study based on the review and analysis of relevant domestic and international literature. This approach was selected because the aim of the paper is to examine existing knowledge about the effects of industrial robotics on productivity, business performance and the labor market, and to identify the main trends and changes described in previous research.

The data used in the research were collected from secondary sources. These sources include scientific articles, professional publications, books, reports of international organizations, statistical data and other relevant publications dealing with industrial robotics, automation, digitalization, productivity and employment [12], [13]. The literature was selected according to its relevance to the research topic, reliability of the source, connection with the research question, and the extent to which the source contributes to understanding the economic and labor market effects of industrial robotics.

Particular attention was given to sources that examine the relationship between automation and labor productivity, the economic effects of robotization, changes in employment and the development of new employee competencies [14], [11]. Sources addressing the application of industrial robotics in production processes, changes in work organization, technological development and the competitiveness of enterprises were also considered relevant for the analysis.

In order to provide a broader perspective on the research problem, the literature review included domestic sources from Bosnia and Herzegovina and Serbia, as well as selected international publications dealing with contemporary trends in industrial automation and robotics [4], [7], [5]. The selection of international literature was important for comparing the findings of domestic and foreign research and for identifying common trends in the development and application of industrial robotics.

The literature selection was also based on the availability of information relevant to the two main aspects of the research: the effects of industrial robotics on enterprise productivity and the effects of automation on employment and labor market requirements. Sources that addressed only general technological development, without a clear connection to these aspects, were not considered central to the analysis. In this way, the selected literature was directly related to the research question and objectives of the paper.

Since the research does not include surveys, interviews or experimental procedures, the sample consists of scientific and professional sources related to industrial robotics and its economic, organizational and social effects. The analyzed sources include scientific articles published in relevant journals, professional and academic books, reports of international organizations, statistical indicators related to the development and application of industrial robots, and examples of companies using automated production systems.

The selected sources enabled the analysis of robotization in different industrial activities, including the automotive, electronics, metalworking and logistics industries. This provided an opportunity to consider the effects of industrial robotics from different perspectives and to identify similarities and differences between individual industries and business environments.

Descriptive, analytical and comparative methods were used in the processing and interpretation of the collected information [15], [9]. The descriptive method was used to present the main characteristics of industrial robotics, automation processes and changes in modern organizations. Its purpose was to provide a clear overview of the basic concepts and trends related to the research topic.

The analytical method was used to examine the relationship between the application of industrial robotics and enterprise productivity. Through the analysis of the selected literature, particular attention was paid to factors related to production efficiency, operating costs, product quality, resource utilization and the competitiveness of companies.

The comparative method was used to compare the findings of different studies and experiences of companies applying industrial robotics. The comparison made it possible to identify common findings concerning productivity growth, changes in employment and the development of new competencies, while also taking into account differences related to individual industries and economic environments.

The analysis of the collected sources was conducted in several stages. First, relevant literature was identified and selected according to the previously defined criteria. The selected sources were then classified according to the main thematic areas of the research, including industrial robotics, productivity, automation, labor market, digitalization, employee competencies and enterprise competitiveness. After classification, the contents of the sources were analyzed in order to identify the most important findings related to the research question.

In the next stage, the findings from different sources were compared and systematized. Particular attention was paid to findings that appeared repeatedly in different studies, as well as to differences in the effects of industrial robotics on productivity and employment. The results of this analysis were then used to identify the main effects of robotization and to connect them with changes in the structure of employment and the requirements of the modern labor market.

Finally, the collected information was synthesized and interpreted in accordance with the research question and objectives of the paper. Based on the analysis and comparison of the selected literature, conclusions were drawn about the relationship between industrial robotics, enterprise productivity, competitiveness and changes in employment structure.

The research has certain limitations. First, it is based on secondary data sources, which means that the findings depend on the availability, quality and scope of the existing literature. The study does not include primary empirical data collected directly from companies or employees. In addition, industrial robotics is developing rapidly, which means that new technological solutions and findings are continuously emerging. The effects of automation may also differ depending on the industry, company size, technological level and economic characteristics of individual countries [6].

Despite these limitations, the applied methodology provides a suitable basis for a theoretical-analytical examination of the impact of industrial robotics on enterprise productivity and changes in the labor market. The combination of descriptive, analytical and comparative methods, together with a systematic selection and analysis of relevant literature, enables the identification of the main trends and effects associated with the increasing application of industrial robotics. Figure 1 shows the application of an industrial robot in an automated production process.



Figure 1. Application of an industrial robot in an automated production process [16]

FINDINGS FROM THE LITERATURE ANALYSIS

The findings presented in this section represent a synthesis of results reported in the reviewed literature and should therefore not be interpreted as original empirical findings obtained through primary data collection. The purpose of the synthesis is to identify recurring patterns, similarities and differences among previous studies concerning the effects of industrial robotics on productivity, production efficiency, employment and employee competencies. By comparing the findings of different sources, the analysis identifies the most consistent effects of robotization and provides a basis for their further interpretation in the Discussion section.

The analysis of the selected literature shows that industrial robotics has a significant impact on the organization and efficiency of modern production systems. Across the reviewed sources, the most frequently identified effects are related to increased productivity, improved product quality, more efficient use of resources and strengthening of enterprise competitiveness [3], [1], [2], [4]. At the same time, the literature points to changes in the employment structure and an increasing need for employees with technical and digital competencies.

One of the most consistent findings in the reviewed literature concerns the relationship between industrial robotics and productivity. The introduction of automated systems enables production operations to be performed more quickly and with a high level of precision. Robots are particularly suitable for repetitive and standardized activities where a large number of identical operations need to be performed. Their ability to operate continuously and maintain a relatively stable level of performance contributes to better utilization of production capacities and reduction of downtime.

The reviewed studies indicate that the effects of robotization are particularly visible in industries in which production processes are highly standardized, such as the automotive, electronics and metalworking industries. In these sectors, industrial robots can perform repetitive activities with a high degree of accuracy, which contributes to increasing production volumes and improving the efficiency of production processes.

Another important finding concerns product quality. The use of industrial robots reduces the possibility of human error in repetitive production activities and enables more consistent execution of predefined operations [15], [8], [7]. Greater precision can contribute to reducing the number of defective products, material waste and the need for subsequent corrections. In this way, the application of robotics can have both a direct effect on production quality and an indirect effect on operating costs.

The literature also indicates that industrial robotics can contribute to greater flexibility in production. Modern robotic systems can be programmed and adjusted to different production requirements, which enables companies to respond more quickly to changes in products and market demand. This characteristic is particularly important in modern business conditions, where companies are required to adapt their production processes to changing customer needs and increasing competition.

Table 1. Key findings from the literature analysis

Area	Main findings identified in the literature
Productivity	Increased production volume, faster operations and more efficient use of production capacities
Product quality	Greater precision, fewer errors and reduction of defective products
Operating costs	More efficient use of materials, energy and working time
Production organization	Greater flexibility, improved process control and better production planning
Labor market	Reduced demand for certain routine jobs and increased demand for skilled personnel
Employee competitiveness	Greater need for digital, technical and analytical skills
Competitiveness	Improved production efficiency, quality and ability to respond to market changes

The economic effects of industrial robotics are also frequently emphasized in the reviewed sources. Although the implementation of robotic systems requires significant initial investment, automation can generate long-term benefits through more efficient use of materials, energy and working time. Greater production precision can reduce waste, while higher production speed can enable companies to increase their production capacity without proportionally increasing labor costs.

The analysis also indicates that the effects of robotization should not be considered only from the perspective of cost reduction. The application of automated systems can influence the organization of business activities, production planning and process control. Companies that successfully integrate robotic technologies can achieve greater flexibility and respond more quickly to changes in market conditions [5], [4]. In this context, industrial robotics represents not only a technological investment but also an element of broader organizational transformation.

A particularly important finding concerns the impact of industrial robotics on employment. The reviewed literature indicates that automation primarily affects jobs involving routine, repetitive and physically demanding activities. These activities are generally easier to standardize and automate, which can reduce the demand for certain types of manual labor.

At the same time, the literature does not support the view that automation should be understood exclusively as a process of eliminating jobs. The introduction of robotic systems also creates a need for employees who can operate, program, maintain and manage automated production systems. The demand for knowledge in industrial automation, robotics, information technology, data analysis and digital production is therefore increasing [1], [2], [5], [6].

The findings suggest that one of the most important consequences of industrial robotics is a change in the structure of employment. Certain routine occupations become less demanded, while new professional profiles emerge. This means that the effects of automation on employment depend not only on the number of jobs that may be affected, but also on the ability of workers and organizations to adapt to changing technological conditions.

The reviewed literature further emphasizes the importance of employee education and continuous professional development. The introduction of modern technologies creates new requirements that traditional forms of education may not always be able to meet fully [14], [11]. Employees increasingly need knowledge related to digital technologies, programming, automated systems, data analysis and industrial informatics.

Continuous learning therefore represents an important condition for successful adaptation to technological changes. Organizations that invest in employee education and professional development can more easily integrate new technologies into their operations and make more effective use of the advantages provided by automation. At the same time, employees who continuously develop their knowledge and skills have greater opportunities to adapt to changes in the structure of the labor market.

Another finding emerging from the literature is the connection between automation and enterprise competitiveness. Companies that successfully implement robotic systems can achieve greater production flexibility, more efficient resource utilization and faster responses to market requirements. Improved quality and reduced production costs can contribute to strengthening the market position of enterprises.

The literature also indicates that the effects of industrial robotics are not identical in all economic environments. They may differ depending on the industry, company size, technological level and economic characteristics of individual countries. This is particularly important when considering Bosnia and Herzegovina and other countries in the region, where the level of application of industrial robotics is lower than in the most developed industrial economies. Nevertheless, the development of digital competencies, technological infrastructure and modern production systems creates opportunities for further application of robotics and automation.

Overall, the findings obtained through the analysis of the selected literature show that industrial robotics has a multidimensional impact on modern enterprises. Its effects are reflected in increased productivity, improved product quality, more efficient resource utilization and stronger competitiveness, while simultaneously contributing to changes in the structure of employment and the competencies required from employees.

The findings also indicate that the successful application of industrial robotics depends on the ability of enterprises and employees to adapt to technological changes. For this reason, robotization should not be viewed only as the replacement of human labor with machines, but as a broader process of transformation in which technology, organization and human resources are closely connected.

The synthesis of the reviewed literature indicates that the effects of industrial robotics can be grouped into two interconnected dimensions. The first concerns economic and organizational effects, primarily reflected in increased productivity, improved precision, more efficient resource utilization, product quality and enterprise competitiveness. The second concerns labor market effects, particularly changes in the structure of employment, reduced demand for some routine occupations and increased demand for technical, digital and analytical competencies.

The reviewed evidence therefore suggests that the economic benefits of robotization and changes in employment should be considered as interconnected processes rather than as separate consequences of technological development. This synthesis provides the basis for the discussion of the broader implications of industrial robotics for enterprises, employees and the labor market.

DISCUSSION

The synthesized findings indicate that the impact of industrial robotics cannot be reduced to a simple relationship between automation and either productivity growth or job displacement. Rather, the literature points to a transformation of production processes and employment structures occurring simultaneously. From an economic perspective, robotization may improve productivity, precision and resource efficiency, while from a labor market perspective it changes the composition of tasks, occupations and required competencies. The significance of these findings lies precisely in the interaction between these two dimensions: productivity gains can create new organizational and economic opportunities, but their long-term benefits depend partly on the ability of enterprises and employees to adapt to technological change.

The analysis of the literature used in this paper shows that industrial robotics plays a significant role in the transformation of modern production systems [3], [8]. The reviewed sources indicate that the application of robotic technologies contributes to increasing productivity, improving product quality and strengthening the competitiveness of enterprises. At the same time, changes in the employment structure are observed that require the adaptation of the workforce to new technological requirements [1], [2].

The analyzed works largely confirm the view that industrial robotics is one of the important drivers of modern economic development. By introducing robots into production processes, companies can increase production volumes without significantly increasing labor costs. Such effects are especially pronounced in industries with complex and continuous production processes, where even minor changes in work organization can lead to significant economic benefits (Figure 2).

The productivity gains often cited in the literature can be attributed to the fact that robots enable tasks to be performed with high levels of precision and reliability [3]. Unlike human labor, which can be affected by fatigue or other limitations, robotic systems can maintain a stable level of performance over a long period of time. This reduces downtime and production losses, and increases the efficiency of production processes [15].

The reviewed sources also indicate that automation has a positive impact on product quality. Reducing errors during production contributes to greater customer satisfaction, fewer complaints, and a better business reputation. In conditions of increasing competition in the market, maintaining stable product quality is an important factor for successful business.

Although the literature mainly emphasizes the positive effects of robotization, it also points to certain challenges related to the labor market. One of the questions that is often raised is the possibility of replacing human labor with automated systems. Based on the analyzed sources, it can

be concluded that the jobs that involve routine, repetitive, and physically demanding activities are exposed to the greatest changes.

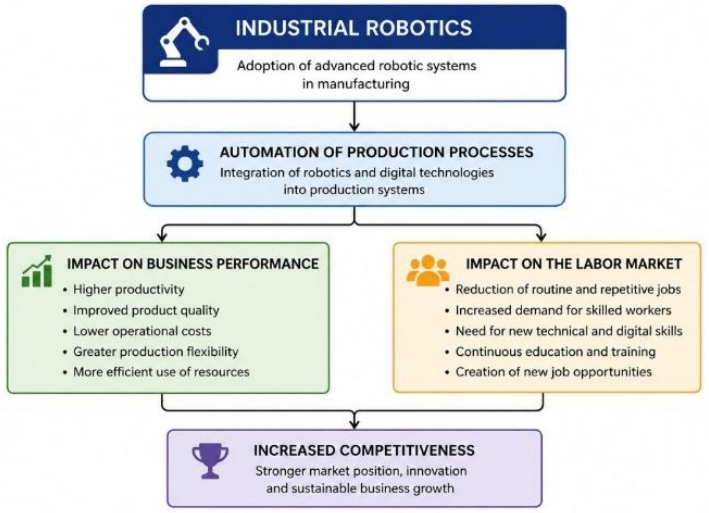

Figure 2. Conceptual representation of the impact of industrial robotics on business and the labor market

These jobs are the areas where automation is easiest and most cost-effective to implement. As a result, workers in these jobs may be at greater risk of job loss during technological change. Such changes are particularly pronounced in sectors that rely heavily on manual labor.

However, a review of the literature shows that automation does not only lead to a reduction in the number of employees [2], [5]. Many studies indicate that at the same time there is a need for new profiles of workers who have knowledge in the fields of information technology, programming, automation and management of modern production systems [6], [11].

The empirical evidence also indicates that the labor market effects of robotization are more complex than a simple reduction in total employment. Dauth et al. [17], examining the German labor market, found that the introduction of industrial robots was associated with substantial changes in the composition of employment, while aggregate employment effects were less pronounced than might be expected from the displacement of individual tasks. This finding supports the view that automation can simultaneously reduce demand for certain routine tasks and increase demand for other activities and competencies. Similar evidence is reported by Koch et al. [18], who found that firms adopting robots experienced changes in productivity, employment and the structure of production. These findings further support the argument that the effects of industrial robotics should be analyzed through changes in tasks, occupations and production organization rather than solely through the number of jobs eliminated.

These findings suggest that technological developments should not be viewed solely in terms of the potential for job losses. It is more important to understand that robotization is changing the structure of jobs and the demands placed on employees by the labor market. In this sense, the key challenge is the ability of individuals, educational institutions, and businesses to adapt to new circumstances.

Special attention should be paid to the education and professional development of employees. The analyzed sources show that the successful application of industrial robotics requires appropriate knowledge and competencies of the workforce. Without sufficient professional staff, it is not possible to fully utilize the advantages that modern technologies provide.

Therefore, lifelong learning and continuous improvement of employees are becoming increasingly important. The modern labor market requires constant acquisition of new knowledge and skills, especially in areas related to digital technologies and automation of production

processes. Organizations that invest in the development of their employees adapt more easily to technological changes and use new technologies more efficiently.

When it comes to Bosnia and Herzegovina and the countries of the region, the issue of developing digital competencies is becoming increasingly important. Although the process of digitalization is present in various economic sectors, the level of application of industrial robotics is still lower than in the most developed industrial countries. At the same time, such a situation opens up opportunities for further development through investment in education, technological infrastructure and modernization of production systems.

The literature also indicates a significant connection between robotization and company competitiveness. Organizations that successfully implement automated systems most often achieve greater production flexibility, use available resources more efficiently, and respond more quickly to changes in market demand. In modern business conditions, the ability to adapt is one of the key factors for success [3], [8], [4].

In addition to reducing costs and increasing productivity, automation can also contribute to the development of innovation within the company. The application of modern technologies often encourages the development of new products, services and business models, thereby creating additional opportunities for the growth and development of the organization.

Although the sources analyzed confirm the numerous advantages of industrial robotics, it is necessary to point out certain limitations of its application. The implementation of robotic systems requires significant financial investments, which can be an obstacle for smaller companies. In addition, the introduction of new technologies often requires additional training of employees and adaptation of existing business processes.

A limitation of this paper is that the research is based on secondary data sources. Such an approach allows for an overview of a large number of studies and experiences from different countries, but does not provide the possibility of directly measuring the effects of robotization in specific companies. Future research could include empirical data collected through surveys, interviews, or case studies to examine in more detail the effects of automation in different organizational settings.

Based on the analyzed literature, it can be concluded that industrial robotics represents an important part of modern industrial development. Its application contributes to increasing productivity, improving product quality and strengthening the competitiveness of companies, but at the same time requires labor market adaptation and development of new employee competencies.

Therefore, industrial robotics should be seen as part of a broader digital transformation that encompasses technological, economic and social changes. Only the coordinated development of technology and human resources can enable the full exploitation of the potential that modern robotics offers to the economy and society.

CONCLUSION

Industrial robotics today represents one of the most important segments of modern technological development and plays an increasingly important role in the functioning of production systems and business organizations [19], [8]. The development of automation and digital technologies has enabled companies to improve production processes, increase work efficiency and strengthen competitiveness in the market. Therefore, the application of industrial robots is no longer just a technological innovation, but an important factor in long-term business development [3], [1].

Literature analysis has shown that industrial robotics significantly contributes to increasing the productivity of enterprises. Automated systems enable faster and more precise performance of production activities, reduce errors and use available resources more efficiently. In addition, robotization has a positive effect on product quality, reduces operating costs and improves overall business results [5], [6]. The above advantages are especially evident in industries characterized by complex and continuous production processes.

The sources analyzed also point to significant changes in the structure of employment that arise as a result of automation. While the need for certain routine and repetitive jobs is decreasing, the demand for employees with technical and digital knowledge is growing. Competencies related

to programming, managing automated systems, data analysis and the application of modern information technologies are becoming increasingly important.

The findings confirm that technological development should not be viewed solely as a replacement of human labor by machines. A much more significant consequence of robotization is the change in the structure of existing jobs and the creation of new professional opportunities that require different knowledge and skills. Therefore, education and continuous professional development become one of the most important conditions for successful adaptation to the modern labor market.

The value of this paper lies in the examination of the connection between the economic effects of industrial robotics and the changes occurring in the labor market. The analysis has shown that increasing productivity and competitiveness cannot be viewed separately from the development of human resources. The long-term success of automation depends on the ability of enterprises, educational institutions, and society to develop competencies that meet the demands of the modern technological environment.

The paper is based on an analysis of relevant domestic and international literature, which enabled the identification of the most important trends and challenges related to the application of industrial robotics. However, a certain limitation is the fact that the research did not include empirical data collection in specific companies, but relied on secondary sources.

Future research would be useful to analyze in more detail the experiences of companies using industrial robots, as well as the attitudes of employees about the changes brought about by automation. Also, research focused on small and medium-sized enterprises, as well as assessing the readiness of education systems for the needs of the labor market in the conditions of digital transformation, could provide a significant contribution.

In conclusion, it can be concluded that industrial robotics represents an important part of the future development of industry and the economy. Its application brings numerous benefits in terms of productivity, quality and competitiveness, but at the same time requires continuous investment in human resource development and adaptation of the labor market to new technological requirements. Only the coordinated development of technology, education and professional competencies can enable the full exploitation of the potential that modern robotics offers to the economy and society [7], [4].

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The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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ECONOMIC BENEFITS AND ECOLOGICAL CHALLENGES OF SUSTAINABLE REAL ESTATE DEVELOPMENT

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ABSTRACT

The real estate sector represents one of the most significant economic industries, directly influencing economic growth, employment, infrastructure development, and the quality of life of the population. At the same time, the construction industry and real estate management are among the largest consumers of energy and natural resources, as well as among the major contributors to greenhouse gas emissions. Consequently, sustainable real estate development has gained increasing importance within contemporary economic and environmental policies. The application of sustainability principles involves the design, construction, operation, and management of buildings in a manner that ensures economic viability, environmental protection, and the improvement of social well-being. The subject of this paper is the analysis of the economic benefits and environmental challenges of sustainable real estate development. Particular attention is devoted to the impact of energy efficiency on reducing operating costs, increasing real estate market value, and the contribution of sustainable buildings to achieving environmental objectives within the construction sector. The research is based on an analysis of relevant domestic and international scientific literature, a comparative assessment of the economic and environmental characteristics of sustainable and conventional buildings, as well as a case study illustrating differences in construction costs, operating expenses, and long-term financial effects between the two types of buildings. The research results indicate that sustainable buildings require higher initial investments but generate significantly lower energy and maintenance costs throughout their life cycle, thereby ensuring higher investment profitability and enhancing market competitiveness. The

study concludes that sustainable real estate development represents one of the key instruments for achieving economic growth aligned with environmental protection objectives. The long-term benefits exceed the initial costs associated with the implementation of sustainable technologies; therefore, green building represents a strategic direction for the future development of the contemporary real estate market.

Keywords: sustainable development, real estate, energy efficiency, economic sustainability, ESG, investments.

INTRODUCTION

Over the past several decades, the real estate market has undergone intensive transformation driven by economic globalization, urbanization, technological development, and the growing need for the preservation of natural resources. The construction industry represents one of the most significant economic sectors in almost all national economies, considering that it generates a substantial share of gross domestic product (GDP), employs a large number of workers, and stimulates the development of numerous supporting industries, including construction materials manufacturing, transportation, energy, and financial services. However, precisely due to its scale and intensive resource consumption, the real estate sector simultaneously represents one of the largest contributors to environmental degradation [1].

In addition to high electricity consumption, the construction sector is characterized by intensive use of water, raw materials, and land resources, as well as by significant generation of construction waste. For this reason, international organizations, national governments, and financial institutions have increasingly focused their attention in recent years on the development of sustainable models for real estate design, construction, operation, and management.

The concept of sustainable development was first systematically defined in the 1987 Report of the Brundtland Commission, according to which sustainable development represents development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs [2], [3]. This approach implies achieving a balance between economic development, social responsibility, and environmental protection, which is referred to in contemporary literature as the three pillars of sustainability or the triple bottom line approach [4].

The application of this concept in the real estate sector has resulted in the development of so-called green buildings, i.e., buildings designed to achieve minimal negative environmental impacts throughout their entire life cycle while maximizing economic efficiency and ensuring a high-quality indoor environment for occupants [5]. Such buildings incorporate energy-efficient heating, cooling, and ventilation systems, renewable energy sources, advanced insulation materials, water conservation systems, and intelligent energy management technologies.

The development of sustainable real estate today represents much more than an environmental initiative. It has become an important factor influencing the competitiveness of investors, developers, and financial institutions. Banks and investment funds increasingly favor projects that comply with ESG criteria (Environmental, Social, and Governance), recognizing sustainability as an important determinant of investment quality and long-term value creation [6].

However, despite numerous advantages, the implementation of sustainable principles faces significant challenges. Investors frequently identify high initial construction costs, insufficiently developed markets for sustainable materials, a shortage of qualified professionals, and inconsistent regulatory frameworks as the main obstacles to the wider adoption of sustainable projects.

In addition to economic and technical aspects, sustainable real estate development also has an important social dimension. Indoor air quality, access to natural daylight, indoor environmental conditions, and acoustic performance directly influence the health, productivity, and satisfaction of building occupants [7].

Based on these considerations, the subject of this paper is the analysis of the economic benefits and environmental challenges of sustainable real estate development through an examination of the relationship between investment costs, long-term financial effects, and

environmental impacts. Particular attention is devoted to a comparative analysis of sustainable and conventional buildings from the perspective of investment costs, operating expenses, and long-term financial benefits. The results of the research are expected to contribute to a better understanding of the economic effects of sustainable investments and provide a basis for improving investment practices, regulatory policies, and future scientific research in the field of real estate development.

The primary objective of this paper is to analyze the economic benefits and environmental challenges of sustainable real estate development, with particular emphasis on the impact of sustainable investments on property market value, operating costs, investment attractiveness, and long-term profitability. Such an analysis provides a foundation for understanding the relationship between investors' economic interests and the requirements of sustainable development.

The methodological framework of the paper is based on a combination of qualitative and quantitative research methods, enabling a comprehensive analysis of the economic and environmental aspects of sustainable real estate development. The research is based on a systematic review of domestic and international literature in the fields of sustainable development, real estate economics, energy efficiency, investment management, and environmental protection.

The central research method is a comparative analysis of a sustainable ("green") building and a conventional building, including a comparison of investment costs, energy expenditures, maintenance costs, and total life-cycle costs during the operational period. This comparative approach enables an objective assessment of the differences between the two models of real estate development.

THEORETICAL FRAMEWORK OF SUSTAINABLE REAL ESTATE DEVELOPMENT

Contemporary literature conceptualizes sustainability through three interconnected pillars:

Economic sustainability – Economic sustainability refers to achieving long-term profitability through the rational utilization of available resources. In the context of sustainable real estate, this implies increased market value of properties, lower operating costs, higher occupancy rates, more stable rental income, and extended building lifespan.

Environmental sustainability – The environmental dimension refers to minimizing the negative impact of buildings on the natural environment. The most important elements include energy efficiency, the use of renewable energy sources, reduction of carbon dioxide emissions, rational management of water resources, recycling of construction waste, and the utilization of sustainable building materials.

Social sustainability – The third pillar relates to improving the quality of life of building occupants. It includes a healthier indoor environment, improved indoor air quality, access to natural daylight, acoustic comfort, building safety, accessibility for persons with disabilities, and increased employee productivity.

The contemporary concept of sustainability assumes that none of these three dimensions can achieve long-term success if developed independently from the others. Sustainable real estate development requires the integration of economic, environmental, and social principles throughout all phases of a building's life cycle – from planning and design, through construction, to operation, management, and final use [8].

The traditional model of economic development was primarily focused on profit maximization, whereas sustainable development emphasizes the rational use of natural resources while preserving the ability of future generations to meet their own needs. Furthermore, academic interest in green building has increased significantly in recent years, demonstrating the growing importance of sustainability in the fields of construction and real estate management [9].

Unlike the traditional approach, sustainable construction considers the entire life cycle of a building. Life-cycle analysis represents one of the fundamental differences between conventional and sustainable construction practices. Sustainable real estate development involves a transition from a traditional model based on minimizing initial investment costs toward a model focused on creating long-term value [5]. This approach is consistent with the concept of strategic corporate

real estate management, according to which real estate represents a strategic resource that contributes to achieving organizational objectives rather than merely an operational cost or physical asset [10].

Contemporary real estate economics increasingly applies the concept of Life Cycle Cost Analysis (LCCA). This approach implies that investment decisions should not be evaluated solely on the basis of initial construction costs, but rather according to the total costs incurred throughout the entire life cycle of a building. Numerous studies indicate that initial investment costs account for only 15–25% of total life-cycle costs, while the largest proportion is associated with operation and maintenance.

In recent years, the investment market has been characterized by the rapid development of ESG standards (Environmental, Social, and Governance). ESG criteria have become one of the most important indicators of investment project quality. In the context of real estate, they include:

Environmental – energy efficiency, renewable energy sources, reduction of CO_2 emissions, and efficient water management.

Social – occupant health, building safety, accessibility, and workplace quality.

Governance – transparent project management, responsible corporate governance, compliance with regulatory requirements, and ethical business practices.

An increasing number of international investment funds now make investment decisions based on ESG criteria, making sustainable real estate a significantly more attractive investment option. Sustainable buildings demonstrate advantages across all three ESG dimensions, including environmental, social, and governance aspects [11].

One of the most important instruments for assessing the quality and sustainability performance of buildings is represented by international certification systems. The most recognized among them include:

- LEED (Leadership in Energy and Environmental Design);
- BREEAM (Building Research Establishment Environmental Assessment Method);
- DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen);
- WELL Building Standard.

These systems evaluate energy efficiency, indoor environmental quality, water consumption, material selection, waste management, and the overall environmental impact of buildings.

Numerous international studies demonstrate that certified green buildings achieve higher market prices, higher rental rates, and higher occupancy rates compared with conventional buildings, further confirming the economic justification of sustainable real estate development [12], [11].

One of the most significant future directions in sustainable real estate development is the integration of digital technologies. Artificial intelligence, the Internet of Things (IoT), and digital twins enable a transition from passive building management toward active optimization of building performance [13]. Applications of artificial intelligence include:

- forecasting energy consumption;
- automatic optimization of heating and cooling systems;
- predictive maintenance of equipment;
- reduction of unnecessary resource consumption;
- analysis of building occupant behavior.

In the future, the value of sustainable buildings will increasingly depend on their ability to autonomously adapt resource consumption to actual operational needs. In this way, digitalization becomes a connecting element between economic efficiency and environmental protection.

ECONOMIC BENEFITS OF SUSTAINABLE REAL ESTATE DEVELOPMENT

From a macroeconomic perspective, the real estate sector represents one of the most important economic sectors in modern economies. Its significance is not limited solely to the

construction of residential, commercial, and industrial buildings, but also lies in the strong multiplier effect it generates across other sectors of the economy. The development of the real estate market stimulates the construction industry, building materials manufacturing, transportation, the financial sector, insurance, trade, architectural and engineering services, as well as information and communication technologies.

Sustainable Development as a Driver of Economic Growth

Over the past two decades, sustainable development has become one of the key drivers of transformation within the construction industry. Investments in energy-efficient buildings are no longer perceived solely as environmental initiatives, but rather as instruments for enhancing the competitiveness of national economies. Increasing investments in green infrastructure generate new employment opportunities, stimulate technological innovation, and contribute to higher economic productivity.

The particular importance of sustainable investments lies in the fact that their economic effects do not end upon the completion of a building project. On the contrary, the majority of benefits are realized throughout the operational phase of a building through reduced energy consumption, lower maintenance costs, and increased real estate market value.

Therefore, contemporary economic literature increasingly emphasizes the transition from the "lowest initial cost" approach toward the "lowest total life-cycle cost" approach. This perspective enables more rational investment decisions and significantly improves the economic sustainability of construction projects.

The Impact of Sustainable Features on Real Estate Market Value

One of the most significant economic benefits of sustainable construction is the increase in the market value of real estate assets. Traditionally, property valuation has been primarily based on location, size, construction quality, and building age. However, in recent years, energy efficiency has emerged as one of the key factors influencing market prices. Today, buyers and tenants increasingly consider a building's energy performance rating, expected monthly energy costs, insulation quality, ventilation systems, the use of renewable energy sources, indoor environmental quality, and other sustainability-related characteristics.

As a result of these market changes, a **market premium for sustainable real estate** has emerged. In practice, this means that energy-efficient buildings achieve higher selling prices and higher rental rates compared with conventional buildings with similar characteristics. One of the most frequently confirmed findings in the literature is the existence of the so-called **"green premium"**, referring to the increased market value of properties that incorporate sustainability features [12].

The increase in market value results from several interconnected factors. First, buyers recognize the long-term financial savings generated by reduced energy consumption. Second, investors assess that sustainable buildings are likely to experience slower depreciation and retain their market value more effectively over time. Third, banks increasingly provide more favorable financing conditions for energy-efficient properties. Fourth, multinational companies seeking office space often prioritize buildings that possess internationally recognized green certifications.

In this way, sustainable features have become an integral component of real estate market value.

Economic Analysis of Sustainable Investments Using Contemporary Financial Indicators

Contemporary investment analysis in the real estate sector increasingly goes beyond the traditional approach based solely on initial construction costs. Today, investors, financial institutions, and the public sector evaluate projects based on their total economic effects throughout the entire life cycle of a building. This approach enables a more objective assessment of the financial feasibility of sustainable investments, given that the majority of their benefits are realized during the operational phase of a building.

In this context, contemporary financial indicators such as **Return on Investment (ROI), Net Present Value (NPV), Internal Rate of Return (IRR), and Life Cycle Cost Analysis (LCCA)** are applied. The combined application of these indicators enables an assessment not only of the economic viability of a project but also of its resilience to changes in market conditions, energy price fluctuations, and regulatory requirements.

Return on Investment (ROI)

ROI represents one of the most frequently used indicators for evaluating the performance of investment projects. Its primary purpose is to measure the relationship between the benefits generated and the capital invested. The mathematical expression is:

ROI=(Total Net Benefit/Total Investment)×100

In sustainable real estate projects, the generated benefits do not include only direct financial savings but also a range of indirect economic effects, including reduced energy costs, lower maintenance expenses, increased market value of the property, higher rental income, improved occupancy rates, lower financing costs, and reduced regulatory risks.

For this reason, the ROI of sustainable buildings tends to increase over time, whereas conventional buildings often experience a gradual decline in investment performance due to rising operating costs.

It is important to emphasize that ROI in construction investments should not be evaluated from a short-term perspective. The lifespan of commercial and residential buildings typically ranges between 40 and 70 years; therefore, an analysis based on a period of only ten or twenty years may provide an incomplete assessment of their actual profitability.

Net Present Value (NPV)

One of the most important indicators in contemporary investment analysis is **Net Present Value (NPV)**, which incorporates the time value of money and represents one of the fundamental criteria for evaluating investment projects [14] (Brealey et al., 2020). Unlike ROI, NPV takes into account the time value of money, i.e., the principle that one dollar today is worth more than one dollar received in the future. The basic formula is:

$$NPV = \Sigma [CF_t / (1+r)^t] - I_0$$

where:

CFt – cash flow in year *t*;

r – discount rate;

I_0 – initial investment.

For sustainable buildings, positive cash flows arise from energy savings, lower maintenance costs, increased market value, higher rental income, and residual value at the end of the building's life cycle. Therefore, discounted cash flow analysis represents a standard approach for assessing their economic feasibility [15].

For the purposes of this research, a discount rate of **5%** has been adopted. This rate represents a moderate assumption frequently applied in analyses of long-term investment projects and building life-cycle assessments. Its purpose in this study is to ensure consistent discounting of future cash flows and comparability of results, rather than to represent a universally applicable market discount rate [14], [15].

The application of the NPV method is particularly important because it enables investors to compare alternative projects of different sizes and different time horizons.

Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) represents the discount rate at which the net present value of a project becomes equal to zero. In other words, IRR indicates the maximum cost of capital that a project can sustain while remaining economically viable.

In sustainable construction projects, IRR is particularly significant due to their long-term nature. Unlike traditional construction investments, where the majority of returns are generated through the sale of the completed property, sustainable real estate assets generate continuous financial benefits throughout their operational life. Therefore, IRR analysis enables a more accurate assessment of overall investment attractiveness.

However, it should be emphasized that IRR should not be considered in isolation. Its interpretation must be combined with NPV analysis, as different projects may have similar internal rates of return but significantly different absolute economic values.

Life Cycle Cost Analysis (LCCA)

Traditional investment analysis is primarily based on comparing initial construction costs. Such an approach may lead to incorrect investment decisions because it ignores the fact that a significant share of total costs occurs after construction has been completed. For this reason, contemporary real estate economics increasingly applies **Life Cycle Cost Analysis (LCCA)**.

This methodology includes all costs incurred throughout the operational life of a building, including:

- design;
- construction;
- financing;
- energy consumption;
- maintenance;
- replacement of technical systems;
- renovation;
- waste management;
- building demolition;
- recycling of construction materials.

Numerous life-cycle studies demonstrate that initial construction costs represent a significantly smaller share of total building costs over its lifespan, while the largest proportion is associated with operation, maintenance, renovation, and replacement of building components. In many analyses, initial investment accounts for approximately 20–30% of total life-cycle costs, whereas the remaining 70–80% consists of operational and maintenance costs. However, this distribution depends on the type of building, the analysis period, and the assumptions applied within the model [16], [15].

Therefore, despite requiring higher initial investments, sustainable buildings frequently achieve lower total costs throughout their life cycle.

Integrated Model for the Economic and Environmental Evaluation of Sustainable Real Estate

One of the limitations of most previous studies is the fact that sustainable investments are evaluated primarily through the relationship between initial costs and energy savings. Such an approach overlooks numerous market and social benefits that significantly influence the overall economic value of a project.

Therefore, it is reasonable to propose an Integrated Model for the Economic and Environmental Evaluation of Sustainable Real Estate, based on five interconnected dimensions of real estate sustainability:

1. Investment sustainability – initial investment costs, availability of financing, and cost of capital.
2. Operational sustainability – energy costs, maintenance expenses, water consumption, and equipment lifespan.
3. Market sustainability – property market value, rental income, occupancy rate, and real estate liquidity.

4. Environmental sustainability – CO_2 emissions, energy efficiency, use of renewable energy sources, and construction waste recycling.
5. Social sustainability – indoor environmental quality, occupant health, employee productivity (in commercial buildings), and resident satisfaction (in residential buildings).

The main advantage of this model lies in its ability to support investment decision-making based on the overall value of a project, rather than solely on initial construction costs. In this way, the limitations of traditional evaluation methods are overcome, and an integrated approach is introduced that connects the financial, market, environmental, and social effects of sustainable investments.

Such a model may also serve as a foundation for the development of a quantitative assessment framework for sustainable real estate in future research.

ENVIRONMENTAL CHALLENGES OF SUSTAINABLE REAL ESTATE DEVELOPMENT

Although sustainable real estate development represents one of the most significant directions in the transformation of the contemporary construction industry, its implementation faces numerous environmental, technological, economic, and organizational challenges [17].

The real estate sector plays a dual role in the process of sustainable development. On the one hand, buildings represent one of the largest sources of energy consumption and greenhouse gas emissions. On the other hand, this sector also offers significant potential for reducing negative environmental impacts through the implementation of energy efficiency measures, renewable energy sources, sustainable building materials, and digital technologies.

Sustainable development requires the rational use of natural resources and the reduction of the construction sector's negative environmental impact [18].

High Initial Costs of Implementing Green Technologies

One of the most frequently cited challenges of sustainable real estate development is the increase in initial investment costs.

The implementation of sustainable technologies requires additional investments in:

- energy-efficient heating, ventilation, and air-conditioning (HVAC) systems;
- higher-quality thermal insulation materials;
- energy management systems;
- solar panels;
- green roofs;
- water efficiency systems;
- sustainability certification;
- advanced design and engineering solutions.

Compared with traditional construction practices, sustainable buildings often require higher upfront investments. According to various studies, the additional costs associated with green construction may range from several percent to several dozen percent of the total investment value, depending on the level of sustainability targeted.

This challenge is particularly pronounced in markets where investors make decisions primarily based on short-term financial indicators. If the evaluation is based solely on initial construction costs, sustainable projects may appear less attractive compared with conventional alternatives.

However, such an approach ignores the fact that the majority of building-related costs occur during the operational phase. Energy savings, reduced maintenance expenses, and increased market value represent benefits that are realized over an extended period.

Therefore, one of the fundamental challenges is not only reducing the cost of sustainable technologies but also changing the investment mindset from a short-term perspective toward an approach based on whole life-cycle cost analysis of buildings.

Regulatory and Legislative Challenges

The development of sustainable real estate largely depends on the quality of the regulatory framework. However, many countries still face significant differences in legislation, standards, and procedures governing the field of green construction. Regulatory challenges include complex permitting procedures, varying energy efficiency standards, insufficient harmonization of regulations, inconsistencies between local and international standards, and, in many cases, the lack of clearly defined criteria for assessing sustainability.

Investors are often required to align their projects with a wide range of different requirements, which increases administrative costs and extends project implementation periods. A particular challenge is the certification of sustainable buildings. International systems such as LEED, BREEAM, and DGNB represent important instruments for assessing sustainability performance; however, their implementation requires additional documentation, professional expertise, and financial resources. Green certifications improve project transparency, enhance investor confidence, increase market competitiveness, and facilitate access to green financing [19].

On the other hand, standardized certification systems play an important role because they enable transparent comparison of different buildings and increase the confidence of investors and users. In the future, harmonization of the regulatory framework will represent one of the key prerequisites for accelerating the development of sustainable real estate.

Technological Limitations and Availability of Sustainable Solutions

Although technological development enables significant progress in the field of green construction, the availability of advanced solutions remains a challenge. For example, the installation of smart building management systems requires the integration of numerous components, including sensors, information systems, energy-related devices, and software platforms. Without adequate technical expertise, there is a risk that these technologies will not achieve their expected performance outcomes.

A particular challenge concerns the adaptation of existing buildings. While sustainable principles can be incorporated into new buildings from the early design stage, the renovation of older buildings often requires complex technical solutions. The energy renovation of the existing building stock represents one of the greatest challenges, as a large number of buildings were not designed according to modern energy efficiency standards.

Challenges of Sustainable Building Materials

One of the key elements of sustainable construction is the selection of materials with lower negative environmental impacts. Traditional production of construction materials, particularly cement and steel, represents a significant source of carbon dioxide emissions. Therefore, sustainable construction increasingly promotes the use of recycled materials, locally available materials, materials with lower embodied carbon, and natural materials.

However, the use of sustainable materials faces several limitations, including higher costs, limited availability, underdeveloped supply chains, and insufficient standardization.

An additional challenge arises from the fact that the environmental performance of materials must be assessed throughout their entire life cycle. A material that has a low environmental impact during production may have unfavorable characteristics during transportation, maintenance, or disposal. Therefore, contemporary approaches require the application of **Life Cycle Assessment (LCA)** rather than the evaluation of individual product characteristics alone.

Shortage of Skilled Professionals and Knowledge

One of the frequently overlooked challenges of sustainable development is the shortage of professionals with multidisciplinary knowledge in the fields of architecture, civil engineering, energy, economics, information technologies, and environmental protection.

Sustainable buildings require a different approach to design and management compared with traditional buildings. Architects must understand the energy performance principles of buildings,

civil engineers must be familiar with advanced construction materials, while facility managers must be capable of using digital systems to optimize resource consumption. Without adequately trained professionals, there is a risk that sustainable technologies may be improperly designed, implemented, or operated, thereby reducing the expected environmental and economic benefits.

Therefore, education and continuous professional development represent one of the key prerequisites for a successful transition toward sustainable real estate development.

COMPARISON OF A GREEN BUILDING AND A CONVENTIONAL BUILDING

In order to provide practical verification of the theoretical assumptions regarding the economic and environmental effects of sustainable real estate development, this study includes a comparative analysis of two hypothetical investment alternatives: a green building and a conventional building. This approach enables a more detailed assessment of the relationship between initial investment costs, operational expenses, and the long-term effects of sustainable construction.

Unlike the traditional approach, in which investments are evaluated primarily based on construction costs, this analysis applies a **life-cycle approach**, assessing the total economic and environmental value of a building throughout its operational period.

The two alternative construction scenarios considered are:

A – Green building, designed according to sustainable development principles, incorporating energy-efficient systems, renewable energy sources, water-efficiency systems, and elements of green architecture;

B – Conventional building, constructed according to standard building practices, without additional sustainable technologies.

For the purposes of this case study, a Life Cycle Cost Analysis (LCCA) approach was applied, based on the methodology recommended by Kneifel and Webb (2020) [15]. The values used in the comparative analysis represent simulation parameters based on realistic assumptions regarding the investment and operational costs of a sustainable and a conventional building, rather than data obtained through direct monitoring of an actual building..

Initial (Investment) Costs

The first stage of the analysis refers to the comparison of initial construction costs. The following table presents the structure of investment costs.

Table 1. Structure of Investment Costs

No.	Cost Category	Green Building (USD)	Conventional Building (USD)
1	Land Acquisition and Legal Costs	100.000	100.000
2	Construction Costs and Sustainable Materials	1.000.000	800.000
3	Energy-Efficient HVAC System	150.000	-
4	Solar Panels and Renewable Energy Sources	120.000	-
5	Water-Efficient System	50.000	40.000
6	Green Roof	70.000	-
7	Labor Costs	600.000	400.000
8	Certification Costs	40.000	-
9	Standard HVAC System	-	80.000
10	Electrical System	-	50.000
Total:		**2.130.000**	**1.470.000**

The results show that the investment in the green building is:

$$2{,}130{,}000 - 1{,}470{,}000 = 660{,}000 \text{ USD}$$

higher compared with the conventional alternative.

The relative increase in the initial investment amounts to approximately:

$$660{,}000 / 1{,}470{,}000 \times 100 = 44.9\%$$

This finding confirms the main conclusion of the previous analysis: sustainable construction requires significantly higher initial investments.

However, the difference in initial costs alone does not represent a sufficient criterion for making an investment decision. Real estate represents a long-term capital investment in which the majority of value is generated throughout the operational period. Therefore, it is necessary to analyze operating costs and environmental effects.

Energy Efficiency of Buildings

Energy efficiency represents one of the key differences between the two analyzed alternatives. The case study data provide the following values:

Table 2. Electricity Consumption

Indicator	Green Building	Conventional Building
Annual energy consumption	120.000 kWh	220.000 kWh
Annual energy cost	7.200 USD	13.200 USD

The green building achieves:

$$220{,}000 - 120{,}000 = 100{,}000 \text{ kWh}$$

lower annual energy consumption.

The percentage reduction amounts to:

$$100{,}000 / 220{,}000 \times 100 = 45.5\%$$

This result confirms the importance of implementing energy-efficient systems. Reducing energy consumption generates multiple benefits:

- directly reduces building operating costs;
- decreases dependence on fluctuations in energy prices;
- contributes to the reduction of CO_2 emissions;
- increases the building's resilience to energy crises.

Under contemporary conditions of energy market instability, energy efficiency is becoming one of the most important factors contributing to investment security.

Maintenance Costs

In addition to energy consumption, a significant share of costs throughout a building's life cycle is related to maintenance. According to the case study data, the following table presents maintenance costs:

Table 3. Maintenance Costs

Indicator	Green Building	Conventional Building
Annual maintenance cost	12.800 USD	24.900 USD

Difference:

$$24{,}900 - 12{,}800 = 12{,}100 \text{ USD per year}$$

The sustainable building achieves approximately:

$$12{,}100 / 24{,}900 \times 100 = 48.6\% \text{ lower maintenance costs}$$

This result is attributable to the application of higher-quality materials, automated management systems, and more advanced technical infrastructure.

Although sustainable systems are more complex during the design and construction phases, their proper management during the operational phase can significantly reduce the need for maintenance interventions and equipment replacement.

Total Initial and Operational Energy and Maintenance Costs

All previously presented data are summarized in the following table:

Table 4. Investment Value and Annual Operational Energy and Maintenance Costs

Element	Green Building	Conventional Building
Total initial investment	2,130,000 USD	1,470,000 USD
Difference in initial investment	+660,000 USD	–
Annual energy cost	7,200 USD	13,200 USD
Annual maintenance cost	12,800 USD	24,900 USD
Total annual operating costs	20,000 USD	38,100 USD

Based on the presented data, it can be concluded that the green building requires approximately 45% higher initial investment, but achieves significantly lower annual operating costs.

The annual difference in operating costs amounts to:

38,100 USD – 20,000 USD = 18,100 USD per year

This difference represents the primary direct financial benefit of sustainable investment.

Investment Payback Period Analysis

One of the most commonly used indicators of investment feasibility is the payback period of additional investment.

Payback Period = Additional Investment / Annual Financial Benefit

In the analyzed case, the following values apply:

Additional investment: 660,000 USD

Annual savings: 18,100 USD

The payback period is: 660,000 / 18,100 = 36.5 years

The result shows that the additional investment in the green building, when evaluated solely through direct energy and maintenance savings, is recovered over a period of approximately 36.5 years.

This result is highly significant because it demonstrates the limitation of a simplified approach to evaluating sustainable investments. If the analysis is based exclusively on operational savings, the payback period may appear relatively long.

However, real estate represents a long-term investment asset whose useful life often exceeds 50 years. Therefore, it is necessary to incorporate other sources of economic value, including increased market value of the property, higher rental income, reduced risk of technological and regulatory obsolescence, compliance with future regulations, and improved access to financing.

For this reason, sustainable investments cannot be evaluated solely through a short-term payback period approach.

Analysis of Total Costs Over a 20-Year Period

According to the case study data, the total energy and maintenance costs over a 20-year period amount to:

Green Building:

Energy costs: 7,200 USD per year × 20 years = 144,000 USD
Maintenance costs: 12,800 USD per year × 20 years = 256,000 USD
Total operating costs: 400,000 USD

Conventional Building:

Energy costs: 13,200 USD per year × 20 years = 264,000 USD
Maintenance costs: 24,900 USD per year × 20 years = 498,000 USD
Total operating costs: 762,000 USD

Difference:762,000 – 400,000 = 362,000 USD

During the first twenty years, the green building generates 362,000 USD in direct savings.

However, when the initial investment difference of 660,000 USD is taken into account, it can be concluded that direct operational savings alone are not sufficient to fully justify the additional investment within a 20-year period.

Tthis outcome should not be interpreted as a negative indicator of sustainable development, but rather as confirmation of the need to apply a comprehensive evaluation methodology.

Expanded Perspective of Economic Benefits

One of the most significant economic effects of sustainable construction is the increase in the market value of the building. In practice, green buildings often achieve a market premium due to lower operating costs, improved space quality, a positive environmental image, and compliance with ESG criteria.

Incorporating the Market Premium of Sustainable Real Estate

Empirical studies show that certified green buildings achieve a market premium compared with conventional buildings. The estimated range of increases in market value varies depending on the market, location, and level of certification. For the purposes of this research, a conservative assumption of a 10% increase in market value has been adopted, which falls within the range of values reported in relevant literature [12], [21](Eichholtz et al., 2010; Fuerst & McAllister, 2011b).

If the initial value of the building amounts to USD 2,130,000:
2,130,000 × 10% = USD 213,000 additional market value

This amount represents an additional economic benefit that is not reflected in a conventional analysis of energy costs but directly affects the investment attractiveness of the building.

Incorporating Rental Income Effects

In the case of commercial real estate, sustainable buildings often achieve higher tenant demand, particularly from international companies that have their own ESG policies. In this simplified analysis, the effects of increased market value and additional rental income are considered separately in order to illustrate different sources of economic benefits, although in real-world assessments certain overlaps may exist. A conservative market premium of 5% on rental income is assumed.

If the building generates annual rental income of USD 150,000:
150,000 × 5% = USD 7,500 additional annual income
For a period of 20 years:
7,500 × 20 = USD 150,000

In this way, a sustainable building generates additional economic benefits that significantly change the overall investment perspective.

Total Economic Effect

When the following benefits are included:

- operational savings: USD 362,000
- increase in market value: USD 213,000
- additional rental income: USD 150,000

an indicative nominal estimate of total economic effects is obtained:

362,000 + 213,000 + 150,000 = USD 725,000

This amount exceeds the additional investment:

725,000 – 660,000 = USD 65,000 positive economic effect

This represents a simplified nominal analysis, while a more precise assessment would require an NPV (Net Present Value) analysis. Nevertheless, based on this expanded assessment, it can be concluded that a sustainable building becomes economically justified when, in addition to direct operational savings, the market effects of sustainability are also taken into account.

DISCUSSION OF RESULTS

The results of the case study confirm that sustainable real estate development represents a complex investment concept that requires a different evaluation approach compared with traditional construction projects. Conventional valuation models often favour buildings with lower initial costs while neglecting long-term effects generated during the operational period.

Contemporary research in the field of real estate economics indicates that the assessment of sustainable buildings must incorporate the entire life cycle of the building. Initial costs represent only one segment of total economic value, while energy costs, maintenance, renovation, and management expenses incurred over decades of use have a decisive impact on overall profitability.

The obtained results confirm this approach. Although the analysed green building demonstrated a 44.9% increase in initial investment costs, it achieved significant operational benefits through:

- a 45.5% reduction in energy consumption;
- a 48.6% reduction in maintenance costs;
- total operational cost savings of USD 362,000 over a 20-year period;
- a significant reduction in CO_2 emissions.

These results confirm the conclusions of numerous international studies indicating that sustainability cannot be evaluated solely through initial costs, but rather through the total value generated by a building throughout its life cycle. Although direct energy and operational savings alone do not fully offset the additional initial investment within a 20-year period, incorporating the market value of the building and additional rental income changes the overall economic assessment.

Numerous studies conducted over the last decade indicate that sustainable buildings achieve measurable economic advantages compared with conventional buildings. One of the most frequently confirmed findings is the existence of the so-called “green premium”, referring to the increased market value of buildings possessing sustainability characteristics.

This finding is particularly important because it demonstrates that sustainable investments create value through multiple channels, rather than solely through cost reduction.

In the real estate sector, ESG criteria are becoming increasingly important because buildings represent long-term capital assets with a direct impact on energy consumption, emissions, and the

quality of life of users. The results of this research indicate that sustainable buildings provide advantages across all three ESG dimensions.

In summary, the analysis identifies three key findings:

First, a green building requires higher initial investment, which represents the primary obstacle to the wider adoption of sustainable technologies.

Second, during the operational phase, a sustainable building achieves significantly lower energy and maintenance costs, thereby improving long-term financial efficiency.

Third, environmental benefits, such as reduced CO_2 emissions and more efficient resource utilisation, represent additional value that cannot be fully captured through conventional financial indicators.

The case study confirms that sustainable real estate development should be viewed as a strategic investment rather than an additional cost. In the future, the combination of economic indicators, ESG criteria, and digital technologies will enable more accurate evaluation of sustainable projects and support higher-quality investment decision-making.

Research Limitations

Although the results confirm the economic and environmental benefits of sustainable real estate development, certain limitations of the research should be acknowledged.

First, the case study is based on a hypothetical building and average cost values, meaning that the results may vary depending on location, climatic conditions, energy prices, technology availability, local regulatory frameworks, and other relevant factors.

Second, the market premium of sustainable buildings is not identical across all markets. In developed economies, it is more pronounced due to higher environmental awareness among buyers and a more developed financial system.

Third, future research should incorporate real-world data from a larger number of buildings and apply advanced statistical models.

Despite these limitations, the results can provide a significant contribution to understanding the relationship between sustainability, real estate economics, and long-term investment decision-making.

CONCLUSION

Sustainable real estate development is no longer a trend but a necessity for the future. The implementation of sustainable principles represents an important step towards achieving economic growth while protecting the environment. Consumer preferences are increasingly shifting towards energy-efficient and environmentally responsible properties. Real estate developers who invest in sustainability will ensure long-term profitability and enhance their brand reputation.

The analysis of the obtained results shows that sustainable real estate development represents a transition from the traditional model based on minimising initial costs towards a model based on the total value generated by the building throughout its life cycle.

The most important conclusions derived from the discussion can be summarised as follows:

- Sustainable buildings require higher initial investments but generate significant long-term benefits.
- Energy efficiency represents one of the most important sources of financial savings.
- The market value of sustainable buildings is increasing due to changing preferences of users and investors.
- ESG criteria are becoming a key factor in the future development of the real estate market.
- Digital technologies and artificial intelligence will represent important instruments for further improving sustainability.

Although sustainable real estate development involves certain financial and technical challenges, long-term benefits justify the initial costs. Real estate developers who integrate

sustainable practices gain a competitive advantage, reduce long-term costs for their customers, and align their projects with future environmental regulations.

Government regulators and policymakers should systematically provide financial incentives, tax benefits, and favourable financing mechanisms for the construction and purchase of environmentally sustainable properties. Standardised sustainability regulations should be implemented in order to create a consistent and transparent market framework. Particular importance should be given to the development of national strategies for energy efficiency and climate neutrality, as they create a more stable framework for long-term investment decision-making.

Based on the above, it can be concluded that sustainable real estate is not merely a response to environmental challenges but represents a strategic direction for the development of the construction sector and capital markets. Furthermore, the role of artificial intelligence in the management of green buildings represents an important challenge and opportunity for future research.

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DECLARATION OF INTEREST STATEMENT

The authors confirm that there are no conflicts of interest related to the research presented in this paper.

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STRATEGIC MANAGEMENT FOR THE LONG-TERM SUSTAINABILITY OF SMALL AND MEDIUM-SIZED ENTERPRISES- CHALLENGES AND OPPORTUNITIES

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ABSTRACT

The SME sector plays an important role in the economy as it contributes to employment, the development of local markets and overall economic growth. However, these enterprises often face limited resources, lack of capital and weaker application of modern management approaches. The paper discusses how strategic management can contribute to better adaptability of SMEs to market changes, strengthening competitiveness and long-term business stability. Special emphasis was placed on factors from the external environment, such as economic changes, digitization and access to financial sources, but also on internal weaknesses such as insufficiently developed strategies and lack of professional staff. The empirical part of the work is based on a SWOT analysis of the SME sector in Serbia, which identified key strengths, weaknesses, opportunities and threats. Based on the analysis, it can be concluded that SMEs have a significant potential for development, but that for its realization it is necessary to improve the strategic approach to management.

Keywords: *S*ME sector, strategic management, sustainability, SWOT analysis, competitiveness, digitalization, innovation.

INTRODUCTION

In modern business conditions, small and medium-sized enterprises are increasingly gaining importance, both in developed countries and in developing economies. Their role is important not only from an economic perspective, but also from the point of view of social development, employment and encouraging entrepreneurial initiatives. The development of this sector greatly

affects the overall economic activity of a country, which is why the issue of their stability and survival is increasingly seen as an important issue of long-term economic development.

In recent years, the business environment has become significantly more complex due to rapid technological changes, market globalization and increasing consumer demands. Companies are forced to continuously improve their operations, adapt the organization of work and find new ways to maintain competitiveness. In such conditions, the existence of clearly defined business goals and methods of achieving them is particularly important.

Small and medium-sized enterprises often have certain advantages over large business systems, primarily in terms of flexibility and faster decision-making. On the other hand, these enterprises are exposed to numerous limitations related to financial resources, human resources and the ability to monitor modern market trends. This is precisely why the issue of strategic management becomes important for their further development and sustainability.

The subject of this paper is to examine the role of strategic management in the function of long-term sustainability of small and medium-sized enterprises, with special reference to the challenges and opportunities for their development in the Republic of Serbia. The aim of the paper is to analyze the factors that influence SME operations and point out the importance of adapting to modern business conditions. The paper uses an analysis of relevant literature, time series analysis and SWOT analysis, in order to better understand the state and position of small and medium-sized enterprises in Serbia.

STRATEGIC MANAGEMENT IN SMALL AND MEDIUM-SIZED ENTERPRISES – CONCEPT AND SIGNIFICANCE

Strategic management represents one of the most important elements of modern business, as it enables companies to plan their goals, adapt to changes in the market and ensure long-term business sustainability. Strategic management involves making decisions and defining the company's development directions in accordance with environmental conditions and available resources [1].

Unlike large companies, small and medium-sized enterprises (SMEs) operate with limited financial, personnel and organizational resources, which is why the importance of strategic management is even more pronounced. SMEs often do not have the ability to easily overcome business mistakes, so proper planning and management is of great importance for their survival and development. Due to all the mentioned limitations, strategic management enables smaller companies to more easily recognize market opportunities, reduce business risks and increase competitiveness. Also, the SME sector is today the backbone of the economy of both the European Union and Serbia.

Strategic management is not only about making long-term plans, but also about the company's ability to adapt to changes in the business environment. The SME sector is the bearer of new business ideas and ventures, vision and perseverance. The changes taking place in many areas are crucial when it comes to the company's positioning and success in the market [2].

The modern market is characterized by frequent changes, technology development, digitization, competition growth and changing consumer needs. Businesses that are market oriented have a greater competitive advantage that comes from creating value for consumers based on their clearly defined needs. Strategic flexibilities and proactive management influence the efficiency and effective achievement of the company's goals. In such conditions, SMEs must react quickly and make decisions that will enable stable business and long-term development.

The process of strategic management usually consists of several basic phases. The first phase refers to the analysis of the company's internal and external environment. In this phase, the company looks at its strengths and weaknesses, as well as the opportunities and threats that come from the environment [3]. This is followed by the definition of goals and the formulation of the strategy, that is, the determination of the way in which the goals will be achieved. The third phase refers to the implementation of the strategy, that is, its implementation through specific activities

and business decisions. The last stage involves controlling and monitoring the results to determine if the strategy is delivering the expected results.

In the case of small and medium-sized enterprises, strategic management has certain specificities. In a large number of cases, the owner of the company performs managerial functions at the same time, so business decisions are often made centrally. Also, SMEs have a simpler organizational structure and greater flexibility compared to large companies, which enables them to adapt more quickly to market changes. On the other hand, limited resources and lack of professional staff can represent a significant problem in the process of planning and implementing the strategy.

The importance of strategic management in SMEs is particularly evident in conditions of economic instability and increased competition. Companies that have clearly defined goals and strategy make business decisions more easily and adapt more successfully to changes in the market. Strategic management enables better business organization, more efficient use of resources and longer-term development planning.

PREVIOUS RESEARCH

The issue of strategic management and long-term sustainability of small and medium-sized enterprises is a significant topic in domestic and foreign literature. The reason for this is the fact that SMEs play an important role in economic development, employment and creating competitiveness, but at the same time they are very sensitive to changes in the market, economic crises and lack of resources. In domestic literature, research related to sustainable business and adaptation of SMEs to modern market conditions is of particular importance. Pavlović and Denčić Mihajlov (2020) analyze the challenges faced by SMEs in the field of sustainable development and sustainable financing [4]. The paper points out that small and medium-sized enterprises often do not have enough financial and organizational capacity to implement modern sustainability standards, but that precisely strategic management can contribute to their easier adaptation to market requirements.

The issue of financing and managing financial risks in SMEs is one of the most important, taking into account the wide variety of forms and sources of financing, methods of use, advantages and disadvantages. Stajić (2015) emphasizes the importance of a strategic approach to this issue in conditions of market instability [5]. The paper indicates that the proper management of finances and working capital is one of the key factors for the survival and long-term development of small and medium-sized enterprises. The author especially points out that SMEs, due to limited resources, must carefully plan business activities and make decisions that will reduce exposure to risks.

In addition to financial aspects, some research is also focused on the competitive strategies of SMEs. Pavlović and Čelić (2020) indicate the importance of market positioning and adaptation to competition through the application of appropriate development strategies [6]. Their research shows that small and medium-sized enterprises can achieve a competitive advantage if they correctly identify market needs and adapt their operations to changes in the environment.

In the European literature, significant attention is drawn to research that connects strategic management with human resources and innovation. Vrchota and Řehoř (2019) point out that quality human resource management plays an important role in the long-term sustainability of SMEs, especially in the conditions of modern market changes and digitalization of business [7]. According to their results, companies that invest in employees and organizational development more easily achieve stability and competitiveness.

Newer research increasingly links the sustainability of SMEs with the concept of circular economy. Latif et al. (2025) analyzed SMEs in Southeast European countries and concluded that the application of circular economy principles can positively affect the financial performance and competitiveness of companies [8]. The authors state that sustainable business models become an important factor in long-term development and adaptation to modern market conditions.

The contribution of this paper is reflected in the integrated analysis of the development and sustainability of the SME sector in the Republic of Serbia. Unlike studies that primarily focus on individual aspects of SME development, this research combines an analysis of the number and regional distribution of SMEs, the average annual growth rate and a SWOT analysis. In this way, the paper provides a broader overview of the current position of SMEs and identifies internal and external factors that may influence their long-term sustainability. Particular attention is given to the period from 2021 to 2023, which enables the identification of recent trends in the development of the SME sector in Serbia.

CHALLENGES AND OPPORTUNITIES OF SUSTAINABLE DEVELOPMENT OF THE SME SECTOR

Sustainable development of the SME sector implies the harmonization of economic growth with social responsibility and environmental protection. Although SMEs are flexible and innovative, they face specific obstacles in implementing sustainable practices. The business of the SME sector is often accompanied by numerous challenges that can affect long-term sustainability and development. Therefore, strategic management becomes one of the key factors of survival and successful adaptation to market changes.

One of the main problems faced by SMEs is limited access to financial resources. Lack of capital and difficult financing represent a significant limitation for business development, investment in new technologies and increasing competitiveness. Ravić and Obradović point out that high interest rates, difficult access to loans and insufficient institutional support are among the most important problems of SME development in Serbia [9]. The authors emphasize that financial support plays a key role in strengthening the stability and development of small and medium-sized enterprises.

In addition to financial challenges, SMEs also face problems of adapting to modern market conditions. The globalization of the market, the development of information technologies and increasingly pronounced competition require companies to continuously improve their operations and implement innovations. Namely, innovation and strategic planning are important factors in the development of SMEs in Serbia, especially in conditions of increased market competition and rapid changes in the business environment [10]. What has been noted above is that small and medium-sized enterprises have a harder time overcoming mistakes in business due to smaller resources and personnel, but they have a significant advantage in flexibility and the possibility of faster adaptation to the market compared to large business systems, especially when major changes occur that significantly change the functioning of the market and activities on it.

A significant challenge for SMEs is also the process of digitization of business. The modern market increasingly requires the application of digital technologies, electronic business and modern information systems. Companies that fail to keep up with technological changes may lose their competitive position and the possibility of further development. This is precisely why strategic management and development planning become very important for the long-term sustainability of SMEs. Valjevac, Sorak and Sorak (2018) emphasize that a clearly defined development strategy, business goals and the planning process represent the basis for improving the business performance of small and medium-sized enterprises [11].

Small and medium-sized companies also have numerous opportunities for business development and improvement. One of the most important opportunities relates to the application of innovations and new business models. Modern business conditions allow SMEs easier access to the market through digital platforms and electronic commerce, which can contribute to increased competitiveness and business expansion.

Nosratabadi et al. (2019) state that sustainable business models are increasingly becoming an important part of strategic management, because they enable the simultaneous realization of economic, social and environmental goals of the company [12]. The long-term sustainability of these companies largely depends on their ability to recognize changes in the environment and adapt their operations to modern market requirements.

METHODOLOGY

The research is based on the analysis of relevant scientific and professional literature, secondary statistical data and SWOT analysis. The empirical part of the research uses data from the Statistical Office of the Republic of Serbia on the number of small and medium-sized enterprises in Serbia for the period from 2021 to 2023.

The data were analyzed using time series analysis, absolute changes, growth rates, base indices and the average annual growth rate. The regional distribution of small and medium-sized enterprises was also analyzed in order to identify differences in the development of this sector between the regions of the Republic of Serbia. The average annual growth rate was calculated using the compound annual growth rate (CAGR) formula.

In addition to the quantitative analysis, a SWOT analysis was conducted to identify the main strengths, weaknesses, opportunities and threats affecting the long-term sustainability of the SME sector in Serbia. The SWOT elements were determined by synthesizing the findings from the analyzed statistical data and relevant scientific and professional literature.

Therefore, the SWOT analysis represents the authors' analytical assessment based on the combination of empirical findings and previously identified factors affecting the development and sustainability of SMEs. The research is descriptive in nature and aims to identify the main development trends and factors that may influence the long-term sustainability and competitiveness of small and medium-sized enterprises in the Republic of Serbia.

EMPIRICAL ANALYSIS OF SMALL AND MEDIUM-SIZED ENTERPRISES IN SERBIA

Time series analysis

Small and medium-sized enterprises in Serbia represent one of the key segments of the economic structure, with a significant participation in employment, creating added value and strengthening the competitiveness of the national economy. Improving the competitiveness of the economy on the domestic and international markets is conditioned by continuous encouragement of the establishment and development of small and medium-sized enterprises, as carriers of economic growth. Small and medium enterprises have multiple roles in the national economy. They contribute to the growth of the gross domestic product, the increase in employment and the strengthening of the country's export capacity. Also, the SME sector is often highlighted as a key factor in the process of economic reforms and modernization of the economy [13].

In the conditions of a limited market and pronounced structural problems, SMEs in Serbia face numerous challenges, including difficult access to financing, insufficient innovation and weaker technological development. All this implies that the development of this sector requires continuous institutional and financial support from the state and improvement of the business environment.

In modern economic analyses, SMEs are often defined as the "motor of economic development" and the key bearers of innovative activities [14]. The special importance of this sector in Serbia is reflected in its role in employment and alleviating unemployment, as well as in strengthening regional development. SMEs are especially important in less developed regions, where they often represent the basic form of economic activity and source of income for the population [15] (Anufrijev, 2024). Table 1 shows the trend in the number of small and medium-sized enterprises in Serbia in the period from 2021 to 2023.

Table 1. Number of small and medium-sized enterprises in Serbia in the period from 2021 to 2023.

Year	Number of MSPs	Absolute change	Growth rate (%)	Base index (2021=100)
2021	326.719	–	–	100,0
2022	339.450	+12.731	3,90	103,9
2023	358.550	+19.100	5,63	109,8

Source: Author's calculation based on the Publication of the Republic Statistical Office *"Enterprises by size and entrepreneurs in the Republic of Serbia, 2021-2023"*

Based on the data presented in the tables, it can be seen that the SME sector in the Republic of Serbia is recording continuous growth in the period from 2021 to 2023. The total number of SMEs increased from 326,719 in 2021 to 358,550 in 2023, which represents an increase of 31,831 business entities. Looking at the growth rates, it can be seen that the number of SMEs in 2022 increased by 3.90% compared to 2021, while in 2023 the growth was 5.63% compared to the previous year. These data indicate a gradual strengthening of the SME sector, as well as the growth of entrepreneurial activities in Serbia. The base index shows that the total increase in the number of SMEs in 2023 was 109.8 compared to the base year 2021. This means that the number of business entities increased by almost 10% in the observed period, which is a positive indicator of the development of this sector.

Regional distribution of SMEs

Table 2 shows the trend in the number of small and medium-sized enterprises by region in the Republic of Serbia in the period from 2021 to 2023.

Table 2. Number of small and medium-sized enterprises by region in the Republic of Serbia in the period from 2021 to 2023.

Region	2021	2022	2023	Total change 2021–2023
Belgrade Region	108.889	115.929	122.862	+13.973
Vojvodina Region	81.646	84.433	89.440	+7.794
Serbia – South	136.184	139.088	146.248	+10.064

Source: Author's calculation based on the Publication of the Republic Statistical Office *"Enterprises by size and entrepreneurs in the Republic of Serbia, 2021-2023"*

In addition to the overall growth, the regional structure of SMEs in Serbia is also significant. The highest concentration of business entities is present in the Belgrade region, where the number of SMEs increased from 108,889 in 2021 to 122,862 in 2023. Such data indicate a high concentration of economic activities, investments and business opportunities in the capital. The Vojvodina region also records continuous growth, from 81,646 companies in 2021 to 89,440 in 2023. Although the growth is lower compared to the Belgrade region, the data show a stable development of entrepreneurship and economic activities in this region.

In the Serbia – South region, the number of SMEs increased from 136,184 to 146,248 companies in the observed period. Although this region has the largest total number of business entities, development is slower compared to the Belgrade region, which indicates the existence of regional differences in economic development and business conditions.

Time series analysis shows that the SME sector in Serbia has a positive development trend, but also that there are certain challenges that may affect the long-term sustainability of business, which will be shown through a SWOT analysis. The growth in the number of companies indicates the development of entrepreneurship and increased economic activity in Serbia, but at the same time, problems such as uneven regional development, limited financial resources and the need for greater digitalization of business remain.

Accordingly, we note that strategic management plays an important role in the long-term development of small and medium-sized enterprises, but the state's strategic approach to this issue is of equal importance. Companies that have clearly defined goals, the ability to adapt to market changes and invest in innovation have greater opportunities for sustainable growth and strengthening competitiveness in the market.

Average annual growth rate

In Table 3, we show the average annual growth rate of SMEs in Serbia for the period 2021 – 2023.

Table 3. Average annual growth rate of SMEs in Serbia for the period 2021 – 2023.

Year	Number of SMEs	Chain index	Growth/decline rate (%)
2021	326.719	–	–
2022	339.450	103,9	3,90
2023	358.550	105,6	5,63
Average growth/decline rate (%)	-	-	4,76

Source: Author's calculation based on the Publication of the Republic Statistical Office *"Enterprises by size and entrepreneurs in the Republic of Serbia, 2021-2023"*

The average annual growth rate was calculated using the formula:

$$G = (Y_n/Y_1)^{1/n-1}-1$$

Where:

- G - average annual growth rate,
- Yn - value in the last year,
- Y1 - value in the first year,
- n - number of years in the analysis

so it follows from that

$$G = (358.550/326.719)^{1/2}$$

$$G = 0,0476\times100 = 4,76\%$$

Based on the results obtained, it can be concluded that the SME sector in the Republic of Serbia recorded stable growth in the period from 2021 to 2023. The growth rate in 2022 was 3.90%, while in 2023 it was 5.63%, indicating an acceleration in the growth of the number of SMEs in the observed period. The average annual growth rate of 4.76% shows a positive trend in the development of the SME sector in Serbia. Table 4 shows the structural participation of the region in the total number of SMEs for the period from 2021 to 2023.

Table 4. Structural participation of the region in the total number of SMEs for the period from 2021 to 2023.

Region	2021 (%)	2022 (%)	2023 (%)
Belgrade Region	33,3	34,1	34,3
Vojvodina Region	25,0	24,9	24,9
Serbia – South	41,7	41,0	40,8
Total	100,0	100,0	100,0

Source: Author's calculation based on the Publication of the Republic Statistical Office
"Enterprises by size and entrepreneurs in the Republic of Serbia, 2021-2023"

Based on the data presented, it can be seen that in the observed period, the Serbia - South region had the largest share in the total number of SMEs, although its share slightly decreased from 41.7% in 2021 to 40.8% in 2023. At the same time, the Belgrade region is recording a gradual increase in its share in the SME structure, which indicates a further concentration of economic activities and entrepreneurship in the capital city. The Vojvodina region has maintained a relatively stable share of around 25% throughout the period, which indicates a moderate and

stable development of the small and medium-sized enterprise sector in this part of Serbia. These data show that there are still significant regional differences in the development of SMEs, which may represent one of the challenges to the long-term sustainability and balanced economic development of the Republic of Serbia.

SWOT ANALYSIS OF THE SME SECTOR IN SERBIA

Based on the time series analysis, a continuous growth in the number of SMEs was observed, which indicates positive trends in the development of this sector. Our analysis also showed the existence of certain limitations and challenges affecting the SME sector, such as regional differences in development, the need for greater digitalization and the dependence of business on economic conditions in the market.

In addition to the statistical analysis, the theoretical part of the paper considers factors that affect the long-term sustainability of SMEs, such as strategic management, innovation, digitalization, access to finance and competitiveness. The combination of theoretical knowledge and the results obtained from the time series analysis created the basis for the preparation of a SWOT analysis.

SWOT analysis is one of the most commonly used methods of strategic analysis, as it allows for the consideration of internal and external factors that affect the business operations of a company. By identifying strengths, weaknesses, opportunities and threats, it is possible to better understand the position of small and medium-sized enterprises in modern business conditions and to identify factors that may affect their long-term sustainability and development (Table 5).

Table 5. SWOT analysis of small and medium-sized enterprises in Serbia

	Strengths	**Weaknesses**
Internal origin	Continuous growth in the number of SMEs	Limited access to finance
	Flexibility and faster adaptation to the market	Insufficient digitalization of some SMEs
	Development of entrepreneurial activities	Lack of skilled personnel
	Possibility of faster decision-making	Regional differences in development
	Growth of the service and IT sectors	High dependence on economic trends
	Opportunities	**Threats**
External origin	Digital Business Development	Inflation and rising business costs
	SME Incentives and Support Programs	Increasing market competition
	Application of Innovation and New Technologies	Economic instability
	Development of E-Commerce	Labor outflow
	Access to Foreign Markets	Frequent changes in market conditions

Strengths and weaknesses

It can be seen that small and medium-sized enterprises in Serbia have significant advantages, primarily related to business flexibility, the ability to adapt more quickly to market changes and the continuous growth of the number of business entities. The development of the service and IT sectors is particularly significant, which in recent years has recorded intensive growth and increasing importance in the structure of the domestic economy.

On the other hand, there are also numerous weaknesses that may affect the long-term sustainability of SMEs. Limited financial resources, insufficient digitalization and a lack of skilled personnel represent significant constraints to development and strengthening competitiveness. In addition, regional differences in development are also noticeable, which indicates an uneven concentration of economic activities in the Republic of Serbia.

Opportunities and threats

The most significant opportunities are the development of digital business, the application of innovations and the increasing availability of e-commerce. Modern business conditions allow SMEs easier access to the market and new consumers, which can positively affect the competitiveness and development of enterprises. Also, various support programs and incentives can contribute to strengthening the SME sector.

However, SMEs are still exposed to numerous environmental threats, such as inflation, economic instability, rising operating costs and increasing competition in the market. Therefore, strategic management plays an important role in ensuring the long-term sustainability and successful operation of SMEs.

CONCLUSION

Small and medium-sized enterprises play a very important role in the development of the economy of the Republic of Serbia, as they contribute to overall economic activity and influence the growth and development of the economy, especially considering that Serbia was one of the countries in transition. Due to the rapid and sometimes unpredictable changes that are taking place, strategic management becomes one of the important factors in the long-term sustainability of small and medium-sized enterprises.

Based on the analysis we conducted, it can be concluded that the SME sector in Serbia is recording a positive growth trend in the period from 2021 to 2023. The increase in the number of business entities indicates the development of entrepreneurial activities and the gradual strengthening of this sector. However, in addition to positive trends, numerous problems remain, such as limited access to financial resources, insufficient digitalization, lack of skilled personnel and regional differences in development.

SWOT analysis showed that small and medium-sized enterprises have significant advantages, which are primarily reflected in the flexibility of their operations and the ability to adapt more quickly to market changes. On the other hand, economic instability, inflation and rising operating costs represent significant threats to their further operations and development.

The latest available data from the Statistical Office of the Republic of Serbia, covering a period of 3 years, were reviewed. It can be concluded that the long-term sustainability of small and medium-sized enterprises largely depends on the ability to adapt to modern business conditions, the application of innovations and adequate strategic management. Investment in digitalization, human resource development and strengthening competitiveness can contribute to a more stable and successful operation of SMEs in the future.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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RAZVIJENOST INKLUZIVNIH INSTITUCIJA: KOMPARATIVNA ANALIZA ZEMALJA ZAPADNOG BALKANA I EU 27

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RESEARCH PAPER

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APSTRAKT

U radu se razvija Kompozitni institucionalni indeks (InstIndex) kao sintetička mera razvijenosti inkluzivnih institucija, konstruisan na osnovu pet dimenzija Worldwide Governance Indicators (Vladavina prava, Kontrola korupcije, Glas i odgovornost, Kvalitet regulative i Efikasnost vlade). Indeks je izračunat kao prost aritmetički prosek pet dimenzija, potom min–max normalizovan na skalu od 0 do 100, za period 1998–2024. godine. Primenom indeksa izvršena je komparativna analiza pet zemalja Zapadnog Balkana (ZB5: Srbija, Crna Gora, Severna Makedonija, Albanija i Bosna i Hercegovina) i proseka zemalja Evropske unije (EU27), sa fokusom na referentne godine 2004, 2014. i 2024. Rezultati ukazuju na strukturni i perzistentan institucionalni jaz: prosečna vrednost InstIndex-a za ZB5 u 2024. godini iznosi 47,92, dok EU27 beleži 71,39, što odgovara relativnom zaostatku od oko 33%. σ-konvergencija ukazuje na homogenizaciju grupe ZB5 (pad standardne devijacije sa 7,37 na 4,78), ali bez konvergencije prema EU27 proseku. Regresiona analiza β-konvergencije potvrđuje apsolutnu konvergenciju na celom uzorku ($\beta = -0{,}0096$, $p < 0{,}01$), uz implicitnu stopu od 1,07% godišnje i vreme poluživota od približno 65 godina. Provera robusnosti primenom analize glavnih komponenti (PCA) daje indeks gotovo savršeno korelisan sa osnovnim ($r \approx 1{,}00$), čime se potvrđuje neosetljivost zaključaka na izbor sheme ponderisanja.

Ključne reči: inkluzivne institucije, Zapadni Balkan, Evropska unija, Worldwide Governance Indicators, kompozitni indeks, β-konvergencija, PCA.

UVOD

Istraživanje institucionalne razvijenosti zemalja Zapadnog Balkana predstavlja jedno od centralnih pitanja savremene razvojne ekonomije i političke ekonomije tranzicije. Institucije, shvaćene kao formalna i neformalna pravila koja oblikuju interakciju između ekonomskih aktera [1] opredeljuju dugoročne razvojne performanse društva. Acemoglu i Robinson (2012) razvijaju distinkciju između inkluzivnih i ekstraktivnih institucija: prve omogućuju široku participaciju građana u ekonomskim i političkim procesima, štite svojinska prava, obezbeđuju vladavinu prava i podstiču kreativnu destrukciju; druge koncentrišu moć i resurse u rukama uskih elita, generišući trajnu stagnaciju [2].

Za pet zemalja Zapadnog Balkana (u daljem tekstu ZB5: Srbija, Crna Gora, Severna Makedonija, Albanija i Bosna i Hercegovina) institucionalna dimenzija razvoja ima dvostruku težinu: s jedne strane, ona je preduslov samoodrživog ekonomskog rasta; s druge, ona predstavlja centralni kriterijum za članstvo u Evropskoj uniji, formulisan kroz Kopenhaške kriterijume i politička poglavlja 23 i 24 pristupnih pregovora. Cilj ovog rada jeste da kvantifikuje relativnu poziciju ZB5 u odnosu na prosek EU27 koristeći originalni Kompozitni institucionalni indeks (InstIndex), uz ekonometrijski test brzine približavanja i proveru robusnosti metodom analize glavnih komponenti.

Naučni doprinos rada je dvostruk: metodološki – operacionalizuje inkluzivnost institucija kroz jasno definisan, reproducibilan i transparentan kompozitni indikator, uz formalnu proveru robusnosti; empirijski – pruža komparativnu sliku institucionalne konvergencije/divergencije u periodu 1998–2024, sa ekonometrijski testiranom stopom β-konvergencije, što je u literaturi o Zapadnom Balkanu retko sistematski obrađivano.

TEORIJSKI OKVIR

Savremena nova institucionalna ekonomija [1], [3], uspostavila je teorijski okvir u kojem se institucije posmatraju kao ključne determinante dugoročnog ekonomskog rasta i razvoja. U ovom pristupu, institucije se definišu kao formalna i neformalna pravila koja strukturiraju društvene i ekonomske interakcije, smanjuju neizvesnost i transakcione troškove, te oblikuju podsticaje ekonomskih aktera [1]. Njihova funkcionalnost ogleda se u sposobnosti da obezbede predvidivo i stabilno okruženje koje podstiče investicije, inovacije i efikasnu alokaciju resursa [3], što ih čini centralnim analitičkim okvirom za komparativno sagledavanje razlika između zemalja različitog nivoa razvijenosti, uključujući zemlje Zapadnog Balkana i EU-27.

Empirijska literatura dodatno potvrđuje centralnu ulogu institucija u objašnjenju razlika u ekonomskom razvoju među zemljama. Acemoglu, Johnson i Robinson (2001) pokazuju da kvalitet institucija predstavlja dominantan faktor u objašnjenju varijacija dohotka po glavi stanovnika, čak i nakon kontrole geografskih i kulturnih determinanti [4]. Ovaj nalaz je posebno relevantan za komparativnu analizu između EU-27, kao grupe zemalja sa relativno visokim i homogenijim nivoom institucionalnog kvaliteta, i zemalja Zapadnog Balkana, koje karakteriše izraženija institucionalna heterogenost i niži prosečni nivo institucionalne razvijenosti. Istovremeno, istorijska ukorenjenost institucionalnih obrazaca ukazuje na postojanje trajnog institucionalnog jaza između ove dve grupe zemalja.

Dalju teorijsku razradu daju Acemoglu i Robinson (2012), koji uvode distinkciju između inkluzivnih i ekstraktivnih institucija. Inkluzivne institucije karakterišu politički pluralizam, zaštita svojinskih prava, jednakost pred zakonom i otvorenost tržišne konkurencije, čime se omogućava široka participacija ekonomskih aktera i podstiče inovaciona aktivnost [2]. Nasuprot tome, ekstraktivne institucije obeležava koncentracija političke i ekonomske moći, ograničena vladavina prava i prisustvo rentijerskih obrazaca ponašanja, što vodi ka neefikasnoj alokaciji resursa i usporavanju rasta [2]. Ova dualna tipologija pruža analitički okvir za pozicioniranje zemalja Zapadnog Balkana u odnosu na institucionalne standarde EU-27, omogućavajući identifikaciju stepena njihove institucionalne inkluzivnosti.

Operacionalizacija koncepta inkluzivnosti u empirijskim istraživanjima zahteva multidimenzionalni pristup. Najčešće korišćen okvir predstavlja sistem indikatora upravljanja

Svetske banke – Worldwide Governance Indicators (WGI), koji obuhvata šest dimenzija: glas i odgovornost, političku stabilnost i odsustvo nasilja, efikasnost vlade, kvalitet regulative, vladavinu prava i kontrolu korupcije [5], [6]. U ovom radu, fokus je na dimenzijama koje neposredno reflektuju inkluzivnost institucija – glas i odgovornost, efikasnost vlade, kvalitet regulative, vladavinu prava i kontrolu korupcije – dok se indikator političke stabilnosti i odsustva nasilja isključuje iz kompozitnog indeksa. Ovakav izbor omogućava preciznije merenje institucionalne razvijenosti u kontekstu komparacije Zapadnog Balkana i EU-27, budući da stabilnost režima ne mora nužno implicirati inkluzivnost institucija.

Savremena istraživanja dodatno naglašavaju komplementarnost institucionalnog kvaliteta sa drugim razvojnim determinantama, uključujući ljudski kapital, tehnološki napredak i međunarodnu ekonomsku integraciju [7]. U tom smislu, viši nivo institucionalne inkluzivnosti u zemljama EU-27 povezan je sa većim stepenom inovativnosti, produktivnosti i otpornosti ekonomije, dok institucionalna ograničenja u zemljama Zapadnog Balkana doprinose sporijem razvoju i većoj ranjivosti na spoljne šokove. Time se dodatno naglašava značaj analize institucionalnog jaza između ove dve grupe zemalja.

Dodatni uvid u vezu između institucionalnog kvaliteta i ekonomskog razvoja pružaju savremena istraživanja koja naglašavaju ulogu institucionalnih reformi i strukturnih faktora regionalnog razvoja. Naime, institucionalne reforme usmerene ka jačanju vladavine prava, unapređenju regulatornog okvira i povećanju efikasnosti javne uprave predstavljaju ključni mehanizam podsticanja dugoročnog ekonomskog rasta i smanjenja razvojnih dispariteta među zemljama [8]. Istovremeno, teorijska razmatranja faktora regionalnog razvoja ukazuju da institucije deluju u interakciji sa drugim determinantama, kao što su ljudski kapital, inovacioni kapacitet i infrastrukturna razvijenost, pri čemu kvalitet institucionalnog okvira određuje efikasnost njihove alokacije i upotrebe [9]. U tom smislu, razlike u nivou institucionalne razvijenosti između zemalja Zapadnog Balkana i Evropske unije mogu se posmatrati ne samo kao posledica istorijskih i političkih okolnosti, već i kao rezultat različitog intenziteta i uspešnosti sprovedenih reformskih procesa.

U kontekstu Zapadnog Balkana, institucionalna slabost identifikovana je kao ključna prepreka ubrzanom ekonomskom razvoju i konvergenciji ka Evropskoj uniji. Estrin i Uvalić (2016) ukazuju da nedostatak institucionalne pouzdanosti ograničava priliv kvalitetnih stranih direktnih investicija, dok Nikolić, & Filipović (2026) naglašavaju postojanje institucionalnog deficita kao strukturnog ograničenja investicionog potencijala regiona [10], [11]. Bartlett (2021) dodatno identifikuje institucionalnu stagnaciju kao ključni faktor koji usporava proces približavanja zemalja Zapadnog Balkana ekonomskim i institucionalnim standardima EU-27 [12].

Teorijski i empirijski okvir konvergencije razvijen u radovima Barro, & Sala-i-Martin, (1992) i Sala-i-Martina (1996) pruža metodološku osnovu za analizu smanjenja razlika među zemljama kroz vreme [13], [14]. Koncepti σ-konvergencije i β-konvergencije u ovom radu se primenjuju na institucionalni kontekst, čime se omogućava kvantitativna procena dinamike približavanja zemalja Zapadnog Balkana nivou institucionalne razvijenosti EU-27. Ovakav pristup omogućava ne samo statičku komparaciju, već i analizu procesa institucionalne konvergencije ili divergencije između posmatranih grupa zemalja.

Polazeći od navedenih teorijskih i empirijskih uvida, cilj ovog rada jeste da kvantitativno proceni razvijenost inkluzivnih institucija i institucionalni jaz između zemalja Zapadnog Balkana i EU-27, identifikuje njegove ključne dimenzije i ispita dinamiku njihove konvergencije. Na taj način, rad doprinosi boljem razumevanju strukturnih ograničenja razvoja regiona, kao i formulisanju politika usmerenih ka jačanju inkluzivnih institucija kao temeljnog preduslova dugoročnog ekonomskog rasta i uspešne integracije u Evropsku uniju.

METODOLOGIJA

Izvor podataka jesu Worldwide Governance Indicators (Svetska banka), sa punom vremenskom serijom 1998–2024. Obuhvat objedinjuje pet WGI dimenzija ((Vladavina prava – RL, Kontrola korupcije – CC, Glas i odgovornost -VA, Kvalitet regulative – RQ i Efikasnost vlade - GE) za 32 zemlje (5 ZB + 27 EU), ukupno 864 opservacije na panelnom nivou. Postupak konstrukcije InstIndex-a sastoji se iz tri koraka: (i) prost aritmetički prosek za pet institucionalne varijable po zemljama i godinama (jednaki ponderi) [15], [16]; (ii) min–max normalizacija na teorijski raspon WGI [−2,5; +2,5] u interval [0; 100]; (iii) EU27 prosek izračunat kao prost neponderisani prosek 27 zemalja članica.

Dopunski analitički postupci uključuju: (a) gap-analizu – procentualni zaostatak svake ZB5 zemlje u odnosu na EU27 prosek za 2024; (b) σ-konvergenciju – kretanje standardne devijacije InstIndex-a unutar grupa ZB5 i EU27 kroz vreme; (c) rangiranje svih 32 zemalja u 2024; (d) β-konvergenciju – OLS regresiju prosečne godišnje stope rasta InstIndex-a (2004–2024) na logaritam početnog nivoa, čime se testira hipoteza apsolutne konvergencije; (e) proveru robusnosti primenom analize glavnih komponenti (PCA) na standardizovanom panelu. Ograničenja uključuju zavisnost rezultata od pretpostavke o jednakim ponderima (testirano kroz PCA) i moguće merne greške u samim WGI podindikatorima [17].

REZULTATI

Vrednosti InstIndex-a u referentnim godinama

Tabela 1 prikazuje vrednosti InstIndex-a u tri referentne tačke: 2004. (prvi talas istočnog proširenja EU), 2014. (post-krizna konsolidacija) i 2024. (poslednja raspoloživa opservacija).

Tabela 1. InstIndex u referentnim godinama (0–100)

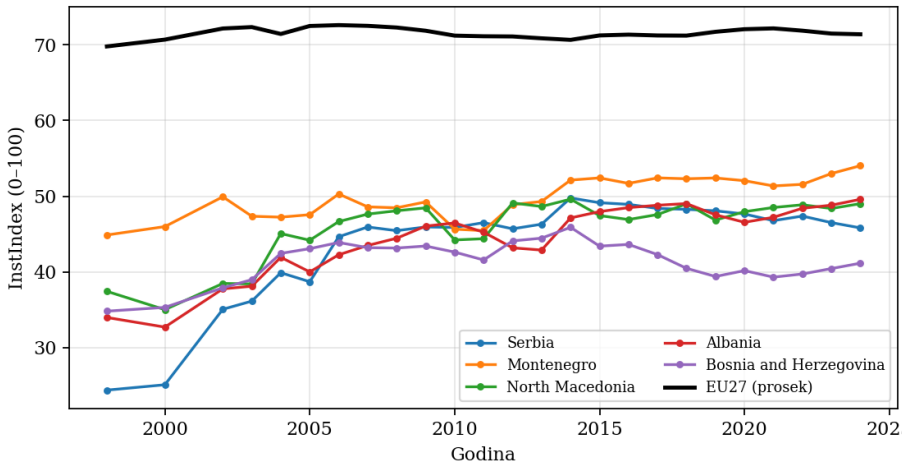
Zemlja / grupa	2004	2014	2024
Srbija	39,89	49,77	45,81
Crna Gora	47,23	52,13	54,03
Severna Makedonija	45,07	49,61	49,01
Albanija	41,93	47,13	49,59
Bosna i Hercegovina	42,45	45,89	41,15
EU27 (prosek)	71,43	70,65	71,39
ZB5 (prosek)	43,31	48,91	47,92

Izvor: autorova kalkulacija na osnovu WGI [18].

Iz Tabele 1 uočava se da EU27 prosek pokazuje izuzetnu stabilnost – oko 71 indeksni poen u sve tri referentne godine – što potvrđuje institucionalnu zrelost bloka. Nasuprot tome, ZB5 prosek se kreće od 43,31 (2004) preko 48,91 (2014) do 47,92 (2024): umeren napredak u prvoj deceniji, stagnacija (pa i blagi pad) u drugoj.

Trendovi u periodu 1998–2024

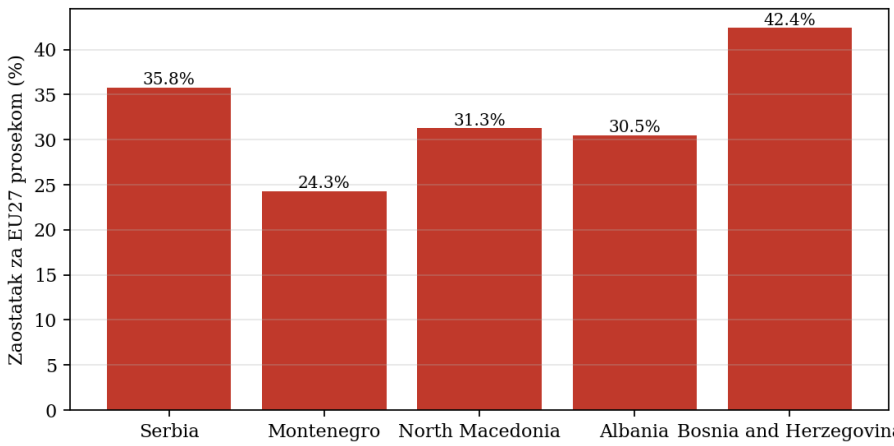
Grafikon 1 prikazuje godišnje kretanje InstIndex-a za svaku od pet ZB zemalja i EU27 prosek. Crna Gora i Severna Makedonija beleže najveći napredak 2004–2014, delom kao rezultat aktivne faze pristupnih reformi. Bosna i Hercegovina, nasuprot tome, pokazuje silazni trend od 2014. godine, što se može povezati sa produbljenom političkom blokadom i sporom konstitucionalnom reformom. Srbija pokazuje oscilirajuću putanju sa regresijom u poslednjih pet godina.



Grafikon 1. Kretanje InstIndex-a, ZB5 i EU27, 1998–2024.

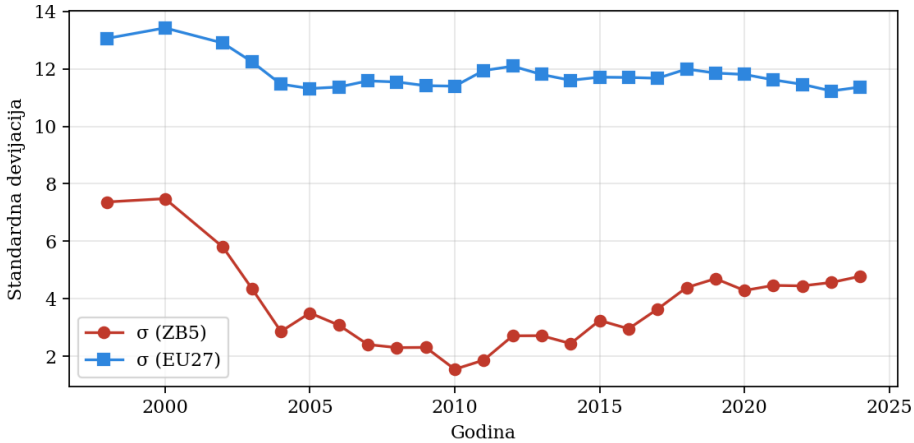
Institucionalni jaz i σ-konvergencija

Gap-analiza (Grafikon 2) kvantifikuje relativni zaostatak ZB5 zemalja u odnosu na EU27 prosek u 2024. Procentualni jaz kreće se od 24,3% za Crnu Goru do 42,4% za Bosnu i Hercegovinu (Srbija 35,8%; Severna Makedonija 31,3%; Albanija 30,5%).



Grafikon 2. Procentualni institucionalni jaz ZB5 u odnosu na EU27, 2024.

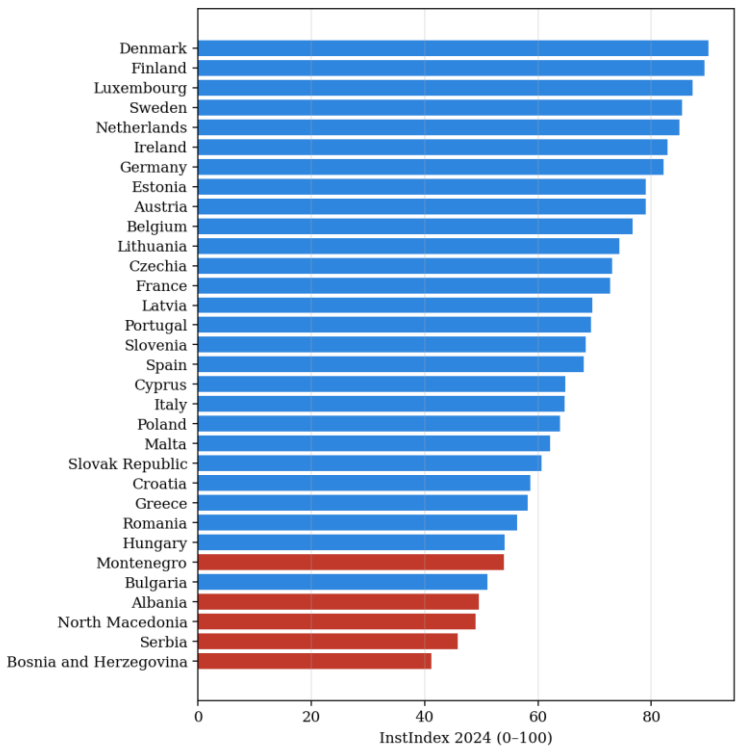
σ-konvergencija (Grafikon 3) pokazuje pad standardne devijacije unutar ZB5 sa 7,37 (1998) na 4,78 (2024), što ukazuje na homogenizaciju regiona - zemlje se međusobno približavaju. Istovremeno, disperzija unutar EU27 ostaje znatno veća (13,06 → 11,37), što reflektuje postojanje „dve brzine" (nordijsko-kontinentalno jezgro vs. periferija). Međutim, ključni nalaz glasi: ZB5 se homogenizuje, ali ne konvergira ka EU27.



Grafikon 3. σ-konvergencija InstIndex-a unutar grupa, 1998–2024.

Rangiranje zemalja u 2024. godini

Grafikon 4 prikazuje rangiranje svih 32 zemalja prema vrednosti InstIndex-a u 2024. godini. Prvu poziciju zauzima Danska (90,12), praćena Finskom (89,39) i Luksemburgom (87,28). Sve zemlje ZB5 nalaze se u donjih deset pozicija: Crna Gora je najbolje rangirana (27. mesto, 54,03), dok je Bosna i Hercegovina na poslednjem, 32. mestu (41,15). Srbija je 31. (45,81), Severna Makedonija 30. (49,01), a Albanija 29. (49,59). Zanimljivo je da pojedine zemlje EU27 - Bugarska, Mađarska i Rumunija – pokazuju performanse bliske najrazvijenijim zemljama ZB, potvrđujući pojavu demokratske erozije unutar Unije.



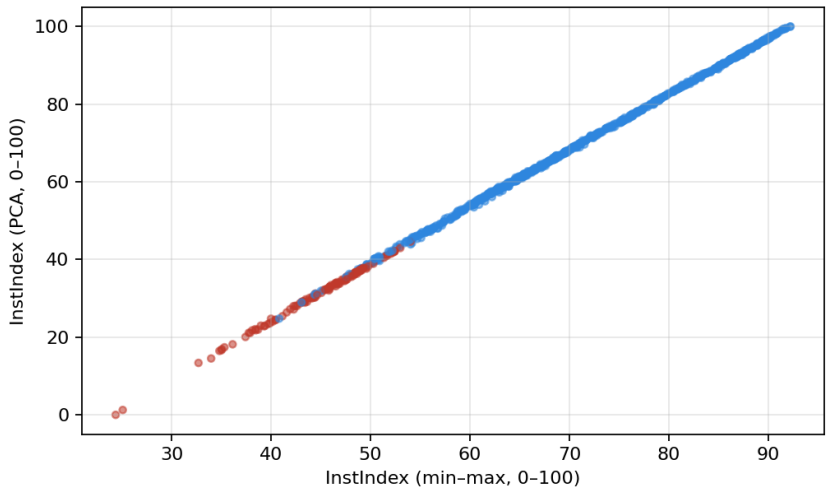
Grafikon 4. Rangiranje 32 zemlje prema InstIndex-u u 2024. (crveno = ZB5, plavo = EU27).

Provera robusnosti: PCA-bazirani alternativni InstIndex

Kako bi se ispitala robusnost u odnosu na metodološki izbor ponderisanja, konstruisan je alternativni indeks zasnovan na analizi glavnih komponenti (PCA). Pet institucionalnih dimenzija standardizovano je (z-skorovi), a prva glavna komponenta ekstrahovana iz panela od 864 opservacija.

Prva glavna komponenta objašnjava 95,06% ukupne varijanse, što potvrđuje visok stepen međusobne korelacije institucionalnih dimenzija i opravdava upotrebu jednog faktora kao sintetičkog pokazatelja. Faktorska opterećenja: Kontrola korupcije = 0,45, Efektivnost vlade = 0,446, Regulatorni kvalitet = 0,444, Vladavina prava = 0,453, Glas i odgovornost = 0,444. Opterećenja su pozitivna i gotovo jednaka (0,444–0,453), što empirijski opravdava pretpostavku o jednakim ponderima u osnovnom indeksu.

Pearson-ov koeficijent korelacije između PCA i min–max verzije iznosi r = 1,0, tj. praktično savršena monotona povezanost. Implikacija: zaključci nisu osetljivi na izbor sheme ponderisanja, čime se pojačava unutrašnja validnost rezultata. U 2024, ZB5 prosek PCA indeksa iznosi 35,47 a EU27 prosek 70,11 indeksnih poena (PCA skala 0–100).



Grafikon 5. Korelacija između min–max i PCA varijante InstIndex-a (svih 864 opservacija).

β-konvergencija: ekonometrijski test brzine približavanja

Dok σ-konvergencija meri smanjenje disperzije unutar grupe, β-konvergencija testira sistematsku tendenciju zemalja sa nižim početnim nivoom da beleže brži rast [13]. Specifikacija modela apsolutne konvergencije glasi:

$$(1/T) \cdot ln(y_i T / y_{i0}) = \alpha + \beta \cdot ln(y_{i0}) + \varepsilon_i$$

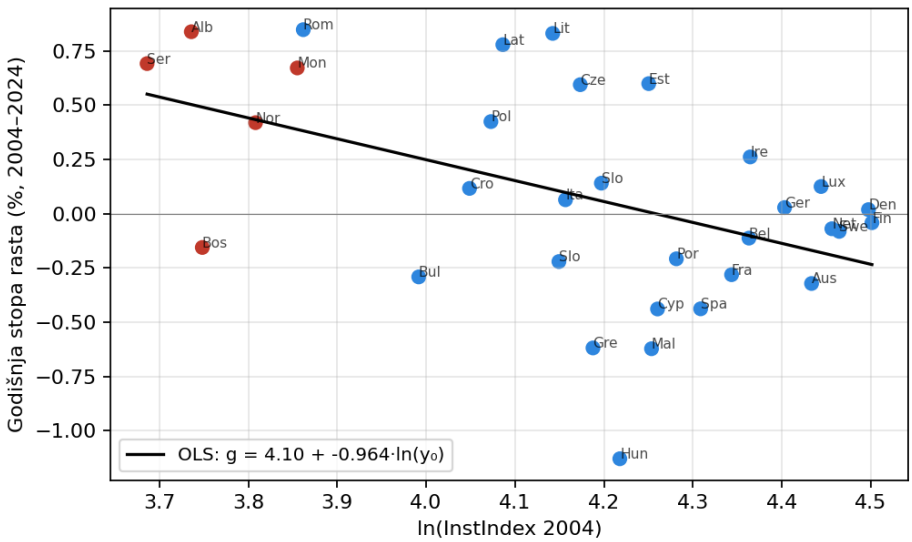
gde je y_{i0} InstIndex u 2004, $y_i T$ u 2024, T = 20. Negativan i statistički značajan β potvrđuje apsolutnu konvergenciju; $\lambda = -\ln(1 + T \cdot \beta)/T$ je implicirana stopa konvergencije, a $\ln(2)/\lambda$ vreme poluživota.

Tabela 2. Rezultati regresione analize β-konvergencije, 2004–2024.

Parametar	Model 1 (apsolutna)	Model 2 (sa ZB5 dummy)
β (ln y_0)	-0,0096 (p = 0,0076)	-0,009 (p = 0,101)
ZB5 dummy	–	0,0006 (p = 0,8703)
R^2	0,215	0,215
Implicirana stopa λ	0,0107 (≈ 1,07% god.)	–
Vreme poluživota	≈ 64,8 godina	–
N	32	32

Koeficijent β = -0,0096 statistički je značajan na nivou 1% (p = 0,0076), čime se potvrđuje hipoteza o apsolutnoj β-konvergenciji: zemlje sa nižim početnim nivoom u 2004. beleže prosečno brži rast InstIndex-a tokom 2004–2024. Implicirana stopa konvergencije iznosi ~1,07% godišnje, a vreme poluživota ~65 godina – dinamika znatno sporija od tipične ekonomske konvergencije (2–3% godišnje), što je u skladu sa literaturom o institucionalnoj inerciji.

U Modelu 2, uz kontrolu početnog nivoa, dummy varijabla za ZB5 nije statistički značajna (0,0006, p = 0,8703). Tumačenje: ZB5 zemlje ne pokazuju sistemsko odstupanje u dinamici rasta - njihova relativno brža putanja proizlazi iz niskog startnog nivoa, a ne iz specifičnih regionalnih karakteristika. Kombinovani nalazi σ- i β-analize glase: iako postoji β-konvergencija na nivou uzorka, njena brzina je toliko niska da projektuje višedecenijski horizont institucionalnog izjednačavanja ZB5 sa EU27.



Grafikon 6. β-konvergencija InstIndex-a, 2004–2024.

DISKUSIJA

Rezultati empirijske analize potvrđuju i preciziraju nekoliko teorijskih očekivanja. Prvo, strukturni karakter institucionalnog jaza – jaz od 30–42% koji opstaje više od dve decenije - ne može se objasniti kratkoročnim političkim ciklusima, već upućuje na duboko ukorenjene obrasce koje Acemoglu i Robinson (2012) nazivaju „virtualnim krugom ekstraktivnih institucija" [2]. Drugo, homogenizacija bez konvergencije podseća na fenomen „konvergencionog klastera niskog nivoa" (low-level convergence trap), gde se zemlje međusobno izjednačavaju na nivou ispod referentne grupe, što sugeriše zajedničke regionalne ograničavajuće faktore (političku ekonomiju

preuzetih država, neformalne mreže, klijentelizam). Treće, ekonometrijski nalaz o β-konvergenciji sa vremenom poluživota od 65 godina ukazuje da bez eksternih šokova i snažne EU uslovljenosti, institucionalno izjednačavanje nije ostvarivo u razumnom političkom horizontu.

Četvrto, stagnacija i regresija u poslednjoj deceniji, posebno izražena u BiH i Srbiji, koincidira sa usporenjem pristupnog procesa i slabljenjem tzv. EU conditionality efekta [18]. Pozitivni izuzetak Crne Gore povezuje se sa ranim zatvaranjem pregovaračkih poglavlja, premda ni ona nije smanjila jaz ispod 24%. Peto, slučajevi Mađarske, Bugarske i Rumunije pokazuju da članstvo u EU nije dovoljan uslov za održavanje visokog institucionalnog nivoa. Robusnost rezultata dodatno je potvrđena PCA analizom.

ZAKLJUČAK I PREPORUKE

Ovaj rad je razvio i primenio Kompozitni institucionalni indeks (InstIndex) kako bi kvantifikovao razvijenost inkluzivnih institucija pet zemalja Zapadnog Balkana u poređenju sa prosekom EU27 u periodu 1998–2024. godine. Glavni nalazi su: (a) ZB5 region u proseku ostvaruje InstIndex od 47,92 u 2024, što je oko 33% niže od EU27 proseka (71,39); (b) Crna Gora je lider regiona, Bosna i Hercegovina najslabije rangirana; (c) region pokazuje σ-konvergenciju, ali ne i konvergenciju prema EU27; (d) β-konvergencija je statistički značajna ali ekstremno spora ($\lambda \approx 1{,}07\%$, poluživot ≈ 65 godina); (e) nalazi su robusni na izbor sheme ponderisanja (PCA $r \approx 1{,}00$).

Iz nalaza proizlaze sledeće preporuke kreatorima javnih politika: (1) institucionalne reforme treba fokusirati na dimenzije u kojima je jaz najveći – vladavinu prava i kontrolu korupcije; (2) potrebno je osnažiti nezavisnost pravosuđa i regulatornih tela; (3) EU treba da razmotri mehanizme „pametne uslovljenosti" koji bi kombinovali pozitivne podsticaje (pristup strukturnim fondovima) sa sankcijama za institucionalnu regresiju; (4) akademska zajednica i civilno društvo treba da razvijaju redovne monitoring mehanizme bazirane na kompozitnim indikatorima.

Pravci budućih istraživanja mogu da podrazumevaju: ekonometrijsko testiranje uslovne β-konvergencije sa dodatnim kontrolnim varijablama (BDP per capita, priliv FDI, indeks demokratije), panel-analiza sa fiksnim efektima, i uporedna primena alternativnih institucionalnih indeksa (V-Dem, Bertelsmann Transformation Index).

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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DEVELOPMENT OF INCLUSIVE INSTITUTIONS: A COMPARATIVE ANALYSIS OF THE WESTERN BALKAN COUNTRIES AND THE EU-27

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ABSTRACT

This paper develops a Composite Institutional Index (InstIndex) as a synthetic measure of the development of inclusive institutions, based on five Worldwide Governance Indicators dimensions: Control of Corruption, Government Effectiveness, Regulatory Quality and Rule of Law, Voice and Accountability. The index is calculated as a simple arithmetic mean of the five dimensions, min–max normalized to a 0–100 scale, for the 1998–2024 period. A comparative analysis is conducted for the five Western Balkan countries (WB5: Serbia, Montenegro, North Macedonia, Albania, and Bosnia and Herzegovina) and the EU27 average, with emphasis on three reference years: 2004, 2014, and 2024. Findings reveal a structural and persistent institutional gap: the WB5 average in 2024 is 47.92, compared with 71.39 for the EU27 – a relative gap of approximately 33%. Sigma-convergence indicates internal homogenization within WB5 (standard deviation declining from 7.37 to 4.78) with no convergence toward the EU27. Beta-convergence regression confirms absolute convergence across the full 32-country sample ($\beta = -0.0096$, $p < 0.01$), with an implied convergence rate of only 1.07% per annum and a half-life of about 65 years. A robustness check using Principal Component Analysis produces an index almost perfectly correlated with the baseline ($r \approx 1.00$), confirming that conclusions are not sensitive to the weighting scheme.

Keywords: inclusive institutions, Western Balkans, European Union, Worldwide Governance Indicators, composite index, beta convergence, PCA.

THE IMPACT OF DIGITAL TRANSFORMATION ON MARKETING COMMUNICATION IN THE BANKING SECTOR

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ABSTRACT

The aim of this paper is to analyze the impact of digital transformations on changes in marketing communication in the banking sector, with special reference to digital communication channels such as social networks, mobile applications and internet platforms. The paper deals with the problem of the impact of the use of these channels on communication with clients and the competitive position of banks. It is assumed that using these digital channels improves communication with clients and strengthens banks' competitive advantages. The paper also clarifies the key challenges banks face when using digital communication channels. The research is based on a descriptive and comparative analysis of relevant domestic and international literature in the fields of banking, digital marketing and information technology. The analysis was conducted to identify key trends and changes in the marketing communication of banks in a dynamic digital environment. The findings indicate that, in the modern business environment, digital communication channels enable banks to improve communication with customers, strengthen their brand and achieve competitive advantages in the market. Future research could focus on the empirical analysis of the impact of modern digital technologies on the effectiveness of marketing communication, as well as customer satisfaction in the banking sector.

Keywords: Banking, Digital marketing, Digital communication channels.

INTRODUCTION

The Fourth Industrial Revolution, coupled with accelerated development of digital technologies and introduction of innovative practices, has brought about significant changes to almost all branches of industry. These changes have been especially visible in the banking sector,

where modern technology has led to redefining financial services and improvements in efficiency, competitiveness and involvement of buyers [1]. This has created conditions for changing traditional practices and open new opportunities for interaction with clients. Digital transformation does not only involve introduction of modern technology in business activities but also reviewing of organizational processes aimed at satisfaction of ever-changing market requirements [2].

Digital transformation has been attracting the attention of numerous authors ever since the 2000s, and Patel and McCarthy (2000) were the pioneers in this field [3]. However, their theories were preliminary and the research of digital transformation concepts was not all-out. Subsequent research led to a better understanding of this concept. Teng et al. (2022) point out that "digital transformation is associated with digital technologies, including artificial intelligence (AI), big data, cloud computing, and blockchain, enabling enterprises to thrive through new technologies, products, models, and approaches, thereby fostering sustainable and diversified growth" [4].

Due to more demanding expectations of clients in the past few years, the banking sector has been continuously facing new challenges. These challenges have additionally gained in weight by strengthening of financial technology (fintech) companies, offering innovative, rapidly adaptable and technology-led alternatives to traditional banking services [5]. In order to stay competitive under such conditions, banks turned to implementation of modern technologies and seeking innovative solutions in communication with clients. Digital transformation in the banking sector has over time imposed itself as a strategic imperative in boosting competitiveness, operating efficiency and highest possible satisfaction of clients' requirements [1]. This process has a double role in the banking sector, enabling banks, on the one side, to offer new channels of services through electronic platforms (e-banking, virtual banking) and service points (e-branch stores, POS), while, on the other side, reducing the number of brick-and-mortar branches and employees, having as an effect reduction in operating costs [6]. As a consequence, the banking industry spends three times more money on IT investments compared with other branches of industry [7].

In terms of attracting clients and improving communication with existing ones, digital marketing and social media have become an inseparable part of modern marketing strategies in the banking sector [8]. Main digital marketing tools in the banking sector are: "search engine optimization (SEO), social media marketing (SMM), content marketing, traffic management, email marketing, contextual advertising, gamification, mobile marketing, etc." [9]. Digital communication channels have become a key tool for banks to cope with the increasing market demands and the ambition to keep loyal users of their services, as well as for winning new service users [10]. In that context, digital transformation of marketing communication has become an essential factor in the process of adjustment of banks to modern business environment, opening space to further research relating to the role of marketing communication digital channels and fostering relations between the banks and their clients.

Although there is a significant number of authors involved in the research of digital transformation in the banking sector, insufficient attention has been paid to looking into its impact on bank marketing communication, particularly in the context of the way in which digital channels affect interaction with clients and the challenges arising once they are implemented in practice. The aim of this paper is to analyse the impact of digital transformation on changes in marketing communication of the banks with a special focus on the analysis of digital channels used in interaction with clients and key challenges occurring in their application. Accordingly, the paper research question is: how is digital transformation affecting bank marketing communication and in what way does the use of digital channels affect relations with clients? The significance of the research is in its improving the understanding of the role of digital channels and determining factors that improve relations with clients in the banking sector.

DIGITAL TRANSFORMATION IN THE BANKING SECTOR

Digital transformation in the banking sector implies not only giving up the traditional frameworks and shift to digital environment, but also the change of organizational structure, manner of doing business and communication, as well as of approach to satisfying customer

demands. Application of technologies such as artificial intelligence and big data has had a further impact on this process accelerating its development. This transformation includes the development of information and communication technologies that significantly affecting the way in which clients conduct banking operations, changes in market expectations and models of financial mediation [11]. "An efficient digital transformation starts with understanding buyers' digital behaviour, their preferences, choices and interests" [12]. In addition to that, digital transformation contributes to increase of bank income and costs reduction with simultaneous greater availability and quality of services. Digital transformation also introduces additional requests regarding digital harmonization and cyber security, being one of the key challenges for modern banks.

Digital transformation has also led to changes in clients' expectations, particularly regarding security, efficiency and practicality. In the past few years these challenges have become more serious due to advent of new banking market participants - financial-technology companies (FinTech), focused on the segments such as mobile payments market, personal lending, general insurance, as well as financial advisory [11]. These companies have become significant competitors to banks, primarily due to the fact that their operations are based on satisfying client expectations, simplicity and transparency. Their advantage is reflected in a high level of specialization, innovation and the fact that they do not carry a burden of outdated information systems like some banks do. Besides, they offer agile, technology-driven alternatives to traditional banking services [5].

FinTech industry is made of diversified companies combining financial services with modern technologies [13]. Shin and Choi (2019) state that these companies constitute a platform for a sustainable economic growth and are important drivers of the Fourth Industrial Revolution [14]. Compared to traditional banks, FinTech have a few advantages. They can give a solution for sustainable finance through microfinance or crowdfunding, while some of them distribute insurance and other financial instruments or provide third-party services [15]. In this way, these companies contribute to cost reduction and financial service quality improvement in the financial services industry. A number of novelties in the financial services sector resulted in change of customer habits and their financial behaviour, as well as in new ways of service provision.

To stay in business under modern market circumstances, banks turned to digital exchange of data and application of an omni-channel approach. To reduce a gap created between them and FinTech companies, banks need to constantly innovate their products and services, develop digital platforms, improve customer experience and improve communication with their clients.

An Omni-Channel approach enables us to see in the most efficient way how a bank can shift from traditional to digital banking. "Omni-Channel is a multi-channel approach to customer service with all channels tightly integrated, keeping the client in the centre of integration" [12]. Hence, this approach relates to integrated management of all communication channels and service distribution, enabling unique customer experience, faster provision of services, greater efficiency and greater client loyalty. In the modern business environment customers are more tech-savvy with increasingly complex demands to the banks, expecting them to follow their ever-changing needs and preferences. In accordance with such requirements, banks adapt their services, products, as well as communication strategies, as only that way they can stay in business in a competitive banking market.

MARKETING COMMUNICATION IN BANKING

Marketing communication in banking refers to the use of various communication channels and tools used by banks to inform clients about products and services and to strengthen trust and loyalty. Modern market conditions implying intense competition mean that banks are forced to apply innovative marketing communication strategies. A well devised strategy is fundamental to establishing long-term relations with clients, satisfying their demands and changing expectations, as well as attainment of business objectives. "Marketing communication strategies can prove to be a mantra for the success of banking" [16]. Compared with other sectors, marketing communication in banking has a pronounced information and educational role due to the complexity of financial

services and the necessity to reduce customer risk perception. In that context, marketing communication is established through a combination of traditional and digital channels that together constitute an integrated system of communication with clients.

The nature of financial services and the complexity of client relations significantly determine marketing communication in the banking sector. Trust is a key factor determining this communication as banks possess sensitive financial information on their clients due to which the communication must be reliable and transparent. In addition to that, marketing communication has an educational function resulting from the complexity of banking products and the need to inform clients on their features and risks. One of the most important factors that contributed to the improvement of communication is the application of CRM (Customer Relationship Management) enabling banks to attract new clients and ensure their long-term loyalty [17]. CRM systems are "a 360-degree view of the clients and this integrated multiple channels to provide the view to the banks" [18]. These systems enable banks to achieve their targeted marketing communication, efficient collection and analysis of data and improve customer experience [19]. Modern research results show that the application of relationship marketing significantly contributes to client satisfaction and loyalty boost in the banking sector [19], [20].

Digital transformation has led to significant changes of the role of traditional and digital marketing communication channels. Traditional channels, such as television, radio and press were used for a long time as the primary marketing communication channels in the banking sector. Their application has a number of limitations in terms of interaction and possibility of targeting certain groups. Development of digital technologies enabled introduction of digital communication channels, such as social networks, mobile applications, bank web pages and e-mail marketing. These channels enable a faster and two-way communication, efficient exchange of information and greater availability of services to customers. They give banks a possibility of a precise market segmentation and personalization of communication messages thus increasing the communication efficiency and client involvement level [21]. Although the importance of traditional channels dwindled over time, the practice has proven that they still have their role in modern marketing strategies, especially in the context of their integration with digital channels that led to the development of an Omni-Channel approach in communication with clients.

THE IMPACT OF DIGITAL TRANSFORMATION ON MARKETING COMMUNICATION

Changes in bank communication with clients were prompted by digital transformation in the banking sector. While the traditional approach had numerous limitations, such as one-way communication, the modern digital framework enables interactive and personalized real-time communication. Electronic media and interactive platforms, such as social networks, websites, mobile apps and email, have a crucial role in this transformation, as well as in changing marketing practices [22]. These channels enable banks to perceive and understand customer needs and adjust communication strategies to their preferences [23]. CRM strategy enables banks to establish long-term relations with clients, as well as to boost their profit through adequate management systems and application of customer-focused strategy [24]. Effective communication with customers has become one of the crucial factors of staying in business. Digital transformation has an impact on the change of the complete marketing communication paradigm, as it not only changes the communication channels used by banks, but also the way in which marketing messages are created and distributed [25].

The way in which banks communicate with clients has an impact on the loyalty of the existing, as well as on a possibility of attracting new clients, due to which modern digital communication channels, and in particular social networks, record a significant growth in modern banking [26]. These channels enable customers to have at all times contact with the banks which adapt communication contents to their needs and preferences. Electronic and mobile banking are the most widely used digital communication channels in the banking sector in the Republic of Serbia, and they are followed by websites and social networks [26]. The use of these

communication channels ensures greater efficiency of marketing activities and more precise client targeting in comparison to traditional channels [10].

Facebook is one of the most influential and most widely used social network which in February 2024 marked its 20th anniversary. According to the data, this platform had over three billion users in April of that year [27], while the number of users in the Republic of Serbia in 2025 was around 4.8 million [28]. In spite of a lower year-on-year growth in comparison with other social networks, Facebook is still the most significant marketing communication channel enabling precise population targeting. This platform offers banks a possibility to communicate with their clients in different ways and to improve their reputation through the use of business page, advertising, promotional posts and application promotion [29]. Its principal function is to inform users and, having in mind a great number of active users, it is possible to derive a conclusion on the scale of impact of this digital communication channel on bank operations [26].

Instagram, as a social network based on sharing image content and visual impression, had over two billion of active users in the month of April in 2024 [27], while the number of users in the Republic of Serbia at the end of 2025 exceeded 3.5 million [28]. Compared with the platforms like TikTok and Snapchat, Instagram has a greater number of users, while almost one third of them are the young between 18 and 24 years of age. This social network offers numerous possibilities of communication with users whereby the success of communication with the targeted audience depends on the ability of the brand to create adequate content [26]. Instagram has had the highest user growth rate in the past few years and has become an important digital communication channel enabling population targeting, usually under the age of 30 [30].

X (formerly Twitter), based on the exchange of short text messages, has over 300 million users globally and over 300,000 users in the Republic of Serbia [26]. Banks with an account on this platform try to attract new clients through a simplified communication and short messages.

LinkedIn is a professional social network through which banks publish contents and build up their digital profile. The number of users in 2025 was over 1.1 billion globally [31], while the number of users in the Republic of Serbia was over 1.6 million. In comparison with other social networks, the specific characteristics of this platform are business-oriented networking and employment, whereby it has a significant role in recruiting staff of specific professional profiles [26]. Therefore, banks use this network both for the promotion of their services and to find qualified staff.

Social networks, as modern digital communication channels, enable not only faster dissemination of information but also collecting of feedback, which pushed the quality of communication between the banks and customers to a higher level, as well the decision-making process. Digital transformation created conditions for development of an omni-channel approach which implies integration of several communication channels and unique customer experience. Only that way the banks can meet modern market demands relating to an efficient communication in the modern digital environment. In order to ensure their position on the competitive banking market, banks need to efficiently integrate and use in an optimal way all available digital communication channels.

Beside social networks, significant marketing communication channels in the banking sector are mobile applications and mobile platforms. With the growing use of mobile phones, conditions have been created for users to have a permanent access to banking services through its simple use [32]. Mobile banking enables a simple and personalized communication between the client and the bank and it is predominantly achieved through real-time notifications and information. The primary role of web platforms is based on informing clients by the banks and on the provision of various types of customer support. Integration of these channels with other bank digital communication channels enables the development of an omni-channel approach and building up long-term relations with customers [33].

Digital transformation in the banking sector also resulted in changes in marketing communication approach, shifting the focus increasingly to data-driven marketing and use of personalization. The main difference between this and traditional approach is in the possibility for

banks to plan and optimize their marketing activities on the basis of available data on clients, bank products and communication channels. Data-driven marketing offers the banks a possibility to better understand their clients thus fostering their loyalty by meeting their requirements. Client communication is based on targeted and personalized messages adapted to client needs and preferences.

This modern digital environment also created conditions for the development of modern concepts leading to a more efficient and personalized marketing communication. In addition to the already mentioned omni-channel approach, some of the most important modern concepts are customer experience management (Customer Experience – CX) and real-time communication. Customer Experience (CX) concept implies managing all customer contact points aimed at boosting client satisfaction and building up long-term relations with them [34]. Real-time communication offers banks a possibility to track customer behaviour and changes in their preferences in order to react in real time.

CHALLENGES AND RISKS

Digital transformation resulted in numerous advantages in the banking sector. Adoption of the new technologies created a need for the banks to undergo significant changes in their operation and strategies [35]. In spite of numerous benefits digital transformation has brought about, its effects on risk management and risk assumption capacity are still an insufficiently researched field [36]. Some of the fundamental challenges of digital transformation in marketing communication the banks are exposed to relate to: data security and protection, technical challenges, organizational and personnel challenges, economic and strategic challenges, customer experience (CX) management challenges, as well as reputational challenges associated with negative impact through digital channels.

Data security and protection of client privacy in marketing are some of the most important challenges encountered by the banks in digital communication with the existing and potential clients. As marketing communication in digital environment is a personalized marketing requiring collection of a great number of security-sensitive data on customers, it is very important for the banks to provide their protection. To mitigate these risks, it is necessary for the banks to invest in cyber-security measures and strictly comply with the regulations on data protection [37]. In addition to that, it is necessary to define efficient strategies and practical tools applicable in day-to-day operations which increase data security [38].

Technical challenges occur at new digital platforms implementation and their connection with the existing systems. The existing systems are often outdated and incompatible, frequently making introduction of new technologies difficult [37]. Their introduction usually requires significant funds and the very process is sometimes very complex. To reduce such risks banks need to introduce new technologies gradually and carefully using mediator software [37]. Banks should choose those communication channels and digital tools that are easier to integrate in the existing infrastructure and help attain goals on the long run.

Organizational and personnel challenges are linked with the fact that digital transformation in marketing communication requires new skills while the employees may resist such changes. In order to create new digital competences banks organize various trainings, workshops and improvement programmes. The openness of employees to the introduction of new digital technologies and their active participation in the very process significantly facilitates a successful digital transformation and increases efficiency of marketing communication in the banking sector.

Economic challenges are connected with the fact that digital transformation implies significant investments and high implementation costs, which is why cost-effectiveness of investments and impact of budgetary restrictions are often questioned. In order to overcome these challenges, banks are expected to perform detailed cost-benefit evaluations, align priorities with strategic objectives, and allocate finance resources strategically [37]. Under such circumstances banks need to plan carefully their marketing communication strategies aimed at optimal costs, boosting efficiently and keeping their competitive market position [25].

Customer experience (CX) management is one of the biggest challenges in the digital transformation of marketing communication. CX management implies coordination of all customer contact points and continuous tracking of their needs, expectations and preferences. It is necessary for the banks to integrate data they collect from different channels and personalize all interactions without undermining customer privacy. If banks fail to adequately analyze data and do not react timely to changes in customer preferences, that will have an adverse impact on customer satisfaction and their loyalty [34].

The risk of negative impacts through digital channels has become particularly pronounced in recent years due to the rapid development of information technologies and the increasingly widespread use of social networks. The spread of negative information on social networks makes it difficult for banks to manage their reputation [39]. The fact that digital channels are accessible to a wide range of users further increases this risk. Furthermore, social networks facilitate the rapid spread of information, as well as misinformation and rumors about the financial condition of banks. On the other hand, the positive tone of banks' posts and their active presence on social networks can mitigate reputational damage [39], as well as have a positive effect on clients' trust. Although social networks facilitate communication between banks and clients, they can also contribute to the spread of negative comments, expressions of dissatisfaction and reputational problems. Therefore, timely responses to inaccurate information and transparency in communication through digital channels are essential for maintaining clients' trust.

In spite of the existence of the above stated, but also of numerous other risks and challenges, digital transformation is the principal driver of bank marketing communication quality improvement. To be able to use the benefits of digital transformation to a highest possible level, banks need to be able to efficiently manage the stated risks. Accordingly, it is necessary for the banks to continuously adapt their strategies, boost digital competences of employees and focus on customer experience.

CONCLUSION

Digital transformation in banking has significantly changed the organizational structure, business practices and communication of banks with clients. On the other hand, it changes clients' expectations, especially in terms of security, efficiency and availability of information when using banking services. Marketing communication with clients in a digital environment is increasingly based on a combination of traditional and digital channels, and such an integrated system is the basis for building stronger and longer-term relationships with clients, as well as gaining their trust and loyalty.

Although digital transformation in banking has numerous advantages, banks in this process also face various challenges related to data security and protection, technical challenges, organizational and personnel challenges, economic and strategic challenges, customer experience (CX) management challenges, as well as reputational challenges associated with negative impact through digital channels. To exploit the full potential of these changes, banks need to continuously adapt their strategies, implement security measures, improve the digital competence of employees and focus on customer experience.

The findings indicate that digital channels improve communication with clients and reinforce competitive advantages of banks. Practical implications indicate the need for banks to integrate communication channels, efficiently manage data and improve customer experience through the application of modern technologies. Future research could focus on the empirical analysis of the impact of modern digital technologies on the efficiency of marketing communication and customer satisfaction in the banking sector. Additionally, future papers could deal in more detail with the impact of modern technologies on marketing communication in other branches of industry.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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PRIMJENA DIGITALNIH TEHNOLOGIJA U INTERNIM KONTROLAMA U JAVNOM SEKTORU REPUBLIKE SRPSKE

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APSTRAKT

Predmet rada je analiza primjene digitalnih alata u procedurama izvršenja, izvještavanja i interakcije finansijskog upravljanja i kontrole i interne revizije u javnom sektoru Republike Srpske. U radu se analiziraju konsolidovani izvještaji Centralne jedinice za harmonizaciju finansijskog upravljanja i kontrole i interne revizije, te preporuke i zaključci sa stručnih seminara i savjetovanja koji se, zbog obuhvata lica angažovanih na poslovima interne kontrole, mogu posmatrati kao reprezentativan uzorak.

Osnovna hipoteza i polazna tačka u istraživanju je da je, bez obzira što su tehnička i informatička osnova na zadovoljavajućem nivou, izazovno proces digitalizacije internih kontrola sprovesti na brz i odgovarajući način. Ovaj proces je izazovan zbog niskog nivoa digitalne pismenosti, posebno lica koji se nalaze pred kraj radnog vijeka i specifičnosti rukovođenja i upravljanja ljudskim resursima u javnom sektoru, s jedne, te kompleksnosti sistema internih kontrola, sa druge strane.

Ključne riječi: interne finansijske kontrole, digitalizacija, Republika Srpska

UVOD

Živimo u eri "nove stvarnosti" gdje tradicionalni metodi privređivanja bivaju modifikovani ili potpuno zamijenjeni primjenom savremenih tehnologija u proizvodnji, lancima snabdijevanja i razmene, komunikaciji, metodama prenosa informacija i svim ostalim segmentima života, a sve ovo je zasnovano na inovacijama o čijem je značaju i ulozi u privrednom rastu pisao i Draker davne 1990. godine [1].

Promjena načina privređivanja u realnom sektoru neminovno utiče i na promjene u javnom sektoru. Ovdje postoji duboka uzročno-posledična veza, dok je javni sektor zbog visokih troškova

generator i finanisijer inovacija i neophodne infrastrukture, dotle privatni sektor prednjači u sposobnosti prilagođavanja promjenama u okruženju. Ovo upućuje na zaključak da je nezaobilazna uloga javnog sektora i u digitalnoj transformaciji i ona se ne ograničava samo na finansiranje i obezbjeđivanje infrastrukture, posebno vezane za informaciono-komunikacione tehnologije (IKT tehnologije) nego i u regulaciji i obezbjeđivanju svih neophodnih uslova za prevazilaženje" digitalnog jaza" u društvu [2]. O nastajanju i ulozi digitalnog jaza pisali su brojni autori. Tako Dijk i Haker [3] kada je riječ u uzrocima njegovog nastajanja navode brojne faktore raznorodne prirode, od nedostatka interesovanja pojedinca i nedostatka raspoloživih mogućnosti digitalnog usavršavanja, do neadekvatne regulative i IKT infrastrukture. Postojanje digitalnog jaza između različitih država danas je jedan od značajnih razloga koji dovode do zaostajanja u razvoju i nemogućnosti društva da pristupi digitalnoj transformaciji, ili barem nekim ranijim fazama primjene IKT tehnologija kao što su digitizacija i digitalizacija [4].

Da bi izvršavao svoje funkcije, javni sektor mora stalno da vodi računa kako o ekonomskim parametrima u svom funkcionisanju kao što su efikasnosti, ekonimičnosti i efektivnosti, tako i o ispunjavanju javnog interesa. Činjenica da finansiranje javnog sektora potiče iz preraspodjele dohotka ostvarenog u realnom sektoru stvara dodatni pritisak da javni sektor bude što ekonomičniji. Kako privatni sektor ostvaruje veću efikasnost i fleksibilnost, razumno je da se, tamo gdje je moguće, metode u upravljanju u korporativnom sektoru primjene i na javni. Ovo je dovelo do razvijanja i primjene internih finansijskih kontrola u javnom sektoru (eng. Public Internal Financial Controls-PIFC) na bazi standarda Međunarodne organizacije vrhovnih revizorskih institucija- INTOSAI koje je 2002. godine propisala i Evropska komisija. Interne finansijske kontrole u javnom sektoru (IFJK) počivaju na tri stuba: finansijskom upravljanju i kontroli (FUK), internoj reviziji (IR) i centralnoj jedinici za koordinaciju finansijskog upravljanja i kontrole (CJH). Sistem IFJK je zasnovan na poslovnim procesima i obuhvata sve segmente poslovanja javnog subjekta, sve nivoe organizacije i sve aktivnosti [5] pri čemu je poseban akcenat stavljen na upravljanje rizicima gdje se za svaki poslovni proces određuju najznačajniji rizici koji se popisiju, opisuju i procjenjuju sa stanovišta njihove visine i uticaja [6].

Potpisivanjem sporazuma o stabilizaciji i pridruživanju, Bosna i Hercegovina se obavezala da, između ostalog, ispuni i zahtjeve iz klastera 1, poglavlje 32 - Finansijska kontrola [7]. Uvažavajući obaveze proistekle iz procesa pridruživanja s jedne strane, te aktuelnu transformaciju razvijenih privreda ka digitalnoj ekonomiji i digitalnom društvu kao i nivo privrednog i društvenog razvoja u Bosni i Hercegovini, Evropska unija je uvidjela potrebu da pruži pomoć u digitalizaciji sistema internih kontrola u javnom sektoru. Provedeno je više projekata: projekat PIFC (Public Internal Financial Control), završen 2011. godine, projekat SPFM (Strengthening Public Financial Management), završen 2015. godine, te projekat „Improving Public Internal Financial Control in Bosnia and Herzegovina" završen 2022. godine [7].

Predmet ovog rada je analiza primjene digitalnih alata u sistemu javne interne finansijske kontrole u javnom sektoru Republike Srpske. Pošli smo od kauzalne veze između uspješnosti i brzine obrade i prenosa podataka, i primjene digitalnih mogućnosti u postizanju većeg nivoa uspješnosti internih kontrola. Na osnovu uvida u sintetičke indekse razvoja digitalnog društva, prije svega jedan od najznačajnijih indeksa za praćenje spremnosti neke zemlje za primjenu IKT tehnologija - Network Readiness Index (NRI) [8], zatim anketiranja prisutnih lica na seminarima koji se organizuju kao kontinuirana edukacija za zaposlene na poslovima interne kontrole, te izvještaja CJH, formirali smo pretpostavku da jedan od značajnijih razloga nedovoljne primjene digitalnih alata leži u nedovoljnoj kapacitiranosti zaposlenih i stilu upravljanja u javnom sektoru.

METODOLOGIJA

Za dokazivanje ovako postavljene hipoteze, koristili smo statističku i deskriptivnu analizu stanja u sistemu internih finansijskih kontrola u Republici Srpskoj na osnovu brojčanih pokazatelja iz konsolidovanih godišnjih izvještaja o stanju internih kontrola u javnom sektoru Republike Srpske koje sačinjava Centralna jedinica za harmonizaciju finansijskog upravljanja i kontrole i interne revizije [9], Objavljenih izvještaja Evropske komisije o napretku BIH u procesu

pridruživanja EU [10], Preporuke pododbora za ekonomska i finansijska pitanja i statistiku EU [11], te preporuke nastale u okviru SIGMA monitoring procesa [12]. Pored ovih zvaničnih izvještaja, analizirali smo dokumente na zvaničnoj internet stranici Centralne jedinice za harmonizaciju finansijskog upravljanja i kontrole i interne revizije [13], te materijale sa seminara za interne revizore koje je organizovala CJH Republike Srpske, kao i zapažanja i prijedloge certifikovanih internih revizora koja su iznijeta u okviru diskusija na pomenutim seminarima, a kojima smo prisustvovali u svojstvu certifikovanog internog revizora.

Pored metoda analize statističkih pokazatelja, koristili smo i metod komparativne analize da bismo pratili uporedne pokazatelje u više posmatranih godina i između različitih subjekata javnog sektora u Republici Srpskoj.

REZULTATI ISTRAŽIVANJA

Primjena IKT tehnologija kao disruptivnih tehnologija koje mijenjaju ustaljene načine privređivanja, a koje se nalaze u samoj osnovi nove ekonomije predstavljaju preduslov digitalne transfo-rmacije. U novije vrijeme su razvijeni pokazatelji koji prate spremnost zemalja da se uključe u tokove digitalizacije. Prema najpoznatijem indeksu za praćenje spremnosti zemlje za primjenu IKT tehnologija - Network Readiness Index (NRI) [14], Bosna i Hercegovina u 2025. godini zauzima 92 mjesto od ukupno 127 posmatranih zemalja i najlošije je rangirana zemlja Zapadnog Balkana. U samoj strukturi indeksa najlošiji skor ima u sekciji primjenjena tehnologija (105) i upravljanje (89), potom slijedi pokazatelj ljudskih resursi (81). Podindeks uticaj koji se odnosi na ekonomiju, održivi razvoj i kvalitet života i pokazuje međudejstvo navedenih faktora ima vrijednost 96.

Tabela 1. Zemlje Zapadnog Balkana prema NRI indeksu za 2025.godinu [14]

Zemlja	NRI	Tehnologija	Ljudi	Upravljanje	Uticaj
Slovenija	33	34	49	27	23
Srbija	47	78	55	47	31
Rumunija	52	61	71	52	32
Hrvatska	53	71	63	35	61
Bugarska	55	51	51	48	72
Crna Gora	64	56	75	65	69
Albanija	79	97	59	77	73
S.Makedonija	89	89	110	64	90
BiH	92	105	81	89	96

Zabrinjava činjenica da je Bosna i Hercegovina prema NRI izvještaju za 2024. godinu [15]zauzimala 90 mjesto od 133 rangirane zemlje. Struktura indeksa je bila sledeća tehnologija (102) ljudski resursi (83) Upravljanje (72) i uticaj (94) što bi moglo da uputi na zaključak da se digitalni jaz povećava.

DIGITALIZACIJA PROCESA INTERNIH KONTROLA

Digitalizacija sistema javnih internih kontrola u BiH provedena je kroz projekat „Unapređenje javne interne finansijske kontrole u BiH“ koji je impleme-ntiran u trogodišnjem periodu, počevši od oktobra 2018. Projekt je podržao razvoj četiri strategije javne interne finansijske kontrole, te osmislio, razvio i pustio u rad PIFC aplikaciju koja omogućava automatizaciju propisa o internim kontrolama. Cilj projekta je bio unaprjeđenje finansijskog

upravljanja javnim sredstvima i sredstvima fondova Evropske unije. Finansiranje je omogućeno iz IPA fondova EU u iznosu od 2.000.000 eura, dok je samu realizaciju izvršio konzorcij međunarodnih kompanija, na čelu s ICE – International Consulting Expertise EEIG iz Belgije [16].

Rezultat ovog projekta je izrada digitalne softerske aplikacije otvorenog koda koja je omogućila digitalizaciju rada svih segmenata interne kontrole, najveću na Zapadnom Balkanu, sa ciljem efikasnog i upravljanja rizicima, jačanje interne kontrole i interne revizije i dosljednija primjena međunarodnih standarda interne revizije.

Aplikacija sadrži četiri modula [17]:

1. Finansijsko upravljanje i kontrola (FUK); sadrži sljedeće sekcije:
   - Mapa poslovnih procesa,
   - Registar rizika,
   - Izvještaj o samoprocjeni,
   - Ključni indikatori performansi i
   - Treninzi i certifikacija FUK.

2. Interna revizija (IR); kroz ovaj modul se obavljaju sve zakonom propisane aktivnosti i procedure interne revizije. One obuhvataju: sačinjavanje strateških i godišnjih planova, planove pojedinačnih revizija, evidentiranje izvršenog testiranja, ispitivanja i ocjene podataka i informacija koje su predmet revizije, izvještavanje o rezultatima i preporukama pojedinačnih revizija, pregled praćenja i izvršavanja preporuka interne revizije, izvještaje rukovodstvu subjekta i CJH, evidentiranje edukacija, evidentiranje aktivnosti u vezi sa kontrolom kvaliteta rada interne revizije i čuvanje dokumentacije
3. Izvještavanje; ova sekcija sadrži niz funkciona-lnosti i to:
   - Pentaho izvještavanje koje predstavlja poslovnu inteligenciju aplikacije i služi za generisanje podataka po različitim parametrima, a koji se nalaze u godišnjim izvještajima koji korisnici dostavljaju CJH. Pristup imaju zaposleni u CJH kojima su dodijeljena odgovarajuća ovlašćenja,
   - Spisak korisnika; sadrži spisak institucija i odgovornih lica unutar njih koji imaju dozvoljen pristup zajedno sa njihovim ovlašćenjima,
   - Procjena kvaliteta FUK; vrši se u skladu sa pravilnikom o procjeni kvaliteta FUK,
   - Praćenje realizacije preporuka i akcionog plana; koristi se unutar jedinica javnog sektora da bi rukovodioci interne revizije i interni revizori mogli da generišu izvještaje o statusu datih preporuka,
   - Godišnji izvještaj interne revizije i procjena kvaliteta; namijenjeno je rukovodiocima jedinica interne revizije za potrebe godišnjeg izvještavanja prema CJH o radu jedinice interne revizije unutar subjekta. Ovi podaci su neophodni za izradu konsolidovanog izvještaja na nivou javnog sektora.
   - Periodično samoocjenjivanje JIR; koriste zaposleni u jedinicama interne revizije da bi ocijenili svoj rad u prethodnom polugodišnjem, odnosno godišnjem periodu.

4. Administracija; Ovaj dio aplikacije sadrži niz funkcionalnosti koje se odnose na njeno funkcionisanje i to: FUK, Interna revizija, Kategorije Institucija, Registri institucija, Kategorije dokumenata i Kaylock administracija. Pristup svim funkcionalnosti imaju lica iz CJH kojima su dodijeljena posebna ovlašćenja, dok zaposleni u institucijama javnog sektora imaju pristup samo za one funkcionalnosti za koje su zaduženi u svojim institucijama.

Sve institucije i preduzeća javnog sektora u Bosni i Hercegovini su obavezni da koriste aplikaciju, a pristupne podatke licima koje po nadležnim propisima imaju pravo pristupa na

pismeni zahtjev uz ovlašćenje rukovodioca institucije ili preduzeća, dodjeljuju administratori ovlašćeni od strane CJH. Pravo pristupa mogu imati [17]:

- članovi radnih grupa za finansijsko upravljanje i kontrolu, osobe zadužene za finansijsko upravljanje i kontrolu u institucijama, koordinatori za upravljanje rizicima ili druge osobe kojima je rukovodilac institucije dodijelio ovlaštenja i odgovornosti za razvoj sistema finansijskog upravljanja i kontrole,
- rukovodioci jedinica interne revizije i interni revizori koji su upisani u Registar internih revizora i jedinica interne revizije u institucijama BiH,
- zaposleni u odjeljenju za razvoj sistema finansijskog upravljanja i kontrole CJH,
- zaposleni u odjeljenju za razvoj sistema interne revizije CJH.

DIGITALIZACIJA RADA CENTRALNE JEDINI-CE ZA HARMONIZACIJU

Centralna jedinica za harmonizaciju je osnovana Zakonom o sistemu internih finansijskih kontrola u javnom sektoru Republike Srpske [18] i organizovana je u četiri odjeljenja:

- Odjeljenje za regulisanje i nadzor sistema finansijskog upravljanja i kontrole,
- Odjeljenje za regulisanje i nadzor funkcije interne revizije,
- Odjeljenje za informacije i komunikacije iz djelokruga aktivnosti CJH,
- Odjeljenje za pripremu programa za obuku internih revizora i FMC osoblja i nadzor nad provođenjem programa za obuku.

Međutim, popunjenost sistematizovanih radnih mjesta je tek 40% [19].

Uvidom u zvaničnu internet stranicu Centralne jedinice za harmonizaciju Republike Srpske [13] ustanovili smo da internet stranica, prije svega, postoji, a potom da sadrži pregledne sekcije koje se odnose na:

- Preostala dva stuba Internu reviziju i Finansijsko upravljanje i kontrolu,
- Registar lica za finansijsko upravljanje i kontrolu,
- Registre iz oblasti interne revizije,
- Izvještaje o uspostavljanju i razvoju interne finansijske kontrole u javnom sektoru Republike Srpske,
- Obuke za interne revizore u javnom sektoru,
- Strategije i smjernice.

U podsekcijama ovih sekcija nalaze se detaljnije informacije o naslovljenoj temi date u formi linkova ka dokumentima u pdf ili word formatu koji se mogu učitati sa stranice CJH. To su, prije svega, pravilnici, uputstva, standardi, planovi, smjernice, sporazumi i memorandumi sa drugim relevantnim institucijama, te strategije razvoja.

Možemo zaključiti da se na stranci CJH nalazi dovoljno neophodnih informacija za sve zainteresovane strane, te da je ispunjen zahtjev za transparentnošću.

DIGITALIZACIJA U INSTITUCIJAMA JAVNOG SEKTORA REPUBLIKE SRPSKE

Prema javno dostupnom Konsolidovanom godišnjem izvještaju o uspostavljanju i razvoju interne finansijske kontrole u javnom sektoru Republike Srpske sa stanjem an dan 31.12.2025. [19], konstatovane su brojne činjenice koje su bitne za našu analizu.

Upotreba digitalizacije u vezi sa sistemom finansijskog upravljanja i kontrole:

- Od janura 2023. godine izvještavanje o sistemu finansijskog upravljanja i kontrole vrši se elektronski, putem PIFC aplikacije.
- Ukupno 466 subjekta javnog sektora Republike Srpske popunio je i zaključio Izvještaj o sprovođenju planiranih aktivnosti na uspostavljanju i razvoju sistema finansijskog upravljanja i kontrola.
- 407 subjekata javnog sektora RS je dostavilo planove za uspostavljanje i razvoj finansijskog upravljanja i kontrole za 2026. godinu, putem PIFC aplikacije.

- 404 subjekata javnog sektora dostavilo je Izjavu u vezi sa dostignutim stepenom razvoja sistema internih finansijskih kontrola u 2025. putem PIFC aplikacije.
- Konstatuje se da je u budućem periodu neophodno intenzivnije edukovanje korisnika o upotrebi i značaju PIFC aplikacije. Isto tako se navodi da digitalizacija sistema nije samo informatički alat za uspostavljanje i razvoj FUK-a i platforme za izvještavanje prema CJH, nego ona omogućava nadzor i jačanje analitičkih kapaciteta CJH, a sve to zajedno doprinosi efikasnijem javnom sektoru.

U domenu interne revizije situacija je nešto drugačija. Interna revizija je uspostavljena u daleko manjem broju subjekata sa značajnom nepopunjenošću kapaciteta. Ukupno 96 subjekata je formiralo jedinicu ili odjeljenje interne revizije sa ukupno sistematizovanih 251 radnih mjesta. Međutim, popunjeno je samo 178 mjesta ili 72% od broja sistematizovanih.

Konsolidovani izvještaj o uspostavljanju i razvoju interne finansijske kontrole u javnom sektoru Republike Srpske u 2025. godini navodi da godišnji izvještaj o radu interne revizije nisu svi subjekti dostavili kroz PIFC aplikaciju, nego putem pošte ne navodeći koliki je njihov broj. Isto tako, od ukupno 92 subjekta koji imaju uspostavljenu internu reviziju, tri nisu uopšte dostavili godišnji izvještaj.

Međutim, nama su interesantne konstatacije u izvještaju [19] koje se odnose na zaključke i preporuke, u okviru kojih su navedene najčešće sugestije zaposlenih na poslovima interne revizije:

- preporuka da se ubrza proces digitalizacije FUK,
- da se inteziviraju obuke za korišćenje PIFC aplikacije,
- da se PIFC aplikacija prilagodi regulatornom okviru za internu reviziju,
- da se osigura neovlašćen pristup podacima u aplikaciji
- da se utiče na podizanje svijesti kod rukovodstva subjekata o značaju internih kontrola.

Zaključci i preporuke od strane CJH u vezi sa internom revizijom takođe se u jednom djelu odnose i na dalju digitalizaciju sistema gdje se navodi da je potrebno uticati na dalju digitalizaciju interne revizije da bi bilo omogućeno da svi subjekti počnu koristiti PIFC aplikaciju za sprovođenje svih faza interne revizije.

MIŠLJENJA ZAPOSLENIH NA POSLOVIMA INTERNE KONTROLE U JAVNOM SEKTORU REPUBLIKE SRPSKE

Neformarlnim anketiranjem kroz razgovore i diskusije na seminarima internih revizora i lica zaduženiz za finansijsko upravljanje i kontrolu, mogli smo izvesti opšti zaključak u vezi sa radom CJH kako slijedi:

- navedena lica su uglavnom zadovoljna sa radom CJH,
- osnovni kanal komunikacije sa zaposlenim u CJH je telefon ili elektronska pošta
- povratne informacije iz CJH se dobijaju u razumnim rokovima,
- neophodno je provesti više seminara sa radionicama i rješavanjem konkretnih problema sa kojima se zaposleni susreću.

Zaposleni na poslovima interne kontrole u vezi sa digitalizacijom sistema internih kontrola navode da:

- na stranici CJH postoji sve uobičajene informacije koje su im neophodne u njihovom radu,
- preferiraju seminare i kontinuiranu edukaciju uživo i u odnosu na webinare,
- metodologija elektronskog popunjavanja i slanja godišnjih izvještaja je savladana od strane lica zaduženih za poslove finansijskog upravljanja i kontrole, dok neki interni revizori još uvijek koriste raniji metod slanjem putem pošte,

- meodologija sačinjavanja i elektronskog slanja izvještaja o nivou dostignutog stepena uvođenja sistema finansijskog upravljanja i kontrole i godišnjeg plana za otklanjanje nedostataka je takođe savladana,
- anketirana lica pokazuju u određenoj mjeri nepoznavanje informatičkih alata za sačinjavanje i učitavanje u PIFC aplikaciju elektronske verzije šeme poslovnog procesa,
- lica zadužena za upravljanje rizicima još uvijek nisu savladala obavljanje ovog posla posredstvom elektronske PIFC aplikacije,
- interni revizoru su iskazali nemogućnost da obavljaju poslove interne revizije korišćenjem PIFC aplikacije zbog nedostataka koji proističu iz odsustva digitalizacije sistema FUK, kao i zbog neusklađenosti PIFC aplikacije sa zakonskim propisima,
- dio učesnika u diskusiji je izjavio da nije dovoljno informatički obučen za obavljanje svih poslova interne kontrole u elektronskom formatu i u tom smislu pokazao interesovanje za sprovođenje dodatnih obuka.

Zaposleni na poslovima interne kontrole ugla-vnom naglašavaju sledeća ograničenja vezana za upravljanje sistemom:

- top menadžment ne razumije opseg i značaj interne kontrole, tako da "ton sa vrha" nije odgovarajući,
- nije propisano da je potrebno sistematizovati posebno radno mjesto za poslove finansijskog upravljanja i kontrole, pa se za njih zadužuju uglavnom referenti iz službe računovodstva koji nemaju dovoljno ingerencija da narede sprovođenje poslova iz domena FUK-a, posebno licima koja se nalaze iznad njih u organizacionoj strukturi subjekta,
- zakon ne predviđa sankcije za rukovodioce i poslovne subjekte ukoliko sistem internih kontrola nije uspostvaljen, pa je i to jedan od razloga zbog kojih menadžment ne pridaje dovoljan značaj ovom segmentu poslovanja.

OCJENE MEĐUNARDONIH AKTERA

Evropska komisija u izvještaju o napretku BiH za 2024. godinu [10] konstatuje da je zakonodavni okvir za interne kontrole u javnom sektoru donijet, ali još uvijek nedovoljno integrisan sa zakonodavstvom koje se odnosi na javne finansije. Pored toga upravljanje rizicima je nedovoljno razvijeno, kao i upravljačka odgovornost. Proces izvještavanja je automatizovan, ali primjena još uvijek nije odgovarajuća. Glavni razlog za to nalazi u nedovoljno razvijenoj upravljačkoj odgovornosti i praksi delegiranja ka višim političkim nivoima, umjesto ka službenicima po administrativnoj hijerarhiji.

Direkcija za evropske integracije na osmom sastanku Pododbora za ekonomska i finansijska pitanja i statistiku održanom 22.05.2025. u domenu digitalizacije internih finansijskoh kontrola u javnom sektoru konstatuje da BiH treba unaprijediti kvalitet praćenja rada javnih preduzeća posredstvom informatičke aplikacije razvijene u te svrhe [11].

Analiza javne administracije u BiH u okviru SIGMA monitoring procesa [12] u dijelu koji se odnosi na interne kontrole samo konstatuje da je značajan napredak ostvaren je uvođenjem PIFC aplikacije sa ciljem da olakša procese praćenja za CJH i procese internih kontrola uopšte, kao i sprovođenje samog procesa interne revizije. Zatim se kaže da je praktična primjena ove aplikacije još uvijek u početnoj fazi ali da pokazuje pozitivan razvojni trend.

DISKUSIJA

Predočeno istraživanje je potvrdilo da nedovoljna upotreba digitalnih alata u internim kontrolama u javnom sektoru Republike Srpske potiče iz dva osnovna razloga; nedovoljnog broja i stručnosti zaposlenih i stila upravljanja u javnom sektoru. NRI indeks pokazuje da je BIH najlošije pozicionirana zemlja Zapadnog Balkana sa tendencijom povećavanja digitalnog jaza, pri čemu posebno zabrinjava što vrijednosti podindeksa tehnologija pada u odnosu na prethodnu godinu.

Međutim, kao što smo naveli, kroz projekat „Unapređenje javne interne finansijske kontrole u BiH" uloženo je 2 milijarde evra iz IPA projekata što je rezultiralo digitalizacijom svih segmenata internih kontrola u 2022 godini, na osnovu čega možemo zaključiti da postoji tehnološka, prije svega softverska, infrastruktura za digitalizaciju u ovom segmentu javnog sektora.

Konsolidovani godišnji izvještaji o internim kontrolama koje izrađuje Centralna jedinica za harmonizaciju koja je jedan od departmana ministarstva finansija, potvrđuju da je proces digitalizacije uspostavljen na zadovoljavajućem nivou u dijelu finansijskog upravljanja i kontrole i rada CJH, dok u dijelu interne revizije značajno zaostaje. Primjetna je značajna potkapacitiranost u sektoru interne revizije gdje je popunjeno samo 72% radnih mjesta. U CJH popunjenost radnih mjesta je još niža-tek 40%. Ovome treba dodati i da međunarodni akteri u ocjeni ovog segmenta digitalizacije uglavnom konstatuju da je proces započet, a da njegova primjena nije zadovoljavajuća. Uzroke ovakvog stanja smo tražili na samom izvoru, tamo gde se procesi internih kontrola sprovode. Vidjeli smo da zaposleni na poslovima interne kontrole uglavnom referišu probleme u vezi sa percepcijom značaja internih kontrola od strane menadžmenta, nedovoljnu obučenost u radu sa PIFC aplikacijom kao i neprilagođenost aplikacije za poslove interne revizije.

ZAKLJUČAK

Ukrštanjem i nalizom podataka iz ova tri izvora: NRI indeksa, izvještaja CJH i međunarodnih institucija, te prikupljanjem mišljenja kroz neformalna anketiranja lica koji izvršavaju poslove interne kontrole u javnom sektoru Republike Srpske, smatramo da smo dokazali početnu hipotezu.

Svjesni smo, međutim, da ovo istraživanje ima i svoja ograničenja. Ona potiču sa dvije strane. Prvo, predmet istraživanja ne potpada pod okvire zvaničnog statističkog izvještavanja, pa smo bili osuđeni na korišćenje sekundarnih izvora podataka. Kao drugo, analiza bi dala više podataka da je rađena na bazi šireg anketnog upitnika koji bi distribuirali među većim brojem internih revizora, licima odgovornim za uspo-stavljanje i razvoj sistema finansijskog upravljanja i kontrole u javnom sektoru kao i među zaposlenim u CJH. Na ovaj način bismo mogli dobiti dodatne informacije u pisanoj ili elektronskoj formi u formatu koji bi omogućavao širu statističku obradu. Međutim, jedno tako široko istraživanje izlazi iz okvira ovog rada, pa ostaje da razmislimo da u budućem periodu, u okviru nekog šireg projketnog zadatka, formiramo opsežniji anketni upitnik i iz njega kao iz izvornog izvora podataka, pokušamo dobiti još jasniju sliku. Imajući u vidu da analize i izvještaji CJH, istraživanja i preporuke SIGMA i Evropske Komisije, takođe govore u prilog naših zaključaka, smatramo da to ne bi bitno promijenilonalaze i rezultate do kojih smo došli.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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APPLICATION OF DIGITAL TECHNOLOGIES IN INTERNAL CONTROLS IN THE PUBLIC SECTOR OF REPUBLIKA SRPSKA

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ABSTRACT

The subject of this paper is the analysis of the application of digital tools in the procedures of implementation, reporting, and interaction within financial management and control, as well as internal audit in the public sector of Republika Srpska. The paper analyzes consolidated reports of the Central Harmonization Unit, together with recommendations and conclusions from professional seminars and conferences which, considering the number of participants engaged in internal control activities, may be regarded as a representative sample.

The main hypothesis and starting point of the research is that, although the technical and IT infrastructure is at a satisfactory level, the process of digitalizing internal controls remains challenging to implement in a fast and appropriate manner. This is due to the low level of digital literacy, particularly among employees nearing the end of their working careers, as well as the specific characteristics of leadership and human resource management in the public sector on the one hand, and the complexity of the internal control system on the other.

Keywords: internal financial controls, digitalization, Republika Srpska

ULAGANJE U LJUDSKI KAPITAL I EKONOMSKI RAST: KOMPARATIVNA ANALIZA ZEMALJA ZAPADNOG BALKANA I SUSEDNIH DRŽAVA EU

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APSTRAKT

Ovaj rad istražuje ulaganja u ljudski kapital kao faktora ekonomskog rasta u deset zemalja – pet sa Zapadnog Balkana (Albanija, Bosna i Hercegovina, Crna Gora, Severna Makedonija i Srbija) i pet susednih članica Evropske unije (Bugarska, Grčka, Hrvatska, Mađarska i Rumunija) – u periodu od 2013. do 2023. godine. Na osnovu balansiranog panela od 110 opservacija, primenom Pooled Model objedinjene obične metode najmanjih kvadrata Model objedinjene regresije primenom metode najmanjih kvadrata (Pooled OLS), modela fiksnih efekata (FE) i modela slučajnih efekata (RE), ispituju se tri hipoteze o uticaju rashoda za obrazovanje, istraživanje i razvoj (IiR) i zdravstvenu zaštitu na BDP per capita prema paritetu kupovne moći. Hausmanov test ($\chi^2(3) = 13{,}50$; $p = 0{,}0037$) potvrđuje model fiksnih efekata kao konzistentni estimator. Rezultati pokazuju da rashodi za IiR imaju statistički visoko signifikantan pozitivan uticaj na BDP p/c ($\beta = 0{,}254$; $p < 0{,}001$), potvrđujući hipotezu H2. Rashodi za zdravstvo ispoljavaju pozitivan efekat u FE modelu ($\beta = 0{,}045$; $p = 0{,}031$), čime je H3 potvrđena. Rashodi za obrazovanje ne pokazuju kratkoročan pozitivan efekat unutar zemalja, te H1 nije potvrđena. Prosečan razvojni jaz između ZB zemalja i EU suseda iznosi oko 13.184 USD per capita godišnje (PKM, 2021 cene). Rad pruža empirijsku osnovu za formulisanje politika usmerenih ka smanjenju razvojnog jaza putem strateških investicija u inovacije i zdravstvenu zaštitu.

Ključne reči: ljudski kapital, ekonomski rast, zemlje Zapadnog Balkana.

UVOD

U savremenom ekonomskom diskursu, ulaganje u ljudski kapital prepoznaje se kao jedan od ključnih determinanti dugoročnog ekonomskog rasta i održivog razvoja. Teorije endogenog rasta, posebno radovi Lucasa (1988) i Romera (1990), naglašavaju da ekonomski rast nije isključivo funkcija akumulacije fizičkog kapitala, već u velikoj meri zavisi od sposobnosti društva da generiše, akumulira i efikasno koristi znanje, inovacije i kvalifikovanu radnu snagu [1], [2]. U tom kontekstu, ljudski kapital predstavlja centralni mehanizam kroz koji se ostvaruju eksternalije znanja i povećava ukupna produktivnost faktora proizvodnje.

Značajni teorijski doprinos dali su Mankiw, Romer i Weil (1992), koji su proširili neoklasični Solow-Swan model uključivanjem ljudskog kapitala kao posebnog proizvodnog faktora [3]. Njihovi rezultati ukazuju da razlike u nivou obrazovanja i veština radne snage objašnjavaju značajan deo varijacija u dohotku po glavi stanovnika između zemalja, čime se dodatno potvrđuje ključna uloga investicija u ljude za konvergenciju ekonomija.

Uprkos jasnim teorijskim i empirijskim nalazima, zemlje ZB i dalje zaostaju u pogledu ulaganja u ljudski kapital i posledičnog ekonomskog rasta u odnosu na susedne članice Evropske unije. Prema raspoloživim podacima, prosečan BDP po glavi stanovnika, meren paritetom kupovne moći (PKM), u zemljama regiona iznosi oko 19.373 međunarodnih dolara (cene iz 2021. godine), što predstavlja svega 59,5% proseka uporedivih EU ekonomija (32.557 međunarodnih dolara). Ovaj jaz ukazuje na postojanje duboko ukorenjenih strukturnih slabosti.

Naime, relativno nizak nivo izdvajanja za istraživanje i razvoj, ograničena ulaganja u kvalitet obrazovnog sistema, kao i nedovoljno razvijen zdravstveni sektor negativno utiču na akumulaciju i kvalitet ljudskog kapitala. Pored toga, institucionalne slabosti – uključujući niži nivo efikasnosti javne uprave, slabiju vladavinu prava i nedovoljnu podršku inovacionim aktivnostima – dodatno usporavaju proces ekonomskog sustizanja. Poseban izazov predstavlja i izražen fenomen emigracije visokoobrazovanog stanovništva (tzv. „odliv mozgova“), koji dovodi do gubitka akumuliranog ljudskog kapitala i smanjuje potencijal za endogeni rast.

Polazeći od navedenog teorijskih i empirijskih konsideracija, cilj ovog rada jeste da empirijski ispita odnos između ključnih dimenzija ulaganja u ljudski kapital – rashoda za obrazovanje, aktivosti istraživanja i razvoja, kao i zdravstvenu zaštitu – i dostignutod nivoa ekonomskog rasta, merenog BDP-om po glavi stanovnika (PPP). Analiza se zasniva na panel podacima Svetske banke za period 2013–2023 i primenjuje savremene panel ekonometrijske metode kako bi se identifikovali kauzalni efekti i izolovao uticaj posmatranih varijabli unutar zemalja kroz vreme.

Na osnovu teorijskih postavki i pregleda relevantne literature, formulisane su sledeće istraživačke hipoteze:

- H1: Veći rashodi za obrazovanje (izraženi kao procenat BDP-a) imaju statistički značajan i pozitivan uticaj na nivo BDP-a po glavi stanovnika.
- H2: Ulaganja u istraživanje i razvoj (izražena kao procenat BDP-a) pozitivno i značajno doprinose rastu BDP-a po glavi stanovnika.
- H3: Povećani rashodi za zdravstvenu zaštitu (kao procenat BDP-a) imaju pozitivan efekat na BDP po glavi stanovnika, kroz unapređenje produktivnosti i radne sposobnosti stanovništva.

PREGLED LITERATURE

Rezultati istraživanja Lucasa (1988) u teoriji endogenog rasta postavlja ljudski kapital kao centralni mehanizam dugoročnog privrednog rasta [1]. U Lucasovom modelu, akumulacija znanja i veština kroz obrazovanje stvara pozitivne eksterne efekte koji povećavaju produktivnost celokupne ekonomije. Ova paradigma opravdava javno finansiranje obrazovanja kao investicije sa pozitivnim eksternim efektima koji prevazilaze privatne prinose.

Romer (1990) proširuje ovaj okvir uvođenjem endogenih tehnoloških promena, gde ulaganja u istraživanje i razvoj generišu nove ideje i pronalaske koji se ne mogu iscrpiti, što predstavlja osnov za trajni rast [2]. Empirijska potvrda ove veze dokumentovana je u nizu radova: Guellec i

van Pottelsberghe de la Potterie (2004) nalaze elastičnost BDP-a na IiR rashode između 0,13 i 0,30 u OECD zemaljama [4], dok Griffith, Redding i Van Reenen (2004) dokumentuju da IiR istovremeno podstiče inovacije i ubrzava difuziju tehnologije [5].

U domenu zdravstvene zaštite, teorijska osnova potiče od Grossmana (1972), koji zdravlje tretira kao oblik investicije koja direktno uvećava produktivni kapacitet radne snage [6]. Empirijski dokazi potvrđuju ovu vezu: Bhargava i dr. (2001) nalaze da preživljavanje odraslih ima pozitivan i signifikantan uticaj na rast BDP-a u zemljama sa niskim dohotkom [7], dok Suhrcke i Urban (2010) pokazuju da kardiovaskularne bolesti negativno utiču na ekonomski rast u Evropi [8].

Analiza usmerena specifično na prostor Zapadnog Balkana relativno je oskudna u literaturi, ali postoje relevantni regionalni uvidi. Pelinescu (2015) pronalazi pozitivan i signifikantan uticaj humanog kapitala na konkurentnost u zemaljama Centralne i Istočne Evrope [9]. Istraživanja Svetske banke i EBRD konzistentno identifikuju nisku inovativnu aktivnost, emigraciju visokokvalifikovanih radnika i nedovoljne zdravstvene kapacitete kao ključne prepreke konvergenciji zemalja Zapadnog Balkana prema EU standardima.

Dodatni teorijski doprinos razumevanju veze između ljudskog kapitala i ekonomskog rasta pružaju Cvetanović, Ilić i Despotović (2017), koji ističu da ljudski kapital predstavlja jedan od ključnih endogenih činilaca razvoja, naročito na regionalnom nivou [10]. Autori naglašavaju da se njegov uticaj ne ispoljava samo kroz povećanje produktivnosti i obrazovnog nivoa radne snage, već i kroz pozitivne eksternalije znanja, difuziju inovacija i migraciona kretanja visokoobrazovanih radnika. Ovakav pristup je posebno značajan za zemlje Zapadnog Balkana, jer ukazuje da efekti ulaganja u ljudski kapital zavise ne samo od visine izdvajanja za obrazovanje i razvoj veština, već i od sposobnosti ekonomije da zadrži i efikasno iskoristi akumulirani ljudski kapital u funkciji dugoročnog privrednog rasta.

PODACI I METODOLOGIJA

Izvor i opis podataka

Podaci su preuzeti iz baze Svetske banke [11] (World Development Indicators; Svetska banka, 2024), a gde oni nisu bili kompletni, dopunjeni su iz zvaničnih izvora statističkih zavoda (MONSTAT i MakStat). Istraživanje obuhvata period od 2013. do 2023. godine za deset zemalja podeljenih u dve grupe: (1) pet zemalja Zapadnog Balkana – Albanija, Bosna i Hercegovina, Crna Gora, Severna Makedonija i Srbija; i (2) pet susednih članica EU – Bugarska, Grčka, Hrvatska, Mađarska i Rumunija. Panel je balansiran, sa $N \times T = 10 \times 11 = 110$ opservacija i bez nedostajućih vrednosti, što omogućava primenu standardnih panel estimatora bez korekcije za neuravnotežene panele.

Zavisna varijabla je BDP per capita prema PPP u stalnim međunarodnim dolarima (baza 2021). U regresionoj analizi koristi se prirodni logaritam (ln GDPpc), što omogućava tumačenje koeficijenata kao semilogaritamske elastičnosti i ublažava potencijalnu nelinearnost u distribuciji dohotka. Nezavisne varijable su: rashodi za zdravstvo (HEALTH, % BDP), rashodi za obrazovanje (EDU, % BDP) i rashodi za istraživanje i razvoj (RD, % BDP).

Ekonometrijski model

Osnovna panel specifikacija je:

$$ln\ GDPpc_it = \alpha + \beta_1\ HEALTH_it + \beta_2\ EDU_it + \beta_3\ RD_it + \mu_i + \varepsilon_it$$

gde i označava zemlju (i = 1,...,10), t godinu (t = 2013,...,2023), μ_i su neposmatrani fiksni (ili slučajni) efekti na nivou zemlje, a ε_it je idiosinkratska greška. Procenjuju se četiri specifikacije: (1) Pooled OLS koji ignoriše heterogenost; (2) Model fiksnih efekata (FE/Within) koji kontroliše sve vremenski stabilne karakteristike zemalja; (3) Model slučajnih efekata (RE/GLS) koji pretpostavlja da su μ_i nekorelirani sa regresorima; i (4) Dvostrani FE koji uključuje i fiksne efekte zemlja i fiksne efekte vremena.

Izbor između FE i RE modela determiniše se Hausmanovim testom [12]. Pod nultom hipotezom oba estimatora su konzistentna, ali je GLS efikasniji. Odbacivanje H_0 ukazuje na korelaciju neposmatranih efekata sa regresorima, čime FE postaje preferiran. U svim specifikacijama primenjuju se robustne standardne greške (sandwich estimator) radi korekcije heteroskedastičnosti i serijalne korelacije.

DESKRIPTIVNA ANALIZA

Tabela 1 pokazuje izražen razvojni jaz između dve grupe zemalja, dok Tabela 2 otkriva unutar-grupnu heterogenost.

Tabela 1: Deskriptivna statistika varijabli (2013–2023)

Varijabla	N	Srednja vred.	St. dev.	Min	Max
BDP p/c PPP (hilj. 2021 int. $)	110	25,965	7,741	12,873	41,320
Zapadni Balkan	55	19,373	3,527	12,873	27,244
EU susedi	55	32,557	4,472	22,954	41,320
Zdravstvo (% BDP)	110	7,595	1,255	4,943	11,422
Zapadni Balkan	55	8,106	1,226	6,209	11,422
EU susedi	55	7,084	1,068	4,943	9,381
Obrazovanje (% BDP)	110	3,735	0,504	2,730	4,709
Zapadni Balkan	55	3,491	0,376	2,730	4,265
EU susedi	55	3,980	0,500	3,026	4,709
IiR (% BDP)	110	0,689	0,425	0,150	1,633
Zapadni Balkan	55	0,400	0,240	0,150	0,948
EU susedi	55	0,979	0,370	0,382	1,633

Napomena: BDP per capita iskazan u hiljadama međunarodnih dolara (PKM, stalne cene 2021). Izvor: World Bank WDI.

Tabela 2: Proseci ključnih indikatora po zemaljama (2013–2023)

Zemlja	Grupa	BDP p/c (000$)	Zdravstvo (%)	Obrazov. (%)	IiR (%)
Albanija	ZB	16.145	6,808	3,336	0,174
Bosna i Hercegovina	ZB	16.251	9,153	3,459	0,214
Crna Gora	ZB	22.899	9,146	3,834	0,382
Severna Makedonija	ZB	20.667	6,972	3,289	0,401
Srbija	ZB	20.903	8,449	3,535	0,828
Prosek ZB	**ZB**	**19.373**	**8,106**	**3,491**	**0,400**
Bugarska	EU	27.739	7,656	4,231	0,785
Grčka	EU	32.688	8,431	3,866	1,196
Hrvatska	EU	33.541	6,966	4,197	1,034
Mađarska	EU	35.115	6,838	4,346	1,410
Rumunija	EU	33.704	5,532	3,258	0,467
Prosek EU suseda	**EU**	**32.557**	**7,084**	**3,980**	**0,979**

Napomena: Neponderirani proseci za period 2013–2023. BDP per capita u hiljadama USD (PKM, 2021 cene). Izvor: World Bank WDI.

Prosečan BDP per capita ZB zemalja iznosi 19.373 hilj. USD, što je za 40,5% niže od proseka EU suseda (32.557 hilj. USD). Paradoksalno, ZB zemlje imaju veće prosečne rashode za zdravstvo (8,1% vs 7,1% BDP-a), što odražava lošije zdravstvene ishode i manji BDP koji čini imenilac. Ključna razlika je u rashodima za IiR: EU susedi troše prosečno 0,979% BDP-a, naspram svega 0,400% u ZB – razlika od 145%.

Među ZB zemaljama, Srbija prednjači u IiR rashodima (0,828% BDP-a) i BDP p/c (20.903 hilj. USD). Albanija i BiH beleže najniže nivoe BDP p/c (~16.000 hilj. USD). Crna Gora ima visoke zdravstvene rashode (9,15%) ali niske IiR rashode (0,38%). Među članicama EU iz susedstva, Mađarska se odlikuje se najvišim IiR rashodima (1,410% BDP-a) i BDP p/c-om, dok Bugarska zaostaje.

Tabela 3: Korelaciona matrica (N = 110)

Varijabla	ln(BDP p/c)	Zdravstvo	Obrazovanje	IiR
ln(BDP p/c)	1,0000	−0,2935	0,3875	0,7377
Zdravstvo (% BDP)	−0,2935	1,0000	0,0745	−0,0441
Obrazovanje (% BDP)	0,3875	0,0745	1,0000	0,5291
IiR (% BDP)	0,7377	−0,0441	0,5291	1,0000

Napomena: Pearsonovi koeficijenti korelacije na osnovu panel podataka (N = 110). Zavisna varijabla u logaritamskom obliku.

Korelaciona matrica ukazuje na snažnu pozitivnu vezu između IiR rashoda i ln(BDP p/c) (r = 0,738), što pruža preliminarnu podršku H2 (tabela 3). Obrazovanje pokazuje umerenu pozitivnu korelaciju (r = 0,388), dok zdravstveni rashodi ispoljavaju negativnu korelaciju (r = −0,294) – fenomen koji se tumači obrnutom uzročnošću i biće reinterpretiran u panel modelima. Umerena korelacija između IiR i obrazovanja (r = 0,529) ukazuje na mogući multikolinearitet koji se adresira robustnim standardnim greškama.

EMPIRIJSKI REZULTATI

Testovi specifikacije modela

F-test za joint signifikantnost fiksnih efekata daje $F(9,97) = 28,07$ ($p < 0,001$), što snažno odbacuje Pooled OLS u korist modela koji dopušta heterogenost na nivou zemalja – jasno ukazujući da postoje sistemske razlike između zemalja koje nije moguće zanemariti. Hausmanov test daje $\chi^2(3) = 13,51$ ($p = 0,004$), čime se odbacuje nulta hipoteza o nekorelisanosti neposmatranih efekata sa regresorima (tabela 4). Model fiksnih efekata je stoga konzistentan i preferiran estimator. RE estimator, iako efikasniji pod H_0, nije konzistentan u ovom uzorku.

Tabela 4: Rezultati testova specifikacije panela

Test specifikacije	Statistika	p-vrednost	Zaključak
F-test za fiksne efekte F(9, 97)	28,073	< 0,001	Odbaciti Pooled OLS; FE signifikantni
Hausman test $\chi^2(3)$	13,505	0,0037	Odbaciti RE; FE konzistentan estimator
F-test za poolabilnost (FE)	28,073	< 0,001	Potvrđena heterogenost između zemalja
Robustne std. greške (sandwich)	–	–	Primenjeno u svim specifikacijama

Napomena: Svi testovi sprovedeni na nivou značajnosti od 5%. Robustne standardne greške u svim specifikacijama.

Rezultati panel regresije

Tabela 5: Rezultati panel regresije – zavisna varijabla: ln(BDP per capita PPP)

Varijabla	Pooled OLS	FE (Within)*	RE (GLS)	Hipoteza
Zdravstvo (% BDP)	**−0,0657*** *(0,0186)*	**0,0445** *(0,0203)*	**0,0249** *(0,0182)*	**H3: potvrđena** *(FE model)*
Obrazovanje (% BDP)	**0,0198** *(0,0321)*	**−0,0669*** *(0,0349)*	**−0,0464** *(0,0331)*	**H1: nije** *potvrđena*
IiR (% BDP)	**0,5193*** *(0,0418)*	**0,2538*** *(0,0718)*	**0,3643*** *(0,0631)*	**H2: potvrđena**
Konstanta	**10,185*** *(0,193)*	**9,855*** *(0,214)*	**9,851*** *(0,203)*	
R^2 (within)	−0,116	0,2098	0,1918	
R^2 (between)	0,728	0,206	0,431	
R^2 (overall)	0,613	0,206	0,399	
Broj opservacija	110	110	110	
FE zemlja	Ne	Da	Ne	
Robustne st. greške	Da	Da	Da	

*Napomena: Robustne (sandwich) standardne greške u zagradama. * p<0,10; ** p<0,05; *** p<0,01.*
Preferiran model: FE (Within) na osnovu Hausmanovog testa. Dvostrani FE prikazan u Pril. A1.

Istraživanje i razvoj (H2): Rashodi za IiR ispoljavaju statistički visoko signifikantan pozitivan uticaj na ln(BDP p/c) u svim specifikacijama bez vremenskih efekata. U preferiranom FE modelu, $\beta_3 = 0{,}254$ ($p < 0{,}001$): povećanje IiR rashoda za 1 procentni poen BDP-a, pri svemu ostalom jednakom, asocirano je sa povećanjem BDP p/c od oko 25,4%. Ova procena je konzervativnija od Pooled OLS (0,519) jer FE eliminiše između-heterogenost. Hipoteza H2 je snažno potvrđena.

Zdravstvo (H3): U FE modelu $\beta_1 = 0{,}045$ ($p = 0{,}031$) je pozitivan i statistički značajan na nivou 5%. Pooled OLS daje negativan koeficijent (−0,066), ali kontrola za fiksne efekte eliminiše pristranost uslovljenu obrnutom uzročnošću: bogatije EU susede sistematski troše manji udeo BDP-a na zdravstvo. Unutar iste zemlje, povećanje zdravstvenih rashoda pozitivno korelira sa BDP p/c. Hipoteza H3 je potvrđena.

Obrazovanje (H1): Koeficijent $\beta_2 = -0{,}067$ ($p = 0{,}058$) u FE modelu je negativan i marginalno signifikantan na nivou 10%. Ovaj nalaz, konzistentan sa delom literature [13], sugeriše da nisu kvantitativni rashodi već kvalitet obrazovnih ishoda ono što pokreće rast. Efekti obrazovnih investicija materijalizuju se sa zakašnjenjem od jedne do dve decenije, što ih čini teško detektabilnim u kratkoročnom panelu. Fenomen brain drain u ZB zemaljama dodatno poništava lokalne efekte. Hipoteza H1 nije potvrđena.

DISKUSIJA

Empirijski rezultati ovog rada nude nekoliko važnih uvida sa stanovišta ekonomske politike. Dominantan nalaz – snažan pozitivan uticaj IiR rashoda – konzistentan je sa Romerovom (1990) teorijom endogenog rasta [2]. Apsolutan nivo IiR rashoda u ZB zemaljama (prosek: 0,40% BDP) dramatično zaostaje za EU prosekom i daleko je ispod cilja od 3% BDP koji je EU Lisabonska agenda postavila. Ova strukturna razlika može biti ključni mehanizam koji perpetuira razvojni jaz.

Pozitivan uticaj zdravstvenih rashoda u FE modelu potvrđuje Grossmanovu (1972) teoriju zdravstvenog kapitala. Negativan predznak u Pooled OLS odražava dobro dokumentovanu endogenost – zemlje ZB zemlje troše relativno više na zdravstvo zbog starije strukture bolesti, a ne zato što su te investicije razvojno neefikasne. FE estimator, kontrolišući za fiksne efekte zemalja, otkriva pravi pozitivan efekat unutar zemalja.

Neznačajan ili negativan koeficijent obrazovnih rashoda u FE modelu nije neočekivan. Hanushek i Woessmann (2015) ukazuju na to da su kognitivne veštine stanovništva i kvalitet obrazovnih ishoda, a ne samo dužina školovanja, ključni činioci dugoročnog ekonomskog rasta [14]. ZB regija karakteristično gubi između 10 i 30% visokoobrazovanih kadrova, što poništava lokalne efekte obrazovnih investicija i objašnjava zašto se pozitivan uticaj ne manifestuje unutar vremenskog horizonta analize.

ZAKLJUČAK

Ovaj rad pruža empirijsku evidenciju o uticaju tri komponente ulaganja u ljudski kapital na ekonomski razvoj u deset zemalja Zapadnog Balkana i susednih EU članica, 2013–2023. Model fiksnih efekata identifikovan je Hausmanovim testom ($\chi^2(3) = 13{,}51$; $p = 0{,}004$) kao preferiran estimator.

Ključni nalazi su: (1) IiR rashodi imaju snažan, pozitivan i statistički visoko signifikantan uticaj na BDP p/c ($\beta = 0{,}254$; $p < 0{,}001$) – H2 je potvrđena; (2) Zdravstveni rashodi pozitivno utiču na BDP p/c u FE modelu ($\beta = 0{,}045$; $p = 0{,}031$) – H3 je potvrđena; (3) Obrazovni rashodi ne pokazuju kratkoročan pozitivan efekat unutar zemalja – H1 nije potvrđena, što se tumači dugim vremenskim horizontom obrazovnih investicija i brain drain efektom.

Sa stanovišta ekonomske politike, rezultati naglašavaju prioritet strateškog povećanja IiR rashoda u ZB zemaljama, koje su strukturno ispod praga od 1% BDP-a. Zdravstveni sistem zahteva veću efikasnost ulaganja, dok obrazovni sektor treba da prioritizuje kvalitet nad kvantitetom. Adresiranje emigracije visokokvalifikovanih kadrova putem strukturnih reformi tržišta rada i inovacionih ekosistema predstavlja neophodan uslov za dugoročnu konvergenciju prema EU.

Ograničenja analize uključuju relativno kratak vremenski period ($T = 11$), mali broj zemalja ($N = 10$), odsustvo instrumenata za kontrolu endogeniteta i nemogućnost kvantifikacije brain drain efekta. Buduća istraživanja trebalo bi da primene dinamičke panel modele (Arellano-Bond GMM), uključe indikatore kvaliteta obrazovnih ishoda (PISA/PIAAC) i prošire uzorak na veći broj zemalja.

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PRILOG A: Detaljna ekonometrijska analiza

A.1 Kompletni rezultati svih specifikacija

Tabela A1 prikazuje potpune koeficijente, standardne greške, t-statistike, p-vrednosti i intervale poverenja za sve četiri panel specifikacije: Pooled OLS, model fiksnih efekata (FE), model slučajnih efekata (RE) i dvostrani FE model (entitetski i vremenski efekti).

Tabela A1: Detaljan prikaz koeficijenata i statistika podesnosti svih specifikacija

Parametar	Pooled OLS	FE (Within)	RE (GLS)	FE Dvostr.
ZDRAVSTVO (% BDP)				
Koeficijent (β)	−0,0657	0,0445	0,0249	−0,0284
Std. greška	(0,0186)	(0,0203)	(0,0182)	(0,0096)
T-statistika	−3,532	2,195	1,367	−2,972
p-vrednost	0,0006	0,0306	0,1747	0,0038
95% CI	[−0,103;−0,029]	[0,004;0,085]	[−0,011;0,061]	[−0,047;−0,009]
Signifikantnost	***	**		***
OBRAZOVANJE (% BDP)				
Koeficijent (β)	0,0198	−0,0669	−0,0464	0,0159
Std. greška	(0,0321)	(0,0349)	(0,0331)	(0,0112)
T-statistika	0,617	−1,915	−1,402	1,425
p-vrednost	0,5383	0,0584	0,1638	0,1576
95% CI	[−0,044;0,083]	[−0,136;0,002]	[−0,112;0,019]	[−0,006;0,038]
Signifikantnost		*		
IiR – ISTRAŽIVANJE I RAZVOJ (% BDP)				
Koeficijent (β)	0,5193	0,2538	0,3643	−0,0918
Std. greška	(0,0418)	(0,0718)	(0,0631)	(0,0456)
T-statistika	12,423	3,533	5,771	−2,012
p-vrednost	< 0,001	0,0006	< 0,001	0,0473
95% CI	[0,436;0,602]	[0,111;0,396]	[0,239;0,490]	[−0,183;−0,001]
Signifikantnost	***	***	***	**
KONSTANTA				
Koeficijent (β)	10,185	9,855	9,851	10,338
Std. greška	(0,193)	(0,214)	(0,203)	(0,092)
p-vrednost	< 0,001	< 0,001	< 0,001	< 0,001
STATISTIKE PODESNOSTI				
R^2 (within)	−0,1164	0,2098	0,1918	0,1954
R^2 (between)	0,7278	0,2058	0,4312	−0,1078
R^2 (overall)	0,6131	0,2064	0,3987	−0,1222
Log-likelihood	24,907	95,431	87,193	230,50
F-stat (robustna)	82,481	12,813	17,279	5,335
p-vred. (F-stat)	< 0,001	< 0,001	< 0,001	0,0020

Broj opservacija	110	110	110	110
FE zemlja	Ne	Da	Ne	Da
FE vreme	Ne	Ne	Ne	Da
Robustne st. greške	Da	Da	Da	Da

*Napomena: Robustne (sandwich) st. greške. Signifikantnost: *** p<0,01; ** p<0,05; * p<0,10. Zavisna varijabla: ln(BDP p/c PKM, stalne cene 2021). FE Dvostrani model uključuje 9 entitetskih i 10 vremenskih dami varijabli. N = 110 za sve specifikacije.*

A.2 Interpretacija testova specifikacije

F-test za zajedničku signifikantnost fiksnih efekata ($F(9,97) = 28{,}073$; $p < 0{,}001$) snažno odbacuje Pooled OLS. Ovaj test poredi RSS Pooled OLS i FE modela i distribuira se kao $F(N-1, NT-N-k) = F(9, 97)$.

Hausmanov test (1978) testira H_0: $\text{Cov}(\mu_i, x_it) = 0$ formulom $H = (b_FE - b_RE)' [\text{Var}(b_FE) - \text{Var}(b_RE)]^{-1} (b_FE - b_RE) \sim \chi^2(k)$, gde $k = 3$ (broj testiranih koeficijenata). Dobijena vrednost $\chi^2(3) = 13{,}505$ uz $p = 0{,}0037$ nedvosmisleno odbacuje H_0 na svim standardnim nivoima značajnosti, potvrđujući FE kao konzistentni estimator. Treba napomenuti ograničenu moć testa pri $N = 10$; ipak, dobijena statistika prelazi prag $\chi^2(3) = 11{,}34$ koji odgovara $p = 0{,}01$.

Dvostrani FE model (entitet + vreme) apsorbuje sve vremenski zajedničke šokove (globalna finansijska kriza 2008–09, COVID-19 šok 2020, energetska kriza 2022). Promena predznaka koeficijenta IiR na negativan ukazuje da je deo unutar-varijanse IiR korelisan sa zajedničkim vremenskim trendovima. Zbog visokog broja parametara (21 fiksnih efekata) i ograničene veličine uzorka, ovaj model se ne preporučuje kao primarni za zaključivanje, ali pruža važnu robusnosnu proveru.

.3 Napomene o robusnosti i ograničenjima

Sve standardne greške su robustne na heteroskedastičnost i unutar-klastersku serijsku korelaciju (klaster = zemlja). Rezultati su stabilni: signifikantnost ključnih koeficijenata ne menja se materijalno između klasičnih i robustnih standardnih grešaka. Odsustvo ozbiljne serijalne korelacije konzistentno je sa relativno kratkim vremenskim horizontom panela ($T = 11$). Potencijalni problem endogeniteta IiR rashoda (ekonomski razvijenije zemlje mogu više da investiraju) adresiran je fiksnim efektima, ali ne i instrumentalnim pristupom; dinamički panel estimator (Arellano-Bond) preporučuje se kao prirodan nastavak ove analize.

INVESTMENT IN HUMAN CAPITAL AND ECONOMIC GROWTH: A COMPARATIVE ANALYSIS OF WESTERN BALKAN COUNTRIES AND NEIGHBORING EU MEMBER STATES

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ABSTRACT

This paper examines investment in human capital as a determinant of economic growth in ten countries – five from the Western Balkans (Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, and Serbia) and five neighboring European Union member states (Bulgaria, Greece, Croatia, Hungary, and Romania) – over the period 2013–2023. Based on a balanced panel of 110 observations, three hypotheses are tested regarding the impact of expenditures on education, research and development (R&D), and healthcare on GDP per capita in purchasing power parity terms. The analysis employs the pooled ordinary least squares (Pooled OLS), fixed effects (FE), and random effects (RE) models. The Hausman test ($\chi^2(3) = 13.50$; $p = 0.0037$) confirms the fixed effects model as a consistent estimator. The results indicate that R&D expenditures have a statistically highly significant positive effect on GDP per capita ($\beta = 0.254$; $p < 0.001$), supporting hypothesis H2. Healthcare expenditures also exhibit a positive effect in the FE model ($\beta = 0.045$; $p = 0.031$), confirming H3. In contrast, education expenditures do not show a short-term positive effect within countries, and thus H1 is not supported. The average development gap between Western Balkan countries and their EU neighbors amounts to approximately USD 13,184 per capita annually (PPP, 2021 prices). The paper provides an empirical basis for formulating policies aimed at reducing the development gap through strategic investments in innovation and healthcare.

Keywords: human capital, economic growth, Western Balkan countries.

EXAMINATION OF THE STRATEGY OF HUNGARIAN YOUTH FOOTBALL ORGANISATIONS

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ABSTRACT

Youth education is of strategic importance for sport enterprises, as it contributes to long-term sustainability and competitiveness. A well-designed youth program supports the identification and development of talent, while the strategy adopted by sports organizations influences both athlete development and the long-term operation of the organization.

The research examined the entire vertical of Hungarian youth football. A well-structured strategy supports the efficient allocation of resources, the professional and infrastructural development of athletes, and the integration of home-grown players into adult teams. It can also contribute to economic stability by reducing transfer costs, supporting diversified sources of income and increasing the attractiveness of organizations to sponsors and investors.

The results highlighted that talent development, and training strategies differ between academies and lower-ranked organizations. The sample also revealed limited employee involvement in setting strategic goals, which may reduce employee engagement and the effectiveness of strategy implementation in practice.

INTRODUCTION

A comprehensive and well-developed strategy covering a number of key areas is essential for the success of youth sports organisations. These include talent management and selection, coaching methodology, economic sustainability, relationships and cooperation, education and mental development, and performance evaluation and career management.

A science-based approach to talent management and selection is important, taking into account the physical, technical, tactical and mental characteristics of athletes. This allows the development of long-term development plans adapted to the individual needs and pace of

development of the athletes. In Hungarian football, for example, youth training plays a key role in the development of the sport, where the identification and development of talent is essential [1].

In order to be economically sustainable, sports organisations need to diversify their sources of income, for example through sponsorships and tenders. In addition to the introduction of self-financed training models, it is also important to plan long-term investments, including the development of infrastructure and the continuous training of coaches [1]. In Hungarian football, the TAO support system plays a significant role in the financing of youth football, contributing to the development of the sport [2].

In terms of contacts and cooperation, close links with professional clubs and national federations help to provide career opportunities for talent. Building international relationships, such as organising training camps and competitions abroad, enriches the experience of athletes and enhances the reputation of the organisation. In addition, strengthening community relations and increasing media presence helps to expand the fan base and the circle of supporters [1].

In the field of education and mental development, dual career support is key to ensure that athletes can successfully pursue both their education and their sporting activities. Mental coaching and psychological support helps athletes to cope with competitive situations and maintain mental health. Life coaching also prepares them for the challenges of life off the field [3].

Another important area for follow-up and performance assessment is the use of data-driven decision making and continuous feedback systems to monitor athletes' progress. This allows for the continuous optimisation of training programmes and development plans, as well as supporting athletes' long-term career development [4].

Talent management and youth training play a key role in increasing the market value of players. The aim of the academy programme, initiated by the Hungarian Football Association, is to support the operation of domestic football academies and elite youth training organisations through in-depth situation analysis and diagnosis, thereby promoting the effective development of talent. Well-trained young players not only contribute to the professional success of clubs, but also represent a significant source of revenue through their subsequent sale [5].

As highlighted by the European Club Association study of youth football sport organisations, the ideal strategy for clubs to build relationships and collaborate with other clubs involves several key elements [6]. These include the optimisation of organisational structures, the integration of talent management and training processes, and the joint implementation of professional and infrastructural improvements

When optimising the organisational structure, it is important that the youth sports organisations operate as a business entity, which allows for more efficient management and better use of resources. Research by Szalánczi (2024) shows that sports sport organisations in the Hungarian pyramid system and in different categories can adapt more flexibly to changing circumstances and can more easily develop partnerships with other clubs [7].

Youth football strategies should address not only physical and technical development but also education, psychological well-being and preparation for life beyond sport. Dual-career support, mental preparation and career planning can help young athletes balance sporting and educational demands and adapt to transitions within and beyond professional football [8], [9].

METHODS USED

The study employed a quantitative questionnaire survey, as this approach enables the efficient analysis of data collected from a relatively large sample [10]. The design of the questionnaire was greatly aided by the use of the UEFA strategy for youth development by North [11], and the analysis of sport academies by Van Hoecke et al. and Double Pass [12], [13]. The aim of the research was to touch on key themes that help to explore the strategic vision of organisations. The questionnaire used in this research employed a five-point Likert scale.

The questionnaires were sent to the appropriate target groups after consultations with the State Secretariat for Sport of the Ministry of Defence and the Hungarian Football Association. A total of 326 respondents participated in the survey, which shows a high participation rate compared

to the target population. Respondents were exclusively drawn from the staff of organisations belonging to the three main training levels of the youth development system - Academies, Talent Centres and District Centres. The questionnaires were filled in by 175 staff from the academies, 79 from the talent centres and 72 from the district centres.

The survey was open to staff members who had an active employment contract with an academy, talent centre or district centre. The questionnaire was sent by e-mail, with the assistance of the National Sports Agency, to the heads of the institutions, who forwarded it to the employees.

RESULTS AND DISCUSSION

The data in the table shows that the perceptions of employees in sport organisations reflect the specificities of the talent selection and recruitment system in different types of organisations.

Table 1. Employees' evaluation of the selection process in the sports organisation (n=326)

Viewpoint	Overall sample mean	Average by classification of organisations		
		Academy	Talent Centre	District Centre
All players in the sports organisation's teams have the potential for a professional career	2,437	2,651	2,244	2,125
The sports organisation selects talent based on guidelines and profiles.	3,465	3,720	3,346	2,972
The selection and recruitment of talent works well in the sports organisation.	3,575	3,629	3,603	3,417
There are talented young people who are not selected.	2,772	2,834	2,872	2,514

Source: own editing (2025)

On the first criterion, which asks whether all players in the teams of the sports organisation have the potential for a professional career, respondents overall disagree with this statement (mean: 2.437). Those working in academies (2.651) see this as slightly more likely, while those working in district centres (2.125) are less realistic about the possibility of all players reaching professional level (Table 1). This suggests that at higher levels of the organisation, where selection is more rigorous, there is more confidence that players have a chance of a professional career.

The second aspect looks at how talent selection works according to guidelines and profiles. The overall average (3.465) suggests that this process is typically carried out along guidelines in sports organisations, although there is considerable variation. Employees in academies (3.720) believe that selection is structured and based on predefined principles, while employees in district centres (2.972) perceive it to be less so. This may suggest that the higher the level of a sports organisation, the more elaborate and conscious the talent selection process.

The third criterion, which assesses the effectiveness of talent selection and recruitment, received the highest average score (3.575), indicating that the majority of employees believe that this process is basically working well. Employees in academies (3.629) and talent centres (3.603) showed slightly higher satisfaction, while employees in district centres (3.417) perceive the system as slightly less effective. This is in line with the fact that organisations with more human resources and a broader structure use more sophisticated selection methods.

The final aspect looks at whether talented young people are being left out of the selection process. The overall average (2.772) shows that respondents somewhat agree with this statement. Employees in talent centres (2.872) are most likely to feel that there are young people who are being left out of the system, while this is less likely to be the case in district centres (2.514). This may suggest that the selection process needs to be improved, regardless of training classification.

Table 2. Analysis of drop-out rates in sport organisations by employees (n=326)

Viewpoint	Overall sample mean	Average by classification of organisations		
		Academy	Talent Centre	District Centre
Are there young people who are "lost" in training?				
Yes	89,23%	89,14%	85,90%	93,06%
No	10,77%	10,86%	14,10%	6,94%

Source: own editing (2025)

The responses (Table 2) of the employees of the sports organisations clearly show what they consider to be the priorities for player development.

Table 3. Employees' definition of the goals of the sports organisation (n=326)

Viewpoint	Overall sample mean	Average by classification of organisations		
		Academy	Talent Centre	District Centre
The aim of the sports organisation is to ensure that the player is professionally prepared for a professional career in sport	4,236	4,600	4,089	3,514
The aim of the sports organisation is to prepare the player for civil life after a career in sport (professional qualification)	3,862	4,029	3,823	3,500
The aim of the sports organisation is to prepare the player for integration into society (not only to be a good athlete, but also to be a good person)	4,460	4,451	4,456	4,486

Source: own editing (2025)

The sports organisation's objective of professional training is clearly being achieved (4,236), especially in the academies (4,600), where this is considered a priority. This is understandable, since the academies' main task is to prepare young people for a professional career in sport. This score is slightly lower in talent centres (4.089) and lowest in district centres (3.514), suggesting that the focus is less on elite sport and more on making people love sport (Table 3).

The second aspect assesses the preparation of players for civil life. Employees in academies (4.029) and talent centres (3.823) attach slightly higher importance to this, while in district centres (3.500) this value is the lowest. This suggests that the time spent at the lower levels does not yet give priority to preparing players for civilian life at an earlier age.

The highest average score (4.460) was given to the aspect that the sports organisation aims to help people integrate into society. Values are relatively balanced across organisations, with employees at academies (4.451), talent centres (4.456) and district centres (4.486) all saying that it is important for players to be not only sportspeople but also useful members of society. The fact that this score is extremely high in all categories shows that educational aspects beyond the world of sport are equally important in sports organisations.

The following table shows the extent to which employees in sport organisations perceive the awareness and structure of development processes.

Table 4. Employees' perception of the training strategy of the sports organisation (n=326)

Viewpoint	Overall sample mean	Average by classification of organisations		
		Academy	Talent Centre	District Centre
It is clear what style of play the teams of the sports organisation want to play	3,992	4,197	3,842	3,655
The sports organisation has a clear vision for player development	4,087	4,299	3,754	3,914
I know the development guidelines of the sports organisation	4,095	4,190	3,772	4,190
Coaches are aware of how to teach and train players (sports pedagogy, sports psychology)	3,730	3,796	3,719	3,586
A formalised career plan for talented players from the sports organisation to the adult team	3,373	3,642	3,105	3,000
Upward flow works properly	3,619	3,759	3,316	3,586
How consistent do you think your sports development programme is with the philosophy of the sports organisation?	3,969	4,008	3,898	3,942

Source: own editing (2025)

In terms of clear ideas about the style of play, the overall sample mean is 3.992, which is a relatively high value. For academies (4.197) this is clear, while the lower score for district centres (3.655) indicates that there is less clarity about the policy on the style of play of the teams (Table 4).

The existence of a vision for player development also received positive feedback (4.087), especially in academies (4.299). This suggests that a more detailed and elaborated development concept is available in higher level organisations, while it is less formalised in talent centres (3.754) and district centres (3.914).

Knowledge of development guidelines shows a mean score of 4.095 across the whole sample, which is the same for academies (4.190) and district centres (4.190). This suggests a relatively uniform level of awareness in this area, although the score is slightly lower for talent centres (3.772), which may indicate that the guidelines are less clear there.

Coaches' awareness of sports pedagogy and psychology (3.730) tends to be higher in academies (3.796) and talent centres (3.719), while it is slightly lower in district centres (3.586). This may indicate a greater emphasis on training coaches and employing specialists in academies and talent centres, but it also clearly raises financial differences.

The existence of a formalised career path for talented players shows an average value of 3.373, one of the lowest values of all the criteria analysed. The academies (3.642) have a better structure, while the district centres (3.000) have the least structure. This may suggest that in smaller organisations there is less opportunity for progression through the formal training system, with no output of training towards a professional adult team. The overall sample rated the proper functioning of upward flow with a mean of 3.619. This process is more noticeable in academies (3.759), while it is less pronounced in district centres (3.586).

Alignment between the sports development programme and the philosophy of the sports organisation scored one of the highest (3.969). Academies (4.008) and talent centres (3.898) scored slightly lower, while the sense of alignment was similarly strong in district centres (3.942). This may suggest that each type of organisation tends to adopt a development strategy in line with its own philosophy.

The data in the following table show how employees of sports organisations assess the role of their own organisation in the development of Hungarian football, their sustainability and the goals of their educational work.

Table 5. Employees' perception of the strategy of the sports organisation (n=326)

Viewpoint	Overall sample mean	Average by classification of organisations		
		Academy	Talent Centre	District Centre
The sports organisation contributes to raising the standard of the Hungarian adult championship	4,064	4,366	3,823	3,597
The sports organisation contributes to the international competitiveness of Hungarian football	3,929	4,343	3,532	3,361
The sports organisation is open to all talented players in the region	4,417	4,434	4,316	4,486
The long-term sustainability of the sports organisation depends on the continuity of public support	4,147	4,217	3,911	4,236
The most important task of the sports organisation is to identify and train talented players of junior age	4,488	4,617	4,354	4,319
The most important task of the sports organisation is to "produce" professional footballers, which ensures the economic success of the sports organisation	3,776	4,183	3,557	3,028

Source: own editing (2025)

According to respondents (Table 5), the contribution of sporting organisations to raising the standard of the Hungarian adult league is relatively strong (4.064), but academies perceive this the most (4.366), while district centres have the lowest (3.597). This is due to the fact that the majority of academies are the base of a professional first division team, while talent and district centres typically have amateur adult teams.

The contribution to international competitiveness scores lower (3.929), with academies (4.343) scoring highest, while district centres (3.361) score lower. This shows that smaller organisations see themselves less as building blocks for international success.

Accessibility to talented players was one of the highest scores (4.417) and is felt to be particularly strong in district centres (4.486), which is logical given the important role these centres play in attracting young talent to the region.

Dependence on public subsidies for long-term sustainability scores relatively high (4.147), and is perceived most strongly in district centres (4.236). This suggests that smaller sports organisations are particularly dependent on the continuity of public funding.

Organisations consider the identification and training of talented youth players to be the most important task (4.488), especially in academies (4.617), where youth education, the basis of professional football, is given a high priority. In contrast, the 'production' of professional footballers and ensuring economic success are less of a priority (3.776). This is high for academies (4.183) and particularly low for district centres (3.028), indicating that at lower levels, the main

objective is not primarily commercial success or training professional players, but rather laying the foundations for the sport.

The table below shows that employees in sport organisations are relatively well aware of their organisation's long-term and short-term strategies, but their involvement in planning these is rated lower.

Table 6. The strategic planning process of a sports organisation (n=326)

Viewpoint	Overall sample mean	Average by classification of organisations		
		Academy	Talent Centre	District Centre
I know the long-term strategy of the sports organisation	4,101	4,137	3,873	4,264
I know the short-term (annual) action/professional programme of the sports organisation.	4,359	4,354	4,203	4,542
The organisation has been involved in the planning of these objectives	3,321	3,160	3,202	3,861
The sports organisation has set realistic goals	4,160	4,160	3,987	4,347

Source: own editing (2025)

For long-term strategic knowledge, the overall sample average is 4.101, indicating that the majority of respondents are aware of the organisation's vision (Table 6). This score is highest in district centres (4.264) and lowest in talent centres (3.873), which may suggest that strategic communication is clearer in smaller centres or more accessible to employees due to a shorter communication chain created by smaller human resources. Knowledge of short-term, annual professional programmes scored even higher (4.359), and is felt to be particularly important in district centres (4.542). This may suggest that employees in lower level organisations have a better insight into day-to-day operations, while in larger organisations this is less evident.

However, employee involvement in planning the organisation's objectives scored significantly lower (3.321) and is moderate (3.160), especially in academies, but higher in district centres (3.861), which may suggest that in smaller organisations, staff are more likely to be consulted or involved in decision-making.

The reality of the goals set by sports organisations was rated positively by respondents overall (4.160), with the highest score again for district centres (4.347). This may suggest that the goals set are perceived as more achievable in lower level organisations, while in larger centres they may be perceived as more ambitious.

The data from the study show that the vast majority of sports organisations have domestic cooperation agreements, while foreign links are much less common, especially in lower level organisations.

Table 7. National and international cooperation of sports organisations (n=258)

Viewpoint	Overall sample mean	Average by classification of organisations		
		Academy	Talent Centre	District Centre
Does the organisation have formal cooperation agreements with national sports organisations?				
Yes	92,16%	95,83%	83,33%	84,21%
No	7,84%	4,17%	16,67%	15,79%
Does the organisation have formal cooperation agreements with foreign sports organisations?				
Yes	46,51%	70,42%	22,03%	12,28%
No	53,49%	29,58%	77,97%	87,72%

Source: own editing (2025)

For domestic partnerships (Table 7), 92.16% of the total sample indicated that their organisation has formal cooperation agreements. This percentage is highest for academies (95.83%), while it is slightly lower for talent centres (83.33%) and district centres (84.21%). This indicates that academies play a prominent role in the national sports professional network and are better embedded in the national system.

However, there are significant differences in terms of cooperation abroad. Just 46.51% of the total sample reported having such partnerships. The academies stand out in this respect, with 70.42% of them having foreign agreements, compared to only 22.03% of talent centres and 12.28% of district centres. This suggests that the maintenance of international relations is primarily the prerogative of academies, while it is more difficult for lower-level sports organisations to cooperate with foreign clubs.

CONCLUSIONS AND PROPOSALS

Based on the research, several important areas can be observed in the work of Hungarian youth sports organisations. Overall, talent selection and development is working effectively, especially in academies, where these processes are rated the highest. However, the perception is less positive in the district centres, suggesting that talent management is less organised or effective. It would therefore be a priority to focus more attention on standardising the selection and development of talent, particularly in the case of district centres, where the ratings were lower. To this end, the development of standardised guidelines and their consistent application could help to increase efficiency.

In terms of the objectives of the organisations, the most important task is the training of youth players, while the development of professional footballers is less emphasised as a factor for economic success. At the same time, the long-term sustainability of sports organisations is seen as heavily dependent on the continuity of public funding, which clearly poses a risk for the future. It would be important for organisations to develop alternative sources of income to ensure economic stability, for example through sponsorship partnerships, international networking or better market positioning of youth training.

Employees are generally aware of the development guidelines and short-term professional programmes of organisations, but are less involved in strategic planning. This is particularly the case in academies where, although many are aware of the long-term strategy, employee participation in the development of objectives is lower. Taking account of staff experience and suggestions could improve decision-making processes and strengthen commitment to organisational goals.

Partnerships with national sports organisations are almost ubiquitous, with a particularly high proportion of academies. However, there are significant differences in terms of cooperation abroad: while the majority of academies have links with international organisations, such cooperation is almost non-existent in talent centres and district centres. This suggests that smaller centres are less able to engage with the international sporting scene, which could be a long-term handicap for their development. It would also be important for lower-ranked organisations to seek to develop partnerships with foreign sporting organisations, which could provide opportunities for professional development, international experience for players and increased competitiveness of domestic football.

Finally, more emphasis should be placed on preparing athletes for life off the field, especially in district centres where this is less of a priority. The provision of post-career opportunities (e.g. through vocational training) could contribute to improving the long-term career and quality of life of athletes.

These steps can help Hungarian sports organisations to operate more efficiently, be more competitive at international level and ensure the long-term success of both players and organisations.

SUMMARY

Feedback from employees shows that selection and recruitment is effective, but the system is not structured in the same way everywhere. Employees in the academies perceive the processes as most conscious and policy-driven, while in the district centres the structure is less visible. At the same time, some talented youngsters are not included in the selection system, according to respondents, suggesting that although the processes work well, there may be players who do not have the opportunity to prove themselves.

In terms of training and education, those working in academies perceive the most thoughtful and structured processes for sport development, while in district centres the guidelines are less clear in some areas. However, the formalisation and upward flow of the youth system at all levels offers scope for further improvement. The data show that the main priority is to promote the social integration of players, while preparation for a professional sporting career is also a priority, but tends to be more focused in academies. Training for civil life after sport is the least emphasised, which may suggest that there is room for improvement in this area.

The strategic theme revealed that academies feel that they have the greatest impact on both Hungarian and international football, while regional centres are more likely to provide access to talent in the region, but at the same time have a stronger need for state support. While proper training and education is the primary objective at all levels, the economic development of professional players is less dominant, especially at lower levels, which could cause sustainability problems in the long term if any reduction in aid intensity occurs.

An examination of organisational communication and planning revealed that employees are well informed about the strategy and operations of sport organisations, but their involvement in planning objectives varies significantly between organisational levels. In the district centres, employees feel most involved in decision-making and objectives seem more realistic to them, while in the academies, participation is more limited.

As far as partnerships are concerned, overall, cooperation with domestic sports organisations is dominant at almost all levels, but relations with foreign organisations are mostly limited to academies. For smaller organisations, building international links remains a major challenge, which may also affect player development.

Overall, the work of Hungarian sports organisations is characterised by both strengths and areas for improvement. Talent management, professional programmes and domestic cooperation work well, but further efforts are needed to improve long-term sustainability, strategic planning and international relations.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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SUBSIDIES AND STRUCTURAL TRANSFORMATION IN SERBIA: IS A PARADIGM SHIFT IN INDUSTRIAL POLICY WARRANTED?

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ABSTRACT

This paper analyzes the impact of Serbia's subsidization policy during 2015–2025 on the structural transformation of the economy. Subsidies in Serbia have been widely used as tools of industrial and fiscal policy aimed at increasing employment, attracting foreign direct investment and supporting domestic sectors. Integrating industrial policy theory, political economy and structural transformation frameworks, the study evaluates whether the current subsidization model has led to a shift toward high-productivity, technologically advanced sectors, or merely sustained a low-cost, investment-dependent growth pattern. The analysis indicates that subsidies have produced short-term gains in employment and investment but have not significantly enhanced long-term productivity or structural change. Additionally, the fiscal burden of subsidies remains considerable, and institutional mechanisms lack transparency and systematic impact evaluation. The paper concludes that reform of the subsidization model is warranted — toward productivity-linked, innovation-oriented support that fosters domestic value chains. Policy recommendations include shifting from employment-based subsidies to productivity-conditioned instruments, instituting rigorous ex-post evaluations, and strengthening domestic supplier networks.

Keywords: subsidies, industrial policy, structural transformation, fiscal policy, FDI, development strategy

INTRODUCTION

Subsidies are among the most important—and most controversial—instruments of economic policy in contemporary states, particularly in transition economies such as Serbia. Between 2015 and 2025, Serbia intensified support for economic activity through direct financial incentives, tax relief and measures designed to attract foreign direct investment (FDI). The central issue is

whether this policy facilitated a transition towards high-productivity and technologically advanced activities or merely sustained a growth model based on low labour costs and externally financed investment.

The arrangement agreed with the International Monetary Fund (IMF) in 2024 placed particular emphasis on macroeconomic stability, fiscal discipline and reforms supportive of sustainable growth. Under the subsequent Policy Coordination Instrument, Serbia committed to keeping the fiscal deficit at no more than 3 per cent of GDP during 2025–2027, while preserving priority expenditure, including public investment [1]. Although the arrangement does not call for the abolition of subsidies, it strengthens the case for assessing whether individual measures generate sufficient economic and social returns. Expenditure that does not improve productivity must be weighed against investment in infrastructure, education and innovation.

Available evidence also requires careful interpretation. State aid includes not only direct subsidies but also tax incentives and other support measures. Lutovac Đaković and Anić report that state aid in Serbia was generally higher relative to GDP than in the European Union during the period preceding the pandemic and increased sharply in 2020. By comparison, state aid in the EU rose from 0.92 per cent of GDP in 2019 to 2.36 per cent in 2020 and subsequently declined to approximately 1.1 per cent in 2023 [2]. These figures demonstrate both the exceptional effect of crisis support and the need to distinguish total state aid from direct budget subsidies.

This paper therefore asks whether Serbia's subsidy system during 2015–2025 produced substantive structural transformation and whether the existing model should be changed. The analysis brings together industrial-policy theory, political-economy arguments, academic studies and selected policy and budget documents. It is primarily qualitative and interpretative; it does not claim to identify the causal effect of subsidies through an original econometric model. The working proposition is that employment- and investment-based incentives can produce short-term gains, but will not generate sustained productivity growth unless they are linked to technological upgrading, knowledge transfer, domestic supplier development and credible performance evaluation.

THEORETICAL FRAMEWORK

Subsidies and Industrial Policy

The literature commonly considers subsidies in two principal ways: as an instrument of industrial policy and as a potential source of market distortion. From the first perspective, selective support may be justified when it helps infant industries overcome coordination failures, acquire capabilities and move towards activities with higher productivity and competitiveness [3]. Modern industrial-policy theory nevertheless treats support as an experimental and disciplined process. Assistance should be conditional on observable performance, limited in duration and withdrawn when beneficiaries fail to meet agreed objectives [4].

The opposing view emphasises government failure. Selective assistance may direct resources away from their most productive use, encourage rent seeking and create a "picking winners" problem because public authorities cannot reliably identify firms that will become competitive [5]. Such risks are particularly pronounced in transition economies with weaker institutions, limited disclosure and insufficient ex-post scrutiny. The relevant policy choice is therefore not simply between intervention and non-intervention, but between poorly governed support and a transparent, conditional system capable of learning from both successful and unsuccessful measures.

The conceptual model used in this paper separates policy inputs, transmission mechanisms and final outcomes. Fiscal subsidies, tax incentives and other forms of state aid can influence FDI and employment directly. Their developmental value, however, depends on intermediate mechanisms - technology transfer, the acquisition of skills and the integration of domestic suppliers. Only when these mechanisms operate can short-term investment contribute to productivity, structural transformation and fiscal sustainability (Figure 1).

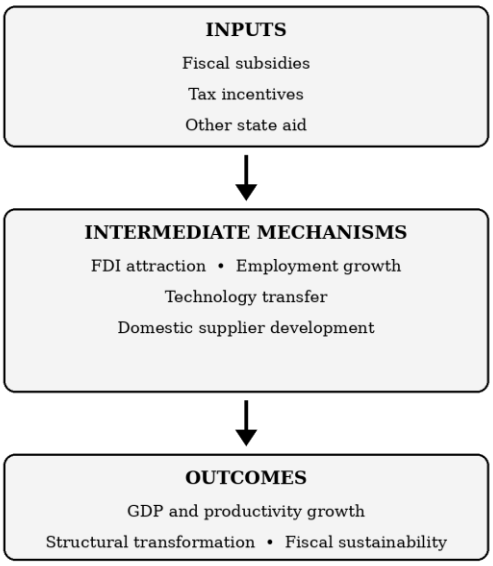

Figure 1. Conceptual framework of the study
Source: Authors' conceptualisation

The model implies an efficiency threshold. Where spillovers, domestic linkages and performance evaluation are absent, subsidies may stimulate investment and employment temporarily without changing the productive structure. In that situation, the fiscal burden can rise while the economy remains dependent on labour-intensive activities. A future quantitative study could test this proposition using sectoral productivity, export sophistication, domestic value added and the participation of Serbian firms in supplier networks.

Structural Transformation

Structural transformation denotes the reallocation of labour and capital from low-productivity activities to sectors with higher productivity and value added. It is a central condition of sustainable long-term growth and generally requires investment in research and development, human capital and technological upgrading. Relevant indicators include the technological composition of exports, domestic value added in production and the depth of local supplier networks.

Ćorović, Gligorijević and Manasijević find that Serbia achieved macroeconomic stabilisation and export growth during the first two decades of the twenty-first century, but that structural transformation remained incomplete because of weak productivity, low technological intensity and an insufficiently developed high-value-added sector [6]. Subsidies in transition economies may consequently serve both a stabilising purpose, by preserving employment, and a developmental purpose, by attracting capital. These objectives are not equivalent. Delević's municipal-level analysis shows that FDI incentives increased employment within subsidised firms but did not produce a statistically significant broader effect on local employment [7].

SUBSIDY POLICY IN SERBIA: A RETROSPECTIVE, 2015–2025

Scale and Structure of Subsidies

Serbian subsidies are distributed through several channels, ranging from agricultural payments and support for public enterprises to financial incentives for companies opening production facilities. Although it falls just outside the period examined, the 2026 budget illustrates the continuing scale of this policy: RSD 214.46 billion was planned for subsidies, with almost half allocated to agriculture [8]. The composition of expenditure therefore matters as much as its

aggregate value, because different instruments pursue different social, regional and industrial objectives.

A prominent feature of Serbian investment policy has been the use of substantial incentives to attract foreign investors. This approach can expand production and employment, yet it can also favour large firms and projects based on labour-cost advantages. Medić argues that the interaction of corporate taxation and subsidy policy has contributed to an uneven investment environment in which domestic private investment remains weak relative to FDI [9]. The relevant assessment should therefore consider not merely the number of supported projects and jobs, but their technological content, duration and links with domestic enterprises.

Effects on Economic Structure and Structural Transformation

Employment generated by subsidised FDI is an important benefit, especially in areas with limited job opportunities. However, project-level employment is not synonymous with structural transformation. When supported firms import most inputs, perform mainly assembly operations and create few links with domestic producers, the effect can remain confined to the beneficiary. Development then risks becoming locked into a peripheral structure instead of progressing towards diversified activities with higher value added. Hausmann and Rodrik emphasise that development requires learning about productive capabilities; policy should therefore reward discovery and capability building rather than the indefinite maintenance of existing activities [10].

The Serbian evidence points to limited spillovers. Delević finds a positive effect on employment in subsidised enterprises, but no corresponding increase in wider local employment [7]. This distinction suggests that the effect has been predominantly quantitative—the creation of supported jobs—rather than qualitative, through technology, productivity and supplier development. The policy problem is not that labour-intensive investment has no value, but that assistance based only on job numbers can preserve a low-cost assembly model unless it is accompanied by training, research collaboration, local procurement and measurable technological upgrading.

Fiscal Effects

From a public-finance perspective, subsidies are justified only when their long-term social return exceeds their direct and opportunity costs. If support does not create durable externalities, it becomes a recurring fiscal burden. The relatively high level of state aid identified by Lutovac Đaković and Anić reinforces the need for transparent selection criteria and systematic evaluation [2]. IMF fiscal commitments add a further constraint: within a deficit ceiling, poorly performing subsidies compete directly with public investment and other priority expenditure [1].

The distribution of incentives also affects domestic investment and regional development. Medić finds that subsidy and tax arrangements may disproportionately benefit large and foreign investors while failing to remove key barriers faced by domestic firms [9]. Uvalić and Bartlett likewise document persistent regional disparities in Serbia and stress the limited effectiveness of regional-development policy instruments [11]. Consequently, the fiscal assessment of subsidies should include additionality, cost per sustainable job, productivity effects, domestic procurement and regional spillovers—not merely the announced value of an investment.

Institutional and Political Framework

Institutional quality determines whether selective support corrects market failures or creates new distortions. In Serbia, detailed and comparable ex-post evaluations are not routinely available for every programme or project. This limits the ability of public authorities, researchers and citizens to determine whether promised employment, investment, training and technology-transfer obligations were fulfilled. It also increases the risk of rent seeking described in the government-failure literature [5].

A regional study by Petreski et al. identifies weaknesses in the transparency, targeting and monitoring of state aid across the Western Balkans [12]. For Serbia, reform should therefore

establish a public register with comparable project data, predefined performance indicators, counterfactual impact evaluation and recovery clauses where commitments are not met. Independent ex-post assessment should be incorporated into the policy cycle, and future assistance should reflect verified results rather than the continuation of established programmes by default.

Directions for Reform

The first direction of reform is to replace predominantly input-based conditions with outcome-based criteria. The amount of capital invested and the number of jobs announced are easy to observe, but they reveal little about the quality and durability of the supported activity. Eligibility and payment schedules should also reflect productivity growth, the share of skilled employment, certified training, research and development expenditure, export sophistication and the proportion of inputs purchased from competitive domestic suppliers. Indicators must be tailored to the sector, defined before support is granted and verified over a period extending beyond the minimum contractual term.

Second, the additionality of public support should be demonstrated. A subsidy creates value only if it induces investment, employment or technological upgrading that would not otherwise have occurred. This requires a documented assessment before approval and a credible counterfactual evaluation afterwards. Similar supported and unsupported firms, regions or projects can be compared where data permit. Results should be reported as ranges and accompanied by methodological limitations, since a simple comparison of outcomes before and after a grant may mistakenly attribute wider economic trends to the subsidy itself.

Third, policy should strengthen connections between foreign investors and the domestic economy without imposing inefficient local-content requirements. Supplier-development programmes can help Serbian small and medium-sized enterprises meet quality, certification, delivery and digitalisation standards demanded by multinational companies. Incentives may reward verified supplier mentoring, joint training, research partnerships and domestic procurement achieved through open and competitive processes. Such measures would convert the presence of foreign firms into an opportunity for capability formation instead of treating the initial investment as the final policy outcome.

Finally, governance safeguards should apply throughout the life cycle of support. Decisions should disclose the legal basis, selection criteria, expected benefits and maximum fiscal exposure, while protecting legitimately confidential commercial information. Contracts should contain proportionate clawback clauses, and evaluations should be published in a standard format that permits comparison across programmes and years. Periodic spending reviews can then redirect resources from measures with weak additionality towards innovation, skills, infrastructure and other public goods that benefit a wider group of firms.

Evaluation Framework and Limitations

A practical evaluation framework should distinguish relevance, efficiency, effectiveness, impact and sustainability, consistently with the established OECD/DAC evaluation criteria [13]. Relevance concerns whether an intervention addresses a demonstrated market or coordination failure. Efficiency compares verified results with the full fiscal cost, including tax expenditure and administrative costs. Effectiveness measures compliance with contractual objectives, while impact asks whether observed changes were caused by support rather than by macroeconomic conditions or firm characteristics. Sustainability examines whether employment, productivity and supplier relationships continue after the assistance expires. Treating these dimensions separately would prevent the number of announced jobs from becoming a substitute for a comprehensive assessment.

Data architecture is equally important. A unique project identifier should link the decision granting aid, the contract, budget execution, tax expenditure, employment records and subsequent monitoring. Aggregate reporting alone cannot reveal concentration among beneficiaries, repeated support, regional distribution or the difference between authorised and actually paid aid.

Publication in a reusable format would enable independent analysis while anonymisation and clearly defined exceptions could protect personal data and legitimate business secrets. Consistent time series would also permit comparison between instruments and reduce the risk that programme redesign obscures poor historical performance.

The sequencing of reform should reflect administrative capacity. Serbia could first standardise contracts, indicators and reporting across existing programmes; it could then pilot counterfactual evaluation in sectors with sufficient firm-level data; and finally integrate evaluation results into future budget decisions. Immediate termination of all incentives would create uncertainty and could weaken legitimate development projects. A gradual transition, announced in advance, would instead allow investors and domestic firms to adapt to stronger productivity, training and supplier-development requirements.

The conclusions of this paper are subject to limitations. State aid, direct subsidies, tax relief and investment incentives are related but not identical categories, and published sources do not always apply them consistently. The available studies also differ in period, unit of analysis and outcome variable, which restricts direct comparison. The paper therefore identifies patterns and institutional implications rather than estimating a single net effect for the entire subsidy system. Further research should combine beneficiary-level fiscal data with employment, productivity, trade and ownership records and should assess heterogeneous effects by sector, firm size, region and type of support.

CONCLUSION

The analysis indicates that Serbia's subsidy policy during 2015–2025 generated short-term benefits in employment and investment, but did not provide convincing evidence of a broad transition towards technologically intensive, high-productivity activities. The principal weakness is not the existence of subsidies as such, but a model that places substantial weight on investment and job counts while giving insufficient attention to productivity, technological spillovers, domestic value added and long-term fiscal returns.

A paradigm shift is therefore warranted. Support should be time-limited, transparent and conditional on measurable productivity gains, worker training, technology transfer and domestic supplier participation. Mandatory ex-post evaluation, publication of project-level outcomes and credible recovery mechanisms would improve accountability. These reforms would enable Serbia to retain useful investment incentives while redirecting public resources towards a more innovative, domestically integrated and fiscally sustainable development model.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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DETERMINING THE IMPORTANCE OF PERFORMANCE INDICATORS FOR ANALYZING PRODUCTION SECTOR EFFICIENCY USING THE DEA METHOD – A CASE STUDY OF VENDOM COMPANY

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ABSTRACT

The efficiency of the production sector largely refers to the effectiveness of management practices in optimizing company performance while minimizing resources and costs, and it represents a key factor in determining productivity and the overall success of a company. Inefficient production and overall business operations do not only represent a waste of valuable time, but also significantly affect the company's market positioning, profitability, customer satisfaction, and the overall business image of the company. For the analysis of the production sector efficiency of the real company Vendom, operating in the metal industry sector, this paper applies the DEA method, or Data Envelopment Analysis, which is considered the most successful and most widely used non-parametric method for performance measurement and efficiency analysis. It is a data-based method for measuring the efficiency of complex entities that use diverse inputs to generate diverse outputs. Considering the availability of data, typical indicators were selected as input and output variables: material costs, labor costs, number of work operations, etc. (as the inputs), and total added value (as the output). Prior to selecting the input and output units, data preprocessing was conducted, and inputs and outputs were created as derived indicators by aggregating the corresponding basic cost or revenue indicators. The obtained correlation coefficients indicated a high degree of interrelationship among the selected variables, confirming the justification for applying the DEA method in efficiency analysis. The results showed that it is possible to improve the efficiency of the production sector for certain decision-making units.

Keywords: performance indicators, DEA method, production efficiency, efficiency analysis, case study

INTRODUCTION

The primary objective of every business is profit; therefore, it is logical that manufacturing companies continuously seek ways to reduce costs and increase earnings. All companies striving to improve profitability generally focus on two directions: producing a greater quantity of high-quality products and services without increasing costs, or improving efficiency and consequently employee productivity without the need to hire additional staff. The path toward improving company efficiency begins with an in-depth analysis of current operations. Internal measures, such as monitoring return on investment or analyzing profit margin trends, can help a company determine where its strengths and weaknesses lie in terms of achieving more efficient operations.

Company efficiency is the ratio between outputs (products/services) and inputs (labor, capital, materials), measuring how effectively a company utilizes resources to generate profit [1]. Among other aspects, business efficiency refers to reducing waste, simplifying processes, and maximizing output per unit of cost or time. Key metrics include inventory turnover, labor productivity, and operating margins, which are often improved through automation, better processes, and employee training.

Inefficient business processes cannot be viewed merely as wasted time; they may also burden company profitability, hinder the company's ability to satisfy consumer demand, and make it more difficult for employees to perform their tasks. Without proper management, small undetected issues may develop into serious problems which, in the worst-case scenario, can jeopardize the entire business operation.

Efficient companies maximize the use of their resources, transforming labor, materials, and capital into products and services that generate profit for the company. On the other hand, inefficient companies lack organization, which may slow down operations, cause losses of time and money, and negatively affect profitability. Efficiency is achieved through the proper identification and analysis of business performance indicators and through strategic actions based on such analysis.

Performance management is the process of ensuring that a set of activities and business results effectively and efficiently fulfills the objectives of an organization [2]. Depending on the level of management and planning, the focus may be placed on the performance of the organization, department, employee, or on the processes applied in carrying out specific tasks.

The measurement of the relative efficiency of business units (*DMUs*) can be conducted in several ways, and in this paper the DEA (*Data Envelopment Analysis*) method was used for this purpose. DEA is a non-parametric linear programming method in which similar inputs are used to produce similar outputs [3]. The DEA Method calculates the exact amounts of excess resources spent or lack of achieved results, which allows decision makers to define precise goals for optimization. Within the DEA approach, organizational units are defined as Decision-Making Units (DMUs). Efficiency, as one of the key business parameters, is measured as the relationship between achieved outputs and the inputs required for their realization. The advantage of this method lies in the fact that, in comparative efficiency analysis, it takes into account all relevant inputs and outputs regardless of the technology used for their transformation. This method identifies best practices (the efficiency frontier), enabling the comparison of efficient units, the identification of inefficient DMUs, and the establishment of targets for business improvement.

EFFICIENCY INDICATORS AND THE MEASUREMENT OF BUSINESS EFFICIENCY

Performance Indicators

There are various definitions of performance, and the definition itself differs from author to author; however, this concept most commonly refers to performance, achieved results, or accomplishments. Thus, the Oxford English Dictionary defines performance as a particular achievement, execution, implementation, or elaboration of something that has been done, that is, how well or poorly something functions [4]. Performance is also defined as the act or process of carrying out a task, action, etc., considering that the verb *perform* means to work or function well or poorly. Throughout the literature, scholars continuously emphasize that there is no standardized

or unique definition of performance, usually stating that it is a multidimensional concept. Regardless of this fact, Samsonova, after analyzing numerous definitions from authors from different regions, concluded that all definitions of performance measurement share one common characteristic: they are connected with two terms – effectiveness and efficiency. Effectiveness is viewed as an indicator of the degree to which objectives are achieved, while efficiency is an indicator of the resources consumed in order to achieve the targeted level of goal attainment [5].

Performance indicators are used in relation to concepts for which direct measurement is not always easily observable, despite continuous monitoring of developments that should lead toward the desired objective. Given this fact, performance indicators were designed as combined relevant quantified values that can be monitored over a certain period of time in order to obtain, as a final result, a partial metric of a particular action. Performance indicators can also be used for reporting functionality by measuring profitability within the commercial sector.

Since they relate to performance, that is, to the results of a process, performance indicators have always been important. The literature commonly states that the roots of performance management date back as far as 221 AD [6]. The importance of performance is linked to performance management, which was initially associated with the evaluation of individual performance. However, in the nineteenth century, during the Industrial Revolution and the introduction of mass industrial production, the focus shifted toward the management of organizational performance, which in most cases refers to operational efficiency and productivity.

Performance Management (PM) refers to the process of planning, monitoring, and improving the performance of individuals, teams, and organizations. Armstrong and Baron define performance management as a strategic and integrated approach intended to achieve sustainable organizational success by improving the performance of employees and enhancing the skills and capabilities of teams and individual contributors [7]. This process includes identifying performance objectives, measuring results, providing feedback, and managing performance development and improvement. It is a continuous and systematic process of improving organizational effectiveness by aligning employee performance with strategic business objectives. Instead of a single annual review, effective performance management involves continuous dialogue, goal setting, feedback, and development. Performance management focuses on how to achieve organizational goals through effective and efficient performance.

Since the management of performance indicators has proven to be productive, this business concept has become increasingly popular in modern times, meaning that companies recognize the need to measure and monitor their performance in order to make higher-quality decisions and improve their operations. Numerous studies testify to the popularity of these indicators. As stated by Ramić and Šabanić, research has shown that more than 90% of the world's most successful companies apply some form of key performance indicators in their operations [8].

When it comes to the production process and its improvement, there is a large number of performance measures and performance indicators that can be measured and monitored. Performance indicators represent a set of data collected through continuous monitoring of specific production activities, processes, or systems. Essentially, these indicators are highly important measures that monitor functioning, supervision, and control, that is, the overall management of activities, processes, and the system as a whole [9]. All performance indicators have both qualitative and quantitative functions, which need to be analyzed periodically, that is, checked to determine whether previously established objectives are being monitored and achieved. As the number of indicators measured for a particular performance increases, Atanasov states that the structure and complexity of measurement also increase; therefore, it is necessary to ensure that each indicator fulfills its intended purpose [10].

With regard to the number and structure of performance indicators that should be used in the production process within a company, they are not clearly defined and therefore vary from case to case depending on the purpose and intended use of the performance indicators. The most important aspect is that each performance indicator, that is, its value, can be compared with the values of performance indicators from similar companies, as well as with benchmark values. Therefore,

performance indicators are not particularly meaningful unless there is a defined objective toward which their value should strive.

Performance indicators are most commonly classified into one of four interconnected categories [6] (Savić, Martić, & Popović, 2022): (1) basic indicators; (2) derived indicators; (3) sets of indicators; and (4) performance measurement systems. Basic indicators are usually generated directly from databases and are synonymous with performance measures. For example, in manufacturing this may refer to the number of products produced, while in the sales sector it may refer to the number of products sold within a certain time interval. On the other hand, derived indicators represent a combination of two or more basic indicators (aggregation). Examples of derived indicators include productivity and technical efficiency as the ratio between outputs and inputs, or efficiency as the relationship between actual and benchmark values. A set of indicators is selected so as to represent and regulate a particular area or business process, while process management and coordination are carried out within the performance measurement system, which occupies the highest level in the hierarchy. Finally, the performance measurement system is responsible for coordinating indicators across different processes and functions, as well as aligning indicators from the strategic to the operational level [6].

According to Franceschini, most performance indicators can be associated with one of the following three types [11]: a) effectiveness – process characteristics indicating the extent to which process outputs correspond to requirements (whether the appropriate processes are being carried out); b) efficiency – process characteristics indicating the extent to which a process provides the required output with minimal resource costs (whether processes are carried out properly); c) customer focus – the extent to which customers/clients value the delivered performance.

On the other hand, certain authors [12] defined five basic criteria that performance indicators should satisfy: they should be precise and accurate, easy to understand, timely, action-oriented, and their implementation should not require costs that would represent a major burden for the company. Despite the fact that many performance measures satisfy these criteria, companies should not approach business process measurement merely for the sake of measuring something. On the contrary, based on established strategic goals, managers should focus on the most important (key) performance indicators, namely those that truly monitor output quality, process efficiency, and customer satisfaction. If there are too many performance measures, focus may be lost, resulting in unnecessary expenditure of time and various resources, especially financial ones [13].

By using performance indicators, companies can analyze the achieved progress in implementing strategic and operational goals through the framework provided by these indicators. Performance indicators also provide highly important insight into various aspects not only of production but also of the company's overall operations, enabling managers and all stakeholders to monitor progress and make timely and high-quality decisions based on such information. From all of the above, it is clear that selecting the best performance indicators is not easy, meaning that defining the criteria and selecting the performance indicators themselves represent a crucial step in measuring system performance.

Business Efficiency and Efficiency Indicators

Modern global economic reality is such that companies, in order to survive in the market, must possess the ability to efficiently manage their own resources and authorities and adapt to a constantly changing environment. This means that the management of a company must accurately assess the situation and anticipate market changes, because high-quality forecasting enables efficient development and the achievement of a certain competitive advantage. In accordance with such a way of thinking, companies in the new global economy are forced either to create projects adaptable to the environment or to seek business ideas that are ahead of the market and have a chance of survival. This requires operational flexibility and the ability to adapt or demonstrate creativity in business operations, which are elements that directly affect economic business efficiency. Under conditions of a changing environment, as Drucker states, companies seek methods that would guarantee them competitive advantage and development [14]. As a key

element of human and entrepreneurial development, serving self-fulfillment, the survival capability of modern society, and the degree of achievement of objectives, efficiency emerges as a central concept. Business efficiency is considered a factor affecting company competitiveness and represents the extent to which a company achieves its objectives [15].

According to most authors, efficiency consists of two basic components: technical efficiency, which reflects the ability to achieve maximum output from a set of inputs, and allocative efficiency, which reflects the ability to use inputs in optimal proportions considering their prices and production technology [16]. On the other hand, Trivedi defines business efficiency as the degree to which a company rationally allocates its limited resources in order to achieve predetermined goals, taking into account the limitations of the internal and external environment [17]. This means that business efficiency represents the ability to maximize results (revenues, products, services) while minimizing investments (time, effort, costs). More efficient operations affect profitability and long-term sustainability through process simplification, automation of repetitive tasks, and optimization of resource allocation. Consequently, business efficiency is one of the main indicators of the business success of every company, from which financial results, market positioning, and effects on customer satisfaction and engagement derive. It represents the result of the synergistic influence of many internal factors inherent to the company, as well as external mechanisms and conditions existing in the environment, thereby creating opportunities for development, benefit realization, and profit generation [18].

As the relationship between operational results (products/services) and invested resources (time, capital, labor), business efficiency also signifies the maximization of obtained value while minimizing waste and costs. This is achieved through process optimization, improvement of existing technologies or implementation of new technologies, and reduction of resource consumption in order to improve profitability.

Business efficiency directly affects profitability, growth, and sustainability because companies that continuously work on simplifying their processes can respond much faster to market changes, efficiently scale operations, and strategically allocate resources. Improving efficiency results in cost savings, better decision-making, and increased productivity, positioning the business toward long-term success.

Considering that the market economy, on the one hand, creates specific operational (managerial) conditions enabling companies to achieve their business objectives, while on the other hand imposing requirements that companies must fulfill in order to ensure the relative sustainability of their existence, it becomes clear how important business efficiency truly is. Based on the above, it is evident that one of the main business objectives is to improve operational efficiency; therefore, every step in this direction should begin with identifying the obstacles that slow down better business performance. Business efficiency can be achieved in several ways, although each of these approaches faces certain obstacles. One of the most common obstacles to improving operational efficiency is inherited operational processes. Namely, many companies believe that their growth and efficiency are directly linked to outdated processes. For example, there are still companies that rely on manual inventory recording and order processing. Such an approach not only results in significant time loss but also leads to frequent errors, such as overproduction or incorrect deliveries, which affect customer satisfaction and increase operational costs. It is clear that transitioning to an automated inventory management system could dramatically improve efficiency and, regardless of software acquisition costs, would prove to be an extremely profitable investment within a relatively short period of time.

Manual data entry, report generation, or invoice tracking have proven not only highly inefficient in modern business operations but also demotivating for employees. Such tasks are monotonous and reduce employee motivation and, consequently, productivity. Another issue related to business efficiency is poor and inefficient communication between departments, which creates fertile ground for confusion. For example, a sales department within a company may be unaware of changes in inventory, or a marketing team may launch a campaign without coordination with other departments. The lack of clear expectations, scattered information, and the

absence of smooth communication channels create delays, costly mistakes, and a poor work environment. In order to improve the business efficiency of a company, especially its production segment, it is often necessary to innovate existing business processes in order to achieve competitiveness. Any innovation process may encounter resistance from certain structures opposed to change. This type of resistance to change is not always malicious and often stems from fear of the unknown. It should be understood, as practice has shown, particularly in increasingly dynamic markets, that adherence to outdated methods hinders the implementation of solutions that could improve operational efficiency. Attitudes such as "we have always done it this way" block the adoption of new technologies, process optimization, and adaptation to constantly changing markets. Namely, in a dynamic business environment, flexibility represents the key to survival [19].

When it comes to business efficiency, another significant issue is the inadequate use of data. As important as it is to possess or obtain all necessary data, it is equally important to know how to use it properly. There are many companies that collect information in various ways and possess large amounts of data, yet lack the tools or expertise necessary to extract the information they currently need. The absence of an effective data analysis system prevents decision-making teams from identifying patterns, accurately predicting trends, and optimizing their strategies. In short, in the information age in which we live, knowledge and possession of information represent power and provide competitive advantage, provided that they are used properly and in a timely manner.

Measurement of Business Efficiency

The measurement of productivity and efficiency has always been and will continue to be of vital importance in a competitive business environment characterized by limited resources. The principles of the modern market and increasingly strong competition force companies to utilize all available resources in the most efficient manner possible. For this reason, performance and efficiency measurement and analysis represent important management tools that help companies determine the relationship between generated outputs and the inputs used, in order to improve their operations. Considering that performance indicators in manufacturing are key tools for measuring efficiency, productivity, and quality, and that they enable managers to make data-driven decisions, their significance is undeniable. The most important performance indicators in manufacturing include equipment efficiency, process time, product quality, and resource utilization. However, they are not easy to define, and even when developed, they may fail to indicate whether an organization operates on its production frontier, that is, efficiently.

In practice, various input and output indicators are used to create an efficiency index as their ratio, while the specific choice depends on the context in which efficiency is measured. For example, "for measuring economic efficiency, which relates to resource optimization, indicators such as the quantity of sold goods and production costs are used with the aim of achieving the highest possible output" [6].

Efficiency represents the ratio between two indicators, outputs and inputs, and it is easiest to determine in organizations that use only one input (costs, engaged resources, etc.) to produce one output (earnings, profit, revenue, etc.), according to the simple formula [6]:

$$Efficiency = \frac{input}{output} \qquad (1)$$

The above definition can easily be extended, particularly in situations where there are multiple homogeneous inputs and outputs expressed in the same value units, which can easily be reduced to a single input or output. Overall or production efficiency consists of two basic components: (1) technical efficiency and (2) allocative efficiency. Technical efficiency is viewed as the ability of a company to avoid or reduce production losses, that is, to produce as much output

as possible using a given quantity of inputs, or to produce the required quantity of output using the minimum amount of available resources. In the analysis of this type of efficiency, emphasis may be placed either on increasing outputs or reducing inputs. On the other hand, allocative efficiency refers to the ability of the observed entity to optimally combine inputs and outputs.

A highly important factor of technical efficiency is the so-called efficiency frontier, which represents a graphical presentation of the maximum production volume (output) that an economy or company can achieve using available resources (labor, capital, raw materials) and technology. There are several methods for obtaining the efficiency frontier curve based on input data, usually in the form of a function $y = f(x)$. If the analytical form of this function were known, measuring business efficiency would be simple. However, since in practice its form is generally unknown because only data on achieved output levels Y for certain inputs X are available for a number of similar organizations, parametric and non-parametric approaches are most commonly used in practice for evaluating the efficiency frontier.

The parametric approach is more frequently used for efficiency measurement. This approach requires imposing an analytical form of the function (regression equation or production function) that defines the relationship between independent and dependent variables [6]. In the parametric approach, the estimation of production function parameters is usually performed using regression analysis or linear programming, depending on how random influences are defined. On the other hand, the non-parametric approach is most commonly based on the so-called Farrell efficiency measure, according to which the efficiency frontier is formed by the best-performing units in the sample, while the remaining units are compared against that frontier. Farrell's efficiency measure represents the basis for measuring technical and allocative efficiency of production units (Data Envelopment Analysis – DEA) and was developed as a response to the inadequacy of partial indicators (productivity, economy) that cannot adequately encompass complex systems with multiple inputs and outputs.

DEA Method

The DEA method, is commonly described as the most successful and most widely used non-parametric method applied in efficiency analysis, performance measurement, and performance analytics. It is a data-based method for measuring the efficiency of complex entities that use diverse inputs to generate diverse outputs [6].

Using this method, which is based on linear programming, the relative productivity of decision-making units (DMUs) that use similar inputs to produce similar outputs is assessed, and deviations of less productive units are measured. In addition to this method, the parametric method known as Stochastic Frontier Analysis – SFA is also frequently used for efficiency measurement. Both approaches are based on comparing current performance with optimal performance located on the efficiency frontier [20].

Practice has shown that when there are multiple input and output indicators heterogeneous in nature (financial, technical, technological, environmental, social, etc.) and expressed in different units of measurement, it is extremely difficult to perform an accurate performance assessment. In such cases, it is not possible to draw high-quality conclusions regarding the level of success based solely on partial efficiency indicators that measure the effectiveness of individual resources, because their values generally move in opposite directions (minimization of undesirable indicators or resource values and maximization of desirable indicators, i.e., outputs). Farrell partially solved this problem by enabling the inclusion of multiple inputs and a single output, or multiple outputs and a single input, in the analysis. However, the simultaneous inclusion of multiple heterogeneous inputs in the process of generating multiple heterogeneous outputs was not possible within his analysis [6]. Farrell's significance lies in the fact that his work served as the basis for the efficiency analysis method known as Data Envelopment Analysis (DEA).

The DEA method was developed in 1978 by Abraham Charnes, William W. Cooper, and Edward Rhodes, and based on the initials of their surnames the basic CCR model was created. To this day, it remains the best-known DEA model and is based on Farrell's work on productivity

measurement. In 1984, these authors expanded their original method by introducing the BBC model, which enabled efficiency analysis under variable returns to scale. A further extension was introduced in 1985 by Banker, Charnes, and Cooper through the BCC model, and later that same year the method was further expanded by defining efficiency through the so-called Pareto-Koopmans efficiency (a production plan – a set of inputs and outputs –Pareto-Koopmans is efficient if it is impossible to increase the production of any output or reduce the consumption of any input without simultaneously reducing the production of another output or increasing the consumption of another input) [21]. Basic DEA models were designed to assess technical efficiency, while modified DEA models were developed for evaluating multiple parameters: scale, costs, price efficiency, and changes in productivity and efficiency over time.

The development of the DEA method was primarily motivated by the need to evaluate the operational efficiency of non-profit organizations such as schools, hospitals, kindergartens, etc., that is, to assess the efficiency of related organizational units where the presence of a large number of inputs and outputs makes comparability difficult. Within the DEA approach, organizational units are defined as Decision-Making Units (DMUs). Efficiency, as one of the key business parameters, is measured as the relationship between achieved outputs and the inputs required for their realization. The advantage of this method lies in the fact that, in comparative efficiency analysis, it takes into account all relevant inputs and outputs regardless of the technology used for their transformation. In this way, a modified form of Equation (1) for efficiency measurement is obtained, in which all inputs and outputs are included:

$$Efficiency = \frac{Sum\ of\ inputs}{Sum\ of\ outputs} \qquad (2)$$

that is,

$$h_k = \frac{\sum_{r=1}^{s} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik}} \qquad (3)$$

where:

h_k – relative efficiency of the k-th DMU
m – number of inputs
v_i – weight coefficient for input i
s – number of outputs
u_r – weight coefficient for output r

The basic problems in calculating efficiency using Equation (3) are scaling problems, that is, the comparability of data located within different value ranges, and weighting, that is, determining the relative importance of inputs and outputs by assigning weight coefficients. The scaling problem was solved through data standardization, by limiting the value of the efficiency index to a scale from 0 to 1, meaning that h_k is assigned a weight coefficient greater than 0 and less than 1. In this way, the need for data scaling prior to DEA implementation is eliminated.

The problem of assigning weight coefficients was solved in such a way that Charnes, Cooper, and Rhodes proposed that efficiency analysis does not require a single objective set of weights. Instead, each decision-making unit (DMU) can define its own set of weight coefficients with the objective of maximizing its own efficiency, provided that the types of inputs and outputs, as well as the minimum allowable weight values, are predefined [22].

In order for the DEA method to be applied, several fundamental assumptions must be satisfied: (1) for every decision-making unit (DMU) whose efficiency is to be evaluated, available data on input and output values must exist; (2) all inputs must have positive values; (3) all data necessary for decision-making must be included in the efficiency analysis; (4) the efficiency index should reflect input minimization and output maximization; (5) input and output measurement units do not have to be homogeneous [3].

Based on the analyzed input and output data, the DEA method evaluates whether a particular decision-making unit is relatively efficient or not. The efficiency frontier, representing the maximum level of output achievable for given input values, is formed as an envelope surrounding the set of observed entities. Decision-making units located on this frontier are considered efficient, while the remaining units are assessed as relatively inefficient. If it is possible for a decision-making unit to produce a greater output using the same inputs, or to produce the same output using fewer inputs, then that unit is considered inefficient [23].

ANALYSIS OF PRODUCTION SECTOR EFFICIENCY USING THE DEA METHOD – A CASE STUDY

Basic Information about the VENDOM Company

The company Vendom d.o.o. Laktasi was established in 2003. The company operates in the field of metal industry manufacturing for both domestic and international markets, with a particular focus on foreign markets (the EU and South America), primarily producing various types of waste disposal containers. At the beginning of 2026, the company employed more than 200 workers and generated annual revenues exceeding EUR 10 million, making Vendom d.o.o. Laktasi one of the largest exporters in the metal sector in Bosnia and Herzegovina.

The company's most important competitive advantages are short delivery times, high reliability, and quality. Compared to competitors, Vendom products stand out due to their design, innovation, and quality. Additional advantages of cooperation with this company include its ability to respond to specific customer requirements, product customization, assembly services, servicing, and product maintenance.

The company's wide product portfolio ranges from industrial and residential fences, smaller steel structures up to 100 t, to highly demanding industrial structures with load capacities of up to 1,000 t. Particularly notable within the Vendom product range are underground and above-ground waste management systems, as well as cranes for container emptying. In addition to the above-mentioned products, the company also offers structures, fences, steel molds, underground and above-ground waste containers, cranes, steel structures for construction facilities, and various steel products manufactured according to customer requirements or based on solutions developed by the company's engineers.

In addition to its own products, the company also offers services on both domestic and international markets, including laser, plasma, and gas sheet metal cutting, sheet metal bending, sheet punching, welding, sandblasting, powder coating, assembly, repair and reconstruction, conceptual solutions, product design, and product development according to customer requirements or based on the company's own conceptual designs. Annually, the company produces more than 2,500 above-ground and underground waste containers, 50 cranes, 100,000 various metal products, and more than 30 steel structures.

Efficiency Analysis of the Production Sector

As previously stated, the company Vendom is engaged in the sale of finished products within the metal industry. Therefore, production utilization and total added value were analyzed for 13 products: containers (1–3), cranes (4–6), antenna towers (7–8), pallets (9–10), and cables (11–13), which in this case study represent the Decision-Making Units (DMUs).

Considering the objective of the analysis and the availability of data, the following were used as input variables: material costs – MC, labor costs – LC, and the number of work operations –

WO, while total added value – TAV (sales price minus product costs) was used as the output variable.

Prior to selecting the input and output variables, data preprocessing was performed, and the inputs and outputs were created as derived indicators through the aggregation of corresponding basic cost or revenue indicators. The positivity check confirmed that all variables had positive values.

Table 1. Input and Output Variables in Euros

DMU	Product	Input Variables			Output Variables
		Material Costs (€)	Labor Costs (€)	Number of Work Operations	TAV (€)
1	**Container Size A**	548.02	230.76	10	1,083.35
2	**Container Size B**	499.87	210.32	10	999.26
3	**Container Size C**	601.43	240.28	11	1,114.74
4	**Crane Height A**	13,675.75	4,724.24	12	24,301.33
5	**Crane Height B**	12,987.46	4,654.23	12	24,134.85
6	**Crane Height C**	15,007.66	5,004.32	13	24,653.47
7	**Antenna Tower A**	21,139.56	3,521.00	16	31,873.65
8	**Antenna Tower B**	22,456.38	3,909.43	17	35,506.66
9	**Pallet A**	34.31	38.73	11	98.52
10	**Pallet B**	39.63	40.23	11	99.81
11	**Cable Length A**	320.17	309.29	11	1,232.67
12	**Cable Length B**	333.78	321.67	11	1,244.77
13	**Cable Length C**	363.29	341.52	11	1,233.75

The results of the correlation analysis conducted on the entire dataset are presented in Table 2. The values of the correlation coefficients indicate that there is a positive correlation between each input and output variable, meaning that the isotonicity assumption has not been violated. An increase in inputs leads to an increase in outputs. Although the correlation coefficients are relatively high in most cases, there is no complete correlation between any two indicators, which means that there are no redundant data. The lowest correlation was observed between the number of work operations and labor costs.

The efficiency index was calculated using the following weighting factors for the input variables, based on the positive operational practices of the Vendom company: $a = 0.8$; $b = 0.8$; $c = 0.6$. In accordance with the selected weighting factors and following the DEA analysis, the most efficient DMUs were identified as Antenna Tower B (8), Pallet A (9), and Cable Length A (11), as shown in Table 3.

Table 2. Correlation Analysis

Correlation Analysis	Material Costs	Labor Costs	Number of Work Operations	Total Added Value
Material Costs	1			
Labor Costs	0.901	1		
Number of Work Operations	0.908	0.660	1	
Total Added Value	0.996	0.931	0.876	1

Table 3. Efficiency Index

	MC	LC	WO	TAV	EI	Normalized EI Value	Relative Efficiency h
1	548.02	230.76	10	1,083.35	1.72	0.71	0.72
2	499.87	210.32	10	999.26	1.74	0.72	0.77
3	601.43	240.28	11	1,114.74	1.64	0.68	0.74
4	13,675.75	4,724.24	12	24,301.33	1.65	0.68	0.76
5	12,987.46	4,654.23	12	24,134.85	1.71	0.71	0.81
6	15,007.66	5,004.32	13	24,653.47	1.54	0.64	0.70
7	21,139.56	3,521.00	16	31,873.65	1.61	0.67	0.98
8	22,456.38	3,909.43	17	35,506.66	1.68	0.70	1.00
9	34.31	38.73	11	98.52	1.51	0.63	1.00
10	39.63	40.23	11	99.81	1.42	0.59	0.82
11	320.17	309.29	11	1,232.67	2.42	1.00	1.00
12	333.78	321.67	11	1,244.77	2.34	0.97	0.95
13	363.29	341.52	11	1,233.75	2.16	0.89	0.76

The results of the conducted DEA analysis indicate the actual state of efficiency within the production sector of the Vendom company, which operates in the field of metal industry manufacturing. The research showed that the efficiency of the DMUs ranges from 70% to 100%. Three DMUs – Antenna Tower B, Pallet A, and Cable Length A (8, 9, and 11) proved to be fully efficient, while two additional units – Antenna Tower A (7) and Cable Length B (12) demonstrated very high efficiency levels, reaching approximately 95% efficiency.

The least efficient units were Crane Height C (6) and Container Size A (1), whose efficiency levels were approximately 70%. Nevertheless, it is certainly possible to improve the efficiency of these units and thereby enhance the overall efficiency of the production sector. This is because the DEA method enables the creation of target values for the observed inputs and outputs, on the basis of which improved business efficiency can be achieved.

The obtained results also indicate the need for continuous monitoring and evaluation of production sector efficiency. The average relative efficiency of the observed DMUs amounted to approximately 85%, which represents a satisfactory level that can certainly be further improved.

Continuous monitoring and comparison of results over specific time intervals will enable the identification of key production-related problems and indicate which DMUs should be influenced through the reduction or increase of inputs or outputs in order to achieve better overall business results for the company.

CONCLUSION

The efficiency of business processes, especially within the production sector, represents a highly important component of the operations of every company. Inefficient business processes not only result in the loss of valuable time and make it more difficult for employees to perform their tasks, but can also significantly affect company profitability and hinder the company's ability to satisfy consumer demand.

Market competition requires companies to utilize their resources to the maximum extent and, more importantly, to use them efficiently by transforming labor, materials, and capital into products and services that generate profit for the company. Improved efficiency is achieved through the proper identification and analysis of business performance indicators and through strategic actions based on such analysis.

Efficiency represents the ratio between two indicators, outputs to inputs, and it is easiest to determine in organizations that use only one input (costs, engaged resources, etc.) to produce one output (earnings, profit, revenue, etc.).

The DEA method, is commonly considered the most successful and most widely used non-parametric method applied in efficiency analysis, performance measurement, and many other analytical tasks. It is a data-based method for measuring the efficiency of complex entities that use diverse inputs to generate diverse outputs. By means of this method, which is based on linear programming, the relative productivity of decision-making units (DMUs) that use similar inputs to produce similar outputs is assessed, and deviations of less productive units are measured.

Using the DEA method, an efficiency index was created, which enabled an objective ranking of the observed units.

The weighting factors of the input variables needed to calculate the Efficiency Index are assigned with reference to the positive practice of the Vendom company.

The results of the DEA analysis indicated the actual state of efficiency in the production sector at the company Vendom.

The research conducted in this paper showed that the efficiency of individual DMUs within the analyzed company ranges between 70% and 100%. Three DMUs (Antenna Tower B, Pallet A, and Cable Length A) proved to be fully efficient, while two additional units (Antenna Tower A and Cable Length B) demonstrated very high efficiency levels of approximately 95%. The least efficient units were Crane Height C and Container Size A, whose efficiency levels barely exceeded 70%. It was concluded that the efficiency of these units could be improved by acting upon the input and output components (through the application of target values), particularly in the case of Crane Height C through the reduction of labor costs, and in the case of Container Size A through increasing the product price, which would improve the efficiency of the production sector within the Vendom company.

The limitations of this research are related to the inability to observe certain additional input-output indicators, since, based on the available company data, it was not possible to systematize such indicators for all DMUs analyzed in this study. Considering that the company's management has recognized the importance of monitoring input-output indicators for improving production efficiency, future research on this topic, which has already been planned, will certainly include additional DMUs as well as new input-output indicators. It is expected that the obtained results will indicate further directions for action aimed at additionally improving production efficiency.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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THE PRODUCTIVITY-ENERGY NEXUS IN NIGERIA: ASYMMETRIC IMPACTS OF EFFICIENCY AND FACTOR SUBSTITUTION

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ABSTRACT

This study investigates the dynamic relationship between energy efficiency, productivity, and factor substitution in Nigeria's manufacturing sector from 1981 to 2023. Using a post-positivist framework and secondary time-series data, we employ Stochastic Frontier Analysis (SFA) to estimate energy efficiency, a Nonlinear Autoregressive Distributed Lag (NARDL) model to assess its asymmetric impact on manufacturing output, and a Translog cost function to compute Morishima Elasticities of Substitution (MES). Results indicate an average energy efficiency score of 82.2%, highlighting significant potential for improvement. The NARDL estimates reveal that energy efficiency asymmetrically affects manufacturing output, with negative shocks exerting a disproportionately larger long-run impact than positive improvements. Furthermore, capital and energy are substitutes (MES > 0), while capital and labor are complements (MES < 0), suggesting that energy price policies could reshape the sector's input structure. The study concludes that energy efficiency is not merely an environmental or cost-saving concern but a strategic determinant of industrial productivity in Nigeria. Policy should therefore prioritize institutionalizing energy efficiency within the national industrial strategy, supported by incentives for technology adoption and skills development.

Keywords: Energy Efficiency, Total Factor Productivity, Input Substitution, Nigerian Manufacturing, Stochastic Frontier Analysis, NARDL, Morishima Elasticity.

INTRODACTION

Energy is a fundamental input in industrial production, influencing both economic output and environmental sustainability [1]. In Nigeria, Africa's largest economy, the manufacturing sector is the second-largest consumer of refined petroleum and the largest consumer of electricity [2]. Despite this high energy intensity, the sector's contribution to Gross Domestic Product (GDP) has

declined from 11.75% in 2011 to 7.61% in 2024 [2]. This paradox of rising energy use alongside stagnant performance raises critical questions about the sector's energy efficiency and its link to productivity.

Theoretical and empirical literature present a complex picture. While studies such as Worrell et al. (2003), Subrahmanya (2006), and Cantore et al. (2016) find that energy efficiency enhances productivity, others, such as Haider and Ganie (2017), report a negative relationship, suggesting context-specific dynamics [3], [4], [5], [6]. Most evidence, however, derives from developed or emerging Asian economies, creating a significant gap for sub-Saharan Africa [7], [8]. Furthermore, the potential to substitute non-energy inputs (capital, labor) for energy—a key mechanism for improving efficiency—remains underexplored at the aggregate level in Nigeria [9], [10].

This study addresses these gaps by asking: (1) What is the extent of energy efficiency change in Nigeria's manufacturing sector? (2) How does energy efficiency affect sectoral performance, and is this relationship symmetric? (3) Do substitution possibilities exist between energy and non-energy inputs? By answering these questions, the research provides novel, policy-relevant insights into the role of energy in Nigeria's industrial development.

THEORETICAL FRAMEWORK AND METHODOLOGY

The study is grounded in production theory [11], [12] and the neoclassical theory of the firm. It incorporates the Energy Efficiency Gap theory (Jaffe & Stavins, 1994) and Jovanovic's (1982) theory of firm selection to explain variations in efficiency [13], [14]. The post-positivist research design employs quantitative, non-experimental methods on secondary time-series data (1981–2023) from the Central Bank of Nigeria (CBN), National Bureau of Statistics (NBS), and World Bank.

Model Specification

Objective 1: Estimating Energy Efficiency

While Debreu introduced the estimation of technical efficiency using an output-oriented approach, Farrell established the measurement of technical efficiency through an input-oriented approach. Based on feasibility, this study adopted the input-oriented approach of the stochastic frontier analysis to estimate energy efficiency (EE) given energy intensity (EI), manufacturing output (MO) and the input of capital (CAP), labour (LAB) and a dummy policy variable (PDUM) capturing the dissolution of The Power Holding Company of Nigeria (PHCN) and the privatization of six generating companies and ten distribution companies

We adopt an input-oriented Stochastic Frontier Analysis (SFA) model [15] to estimate energy efficiency (EE), distinguishing between inefficiency and random noise. The model is specified as:

$$lnEI_t = \beta_0 + \beta_1 lnMO_t + \beta_2 lnCAP_t + \beta_3 lnLAB_t + \beta_4 POLDUM_t + \vartheta_t + \mu_t$$

where EI is energy intensity, MO is manufacturing output, CAP is capital input, LAB is labor input, POLDUM is a dummy for the 2013 power sector reform, ϑ_t is random noise, and μ_t is the inefficiency term.

Objective 2: Assessing the Impact on Productivity

Several econometric techniques are available for estimating energy efficiency and its impacts on Nigeria's manufacturing sector. However, in time series analysis, the properties of standard estimation and testing techniques depend on the assumption that the variables under consideration are stationary. Regression analysis applied to a non-stationary series can yield misleading results. This is referred to as "spurious regression". As such, among other tests, unit-root tests were conducted on all the data to guide against spurious regression results.

To capture asymmetric effects, we employ a Nonlinear Autoregressive Distributed Lag (NARDL) model [16]. The NARDL was employed to estimate the asymmetric relationships between energy efficiency and manufacturing output performance (productivity). This model

captures both short-run and long-run asymmetries, allowing for the examination of distinct positive and negative effects of energy efficiency on manufacturing output.

$$\Delta MO_t = \gamma + \sum_{i=1}^{p} \alpha_i \, \Delta MO_{t-i} + \sum_{i=0}^{q} \beta_i^{+} \Delta EE_{t-i}^{+} + \sum_{i=0}^{q} \beta_i^{-} \Delta EE_{t-i}^{-} + \varphi ECM_{t-1} + \varepsilon_t$$

where EE^{+} and EE^{-} are partial sum decompositions of positive and negative changes in energy efficiency, and ECM is the error correction term.

Objective 3: Analyzing Input Substitution

The manufacturing sector plays a dynamic role in Nigeria's economic development, and understanding the relationships between its inputs is crucial for informed decision-making. One key aspect of this is the substitutability between energy and non-energy inputs, including labor and capital. The objective herein investigates energy and non-energy input substitution possibilities in Nigeria's manufacturing sector using the translog cost function, focusing on the Morishima Elasticity of Substitution (MES).

The translog cost function provides a flexible framework for estimating the relationship between input and output in a production process. By analyzing the total manufacturing cost (C) in relation to labor price (PL), price of capital (Pk) proxied by the maximum lending rate, and energy price (Pe), we can estimate the MES between these inputs. The MES measures the percentage change in the ratio of two inputs in response to a percentage change in the price of one of the inputs, holding output and other input prices constant.

The analysis utilized input shares, including energy share (ES), labor share (LS), and capital share (CS), to calculate the MES between energy and non-energy inputs. Real manufacturing output (MO) was also considered to account for the impact of output levels on input demand. The findings of this analysis will have significant implications for Nigeria's manufacturing sector. For instance, if energy and non-energy inputs are found to be substitutes, firms may be able to adjust their input mix in response to changes in input prices, which could have important implications for energy policy and industrial development. Conversely, if inputs are found to be complements, firms may need to adopt a more integrated approach to input management. However, it could be possible for inputs to be independent of one another.

A Translog cost function [17] is estimated via Iterated Seemingly Unrelated Regression (iSUR):

$$ln\left(\frac{C}{P_L}\right) = \alpha_0 + \sum_i \delta_i \, ln\left(\frac{P_i}{P_L}\right) + \frac{1}{2}\sum_i \sum_j \alpha_{ij} \, ln\left(\frac{P_i}{P_L}\right) ln\left(\frac{P_j}{P_L}\right) + \tau lnMO + \theta T$$

for i, j = K, E. From the estimated parameters, we compute the Morishima Elasticity of Substitution (MES) [18]:

$$MES_{ij} = \frac{\delta \ln(X_i/X_j)}{\delta ln P_j} = \epsilon_{ij} - \epsilon_{jj}$$

Data Source and Type

The study utilized secondary time-series data. Data sourced from publicly available and reputable institutions to ensure reliability and validity. The data covered the period from 1981 to 2023. This timeframe is chosen as it captures significant periods of oil price volatility, structural adjustment programs, and recent power sector reforms in Nigeria, providing a rich context for analysis.

Table 1. Definition and Measurement of Variable

Variable Category	Variable Name	Symbol	Measurement
Dependent Variables	Manufacturing Output	MO	Total annual sales/value of output (NGN)
	Energy Intensity	EI	Total cost of energy / Manufacturing Output
	Total Manufacturing Cost	C	Sum of capital, labour, and energy costs (NGN)
Independent Variables	Capital Input	CAP	Total value of machinery and equipment (NGN)
	Labour Input	LAB	Total wages paid to employees (NGN)
	Energy Input	E	Total cost of electricity and fuel (NGN)
	Energy Efficiency	EE	Score derived from Stochastic Frontier Analysis (0 to 1)
Price Variables	Price of Capital	P_K	User cost of capital (proxied by maximum lending rate)
	Price of Labour	P_L	Mean wage earnings per employee
	Price of Energy	P_E	Weighted average cost per tonne of oil equivalent (TOE)
Policy Variable	Power Sector Reform Dummy	POLDUM	Dummy variable: 0 for years before 2013, 1 for 2013 and after

RESULTS AND DISCUSSION

Energy Efficiency Trends

The SFA results reveal an average energy efficiency score of 0.822 (82.2%) for the period, with a standard deviation of 0.151. This indicates substantial room for improvement, consistent with the Energy Efficiency Gap theory. The likelihood ratio test (LR = 7.44, p = 0.003) confirms the presence of significant technical inefficiency. Capital investment (β = -1.213, p = 0.000) and the 2013 power sector reform (β = -1.669, p = 0.000) were associated with reduced energy intensity (improved efficiency), while labor input increased it (β = 2.134, p = 0.000).

Table 2: Stochastic Frontier Analysis Results

Variable	Coefficient	Std. Error	p-value
Constant	-39.165	0.0003	0.000
ln_MO	2.284	0.00001	0.000
ln_CAP	-1.213	0.00002	0.000
ln_LAB	2.134	0.00002	0.000
POLDUM	-1.669	0.00001	0.000
σ_μ	0.716	0.077	-
σ_θ	1.58e-08	3.50e-06	-
Lambda	4.54e+07	-	-

The SFA model estimation slope coefficients shown in Table 2 above indicate that manufacturing output (MO) yielded a significant and positive impact on energy intensity (EI), with a coefficient of 2.2841. This implies that a 1% increase in output would lead to a 2.28% increase in output, ceteris paribus. The *p*-value of 0.000 indicates that this relationship is highly significant. This finding suggests that as the manufacturing sector produces more output, it requires more energy per unit of output. The changes in capital (CAP) yielded a negative and significant impact on energy intensity (EI), having a partial slope coefficient of -1.2126 and a corresponding *p*-value = 0.000. The foregoing implies that as capital increases, energy intensity decreases significantly;

thus, increased investment in capital leads to more energy-efficient production processes. In contrast, labour has a significant and positive impact on energy intensity (EI), with a slope coefficient of 2.134 and a p-value of 0.000. This suggests that a 1% increase in labour would lead to a 2.13% increase in energy intensity (EI), ceteris paribus. The foregoing suggests that increased labour input may lead to less energy-efficient production processes. Policy Dummy (*POLDUM*), with a slope coefficient of -1.669, indicates a negative relationship between the policy dummy variable and energy intensity. The restructuring of the power sector in 2013 (captured by the dummy variable) is associated with a decrease in energy intensity. This suggests that the policy change had a positive impact on energy efficiency in the manufacturing sector. The *p*-value (0.000) indicates that this relationship is statistically significant.

Asymmetric Impact on Manufacturing Output

The NARDL model (AIC = -5.6623) confirms a long-run cointegrating relationship (Bounds test F = 9.0357). The results demonstrate a significant but **asymmetric** impact. In the long run, a 1% increase in energy efficiency raises manufacturing output by 0.93% (φ^+ = 0.9346, p = 0.012), while a 1% decrease reduces output by 2.24% (φ^- = 2.2447, p = 0.018). The symmetry test rejects the null hypothesis for the long run (F = 11.6125, p = 0.002), confirming the presence of asymmetry. This implies that the sector is more vulnerable to efficiency declines than it benefits from improvements, a critical insight for risk management.

The NARDL model (optimal lag structure: 1,1,1,1,1,1 based on AIC) confirms cointegration (Bounds test F-statistic = 9.0357 > I(1) critical value at 1%). The error correction term is negative and significant (γ = -0.194, p = 0.000), indicating convergence to long-run equilibrium.

Long-run asymmetry is evident in the differential coefficients for positive versus negative efficiency changes. A 1% improvement in energy efficiency increases TFP by 0.93% (θ^+ = 0.9346\), p = 0.012), while a 1% deterioration decreases TFP by 2.24% (θ^-= 2.2447), p = 0.018)—approximately 2.4 times greater in magnitude. This asymmetry is statistically confirmed by the long-run symmetry test (F = 11.6125, p = 0.002).

Short-run dynamics also reveal asymmetry, though less pronounced. Immediate responses to efficiency changes show similar directional effects but smaller magnitudes. The joint symmetry test confirms overall asymmetry (F = 5.9976, p = 0.007).

Table 3: NARDL Model Results - Long-run Coefficients

Variable	Coefficient	Std. Error	p-value
EE^+	0.9346	0.3662	0.012
EE^-	2.2447	0.9321	0.018
CAP	0.9839	0.1845	0.000
LAB	-0.9627	0.2743	0.001
EI	-0.2609	0.0782	0.001
POLDUM	0.6376	0.5821	0.278
Trend	0.0315	0.0201	0.124

Input Substitution Possibilities

The Translog cost function estimates fit well (R^2 = 0.9934). The computed Morishima Elasticities reveal distinct input relationships:

- Capital and Energy are Substitutes: MES_{KE} averages 3.66, indicating that a rise in energy price would lead to a significant increase in the capital/energy ratio.
- Energy and Labor are Substitutes: MES_{EL} averages 2.32.

- Capital and Labor are Complements: MES_{KL} averages -1.94, suggesting that capital deepening accompanies increased skilled labor demand.

The MES results (Table 3) reveal more nuanced and policy-relevant relationships.

Table 4: Morishima Elasticities of Substitution - Summary Statistics

Elasticity	Mean	Std. Dev.	Min	Max	Interpretation
MES_KE	3.659	0.862	1.948	4.496	**Substitutes**
MES_EL	2.318	0.275	1.927	2.714	**Substitutes**
MES_KL	-1.937	0.432	-2.484	-1.165	**Complements**

The positive MES for capital-energy (3.66) indicates that a 1% increase in energy price would increase the capital-energy ratio by approximately 3.66%, suggesting strong substitution potential. Similarly, the energy-labor MES (2.32) indicates substitution possibilities, though less pronounced. The negative MES for capital-labor (-1.94) reveals complementarity, implying that capital deepening is associated with increased skilled labor demand rather than labor displacement.

CONCLUSION AND POLICY IMPLICATIONS

This study on Nigeria's manufacturing sector (1981–2023) reveals three key findings:

1. **Significant Energy Efficiency Gap**: The sector operates at an average energy efficiency of only 82.2%, indicating substantial room for improvement. The 2013 power sector reforms and increased capital investment were found to improve efficiency, while labor input was associated with higher energy intensity.
2. **Asymmetric Impact on Productivity**: Energy efficiency has a disproportionate effect on manufacturing output. While a 1% improvement in efficiency boosts output by 0.93%, a 1% decline reduces output by a much larger 2.24%. This "risk asymmetry" means the sector is far more vulnerable to efficiency losses than it is benefited by equivalent gains.
3. **Clear Input Substitution Possibilities**: The analysis confirms that capital and energy are strong substitutes. This means rising energy prices would likely incentivize a shift toward more capital-intensive, energy-efficient technologies. However, capital and labor were found to be complements, suggesting that such technological upgrades would increase the demand for skilled labor rather than replace workers.

Policy recommendations include:

1. Integrate energy efficiency into core industrial policy, offering targeted fiscal incentives for audits, retrofits, and adoption of efficient technologies.
2. Ensure stable energy pricing and supply to reduce uncertainty and encourage long-term investments in efficiency.
3. Develop skills training programs aligned with the technological upgrading prompted by energy policies, addressing the capital-labor complementarity.
4. Utilize Morishima Elasticities in modeling the economic impact of energy price reforms to anticipate shifts in factor demand accurately.

By addressing the energy-productivity nexus with these nuanced, evidence-based strategies, Nigeria can unlock sustainable industrial growth, enhancing both economic resilience and environmental sustainability.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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ENERGY TRANSITION, ENVIRONMENTAL QUALITY, AND FINANCIAL DEVELOPMENT IN NIGERIA: AN EMPIRICAL ANALYSIS

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ABSTRACT

This study investigates the dynamic relationship between renewable energy consumption and financial development in Nigeria from 1990 to 2023. Against the backdrop of Nigeria's significant energy poverty, underutilized renewable resources, and a growing yet challenged financial sector, the research aims to determine the nature of the nexus between these two critical variables. Employing a quantitative research design and the Autoregressive Distributed Lag (ARDL) bounds testing approach, the study analyzes annual time series data on financial development (proxied by domestic credit to the private sector), renewable energy consumption, economic growth (GDP per capita), and CO_2 emissions.

The empirical results confirm a significant long-run cointegrating relationship among the variables. The findings reveal that renewable energy consumption has a positive and statistically significant impact on financial development in the long run, suggesting that investments in clean energy technologies act as a catalyst for deepening financial markets. Economic growth also exhibits a strong positive effect on financial development. In contrast, CO_2 emissions show a marginally significant negative relationship, indicating that environmental degradation may slightly erode investor confidence.

The study concludes that renewable energy adoption is not only an environmental imperative but also a financial catalyst for Nigeria. It recommends the integration of financial sector reforms with energy policies to enhance credit availability, attract green investments, and foster a sustainable economic transformation. Strengthening the financial system is thus crucial for scaling up renewable energy technologies and achieving inclusive long-term development.

Keywords: Renewable Energy, Financial Development, ARDL, Nigeria, Sustainable Growth, CO_2 Emissions.

INTRODUCTION

In recent decades, the global energy sector has changed significantly due to the need to address climate change, reduce reliance on fossil fuels, and support sustainable economic growth. In countries like Nigeria, where many people lack energy and face environmental issues, renewable energy can help tackle these problems and promote equitable economic development. Nigeria has dealt with many challenges because of years of poor and dirty energy use. Despite investments, there has been little progress in the power sector.

The country has abundant renewable energy sources, including biomass, solar, wind, and hydro, that remain underutilized. A major challenge for renewable energy in Nigeria is the high cost of running these projects. A strong financial system is necessary to manage risks in the energy market, use capital effectively when public funds are limited, and shift resources away from the less efficient and polluting traditional energy sources. Unfortunately, Nigeria's electricity consumption per person is only 181.63 kWh, which is low compared to other sub-Saharan African countries like Côte d'Ivoire (357 kWh), Ghana (567 kWh), and Zimbabwe (625 kWh). By mid-2025, about 86.8 million Nigerians still lacked electricity.

The financial sector plays a key role in raising capital for renewable energy projects, expanding electricity access, and strengthening the economy. Nigeria's financial sector has grown greatly and is now a leading market in Africa. The banking industry is vital for the country's development and economic growth. Between 2017 and 2020, the financial sector added N44.2 trillion to Nigeria's GDP. It grew from N78.10 trillion in 2017 to N122.30 trillion in 2020. Banking is the largest part of this sector, contributing N42.7 trillion in 2019, an increase from previous years. Compared to other regions, Nigeria has a well-structured banking system with high adoption rates (44.2%, exceeding West Africa's average of 17.8%) and widespread use of modern financial tools. Nigeria is also linked to global markets. Following the 2016-17 oil shock, foreign investments surged to US$6.3 billion in early 2018, a significant increase from previous years.

LITERATURE REVIEW

Conceptual Review

Renewable Energy

Renewable energy refers to energy derived from natural processes such as water, wind, and sunlight [1]. It is also called clean energy because it is naturally replenished and environmentally friendly. Although availability may depend on weather and time, natural energy sources like sunlight and wind do not become exhausted. Solar energy, for example, is widely used for heating and lighting through photovoltaic (PV) cells made from silicon that convert sunlight into electricity.

Financial Development

Financial development refers to the improvement in the size, efficiency, and stability of a country's financial institutions and markets. It involves increased access to credit, deeper financial markets, stronger financial regulation, and improved financial intermediation. A well-developed financial system mobilizes savings, allocates resources efficiently, reduces transaction costs, and supports economic activities, including investment in renewable energy technologies.

Theoretical Review

Neoclassical Growth Theory

The Neoclassical Growth Theory, introduced by Solow (1956), explains long-run economic growth through capital accumulation, labour, and technological development [2]. Technology is considered the primary driver of sustained growth in the long run.

Role of Financial Development in Neoclassical Theory

Financial development enhances the allocation of capital. According to King and Levine (1993), efficient financial systems channel funds to productive sectors, encourage investment, and promote long-term economic growth [3].

Integrating Energy into Neoclassical Growth

Energy is a crucial production input. Jorgenson and Wilcoxen (1993) argue that improvements in energy efficiency increase productivity and growth [4]. Extending the neoclassical framework to include energy helps explain how financial development, energy use, and technological progress interact in the production process.

Relevance of Africa to the Energy–Finance Nexus

Africa serves as a crucial case study for examining the financial development–energy nexus due to several interrelated factors. Firstly, the continent experiences low levels of financial development [5], which hampers investment in energy infrastructure. Additionally, despite contributing minimal emissions, Africa is highly vulnerable to climate change [6]. Another pressing issue is the widespread energy poverty, with nearly half of the population lacking access to electricity [7]. Furthermore, weak governance structures and negative performance indicators exacerbate these challenges [8]. Collectively, these conditions highlight Africa's unique context, making it a critical environment for studying renewable energy development and its potential impact on sustainable growth.

Empirical Review

A large volume of empirical research examines the relationships among financial development, renewable energy consumption, and economic growth.

Financial Development and Renewable Energy

The renewable energy sector plays a crucial role in addressing global energy needs, but its capital-intensive nature necessitates robust financial structures to attract investment [9]. A well-developed financial system mitigates investment costs while broadening access to essential funding through credit and equity markets. Shahbaz et al. (2021) identified three primary channels through which financial development influences renewable energy [10]. The direct effect highlights how access to credit facilitates investments in clean technologies, while the business effect emphasizes that increased financial capital nurtures renewable energy firms and spurs innovation. Additionally, the wealth effect illustrates how thriving stock markets can enhance investor confidence, incentivizing green investments. Their research, focusing on 34 developing countries from 1994 to 2015, demonstrated a significant positive correlation between financial development and renewable energy consumption, underscoring the importance of financial systems in fostering a sustainable energy transition.

Evidence from Nigeria

Stephen et al. (2023) used ARDL analysis to examine Nigeria's financial development and renewable energy consumption from 1981–2019 [11]. Results showed that financial development positively influences renewable energy use, moderated by GDP, FDI, and inflation. In Nigeria, inadequate electricity supply increases reliance on imported petroleum products, which account for more than 50% of mineral imports. Financial sector conditions influence credit costs for petroleum importers [12], [13], affecting energy supply and increasing dependence on biomass, which contributes to deforestation.

Energy Consumption and Economic Growth

Empirical evidence on the energy–growth relationship remains inconclusive [14]. Some studies argue that financial development increases industrial activity, raising energy demand and contributing to CO_2 emissions [15], especially in regions with weak governance.

Research Gap

The existing literature on financial development and renewable energy consumption reveals notable gaps that warrant further investigation. Notably, there is a dearth of studies examining the moderating role of governance in this context, which is especially significant given the variety of governance structures across regions. Moreover, research focusing on Africa remains limited, even though the continent faces unique challenges such as weak governance, energy poverty, and heightened climate vulnerability. The findings from existing studies are often inconclusive, highlighting the influence of country-specific factors like governance quality, financial market depth, and regulatory environments on energy outcomes. Furthermore, many analyses rely on narrow financial development indicators when evaluating renewable energy transitions, which demand a more multidimensional approach. Lastly, limited disaggregation of renewable energy types like solar, wind, and hydro prevents a comprehensive understanding of how different energy sources respond to financial and governance variables. Addressing these gaps is crucial for developing informed policy interventions.

RESEARCH METHODOLOGY

Research Design

This study adopts a quantitative, ex-post facto research design. The design is appropriate because it utilizes existing secondary data to examine the relationship between renewable energy consumption and financial development in Nigeria over time. It does not manipulate variables but rather analyzes historical data to infer causality and long-run relationships.

Nature and Sources of Data

The study uses annual time series data from 1990 to 2023, sourced from:

- World Bank Development Indicators (WDI) – Renewable energy consumption (% of total final energy), GDP per capita, and CO_2 emissions.
- Central Bank of Nigeria (CBN) Statistical Bulletin – Domestic credit to the private sector (% of GDP), representing financial development.

Model Specification

$$FD_t = \beta_0 + \beta_1 REC_t + \beta_2 GDP_t + \beta_3 CO_{2t} + \mu_t$$

Where:

FD = Financial Development (domestic credit to private sector % of GDP)
REC = Renewable Energy Consumption (% of total final energy use)
GDP = Economic Growth (GDP per capita growth rate)
CO_2 = Carbon dioxide emissions (metric tons per capita)
μ_t = Error term
β_0 to β_3 = Coefficients to be estimated

Estimation Technique

The Autoregressive Distributed Lag (ARDL) Bounds Testing Approach is used to test for long-run cointegration among variables and estimate both short-run and long-run dynamics. This method is suitable for variables integrated at I(0) and I(1).

A Priori Expectation

Variable	Expected Sign	Economic Justification
REC	+	Renewable energy drives sustainable investment and credit growth.
GDP	+	Economic growth supports financial system expansion.
CO_2	–	Environmental degradation may discourage investment confidence.

DATA ANALYSIS AND INTERPRETATION

Table 1 Descriptive Statistics

Variable	Mean	Std. Dev.	Min	Max	Obs
FD	16.82	4.92	8.74	25.36	34
REC	31.54	5.80	22.10	41.60	34
GDP	2.45	4.31	-1.79	8.35	34
CO_2	0.65	0.19	0.38	0.95	34

Financial development averaged 16.82% of GDP, indicating moderate credit depth in Nigeria's economy. Renewable energy consumption averaged about 31%, reflecting dependence on renewable sources (mainly biomass and hydro).

Table 2 Correlation Matrix

Variables	FD	REC	GDP	CO_2
FD	1	0.63	0.41	-0.32
REC	0.63	1	0.27	-0.45
GDP	0.41	0.27	1	-0.11
CO_2	-0.32	-0.45	-0.11	1

There is a moderate positive correlation (0.63) between renewable energy consumption and financial development.

Table 3 Unit Root Test (ADF)

Variable	Level	1st Difference	Order of Integration
FD	Non-stationary	Stationary	I(1)
REC	Stationary	—	I(0)
GDP	Stationary	—	I(0)
CO_2	Non-stationary	Stationary	I(1)

Table 4 ARDL Bounds Test for Cointegration

Test Statistic	Value	Lower Bound	Upper Bound	Decision
F-statistic	5.31	3.79	4.85	Cointegration Exists

Table 5 Long-Run Coefficients

Variable	Coefficient	Std. Error	t-Statistic	Prob.	Inference
REC	0.217	0.081	2.68	0.013	Significant
GDP	0.498	0.122	4.08	0.000	Significant
CO_2	-0.091	0.047	-1.93	0.061	Marginally significant

Table 6 Short-Run Dynamics (Error Correction Model)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(REC)	0.145	0.056	2.59	0.016
D(GDP)	0.213	0.092	2.31	0.027
D(CO_2)	-0.048	0.034	-1.41	0.167
ECT(-1)	-0.562	0.098	-5.73	0.000

Table 7 Diagnostic Tests

Test	Statistic	Prob.	Decision
Breusch-Godfrey (Serial Corr.)	0.62	0.43	No autocorrelation
Breusch-Pagan (Heteroskedasticity)	1.10	0.31	Homoscedastic
Jarque-Bera (Normality)	1.54	0.46	Normal distribution
Ramsey RESET	0.78	0.37	Correct model specification

Diagnostic results confirm the model is statistically valid, well-specified, and free from major econometric problems.

CONCLUSION

This study examined the relationship between renewable energy consumption and financial development in Nigeria using annual data from 1990 to 2023. The findings show that renewable energy consumption, economic growth, and environmental quality all play significant roles in shaping the country's financial system. The empirical results from the ARDL model indicate a long-run cointegrating relationship among financial development, renewable energy consumption, GDP per capita, and CO_2 emissions. This confirms that Nigeria's financial and energy sectors are structurally linked.

In the long run, renewable energy consumption has a positive and statistically significant impact on financial development. This suggests that increasing the use of renewable energy technologies such as solar, wind, hydro, and biomass supports investment expansion, strengthens credit markets, and encourages financial intermediation. The finding aligns with studies by Shahbaz et al. (2021) and Wang et al. (2021), who emphasized that renewable energy projects depend heavily on strong financial systems to mobilize capital and reduce investment risks [10], [9].

Economic growth also exhibits a strong positive effect on financial development, reinforcing the principle that a growing economy increases savings, investment demand, and overall financial market depth. This is consistent with King and Levine (1993), who argue that financial development and economic growth reinforce each other over time [3].

CO_2 emissions, on the other hand, show a mild negative relationship with financial development. Although marginally significant, this relationship suggests that environmental degradation may weaken investor confidence and discourage long-term financing—especially in economies seeking to transition toward greener and more sustainable energy systems.

The study concludes that renewable energy adoption is not just an environmental necessity but a financial catalyst capable of improving credit availability, attracting investment, and supporting sustainable economic transformation in Nigeria. Strengthening Nigeria's financial system through deeper capital markets, improved regulation, and affordable lending will be crucial for scaling renewable energy technologies. Policymakers should therefore integrate financial reforms with energy policies to ensure that renewable energy becomes a backbone for inclusive growth and long-term development.

Data Availability Statement

The datasets generated and used during the current study are available in the study.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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LAW SECTION
PRAVO

KRIVIČNOPRAVNI ASPEKTI ZAKONA O PRAVDI PROTIV SPONZORA TERORIZMA (JASTA) U ZAKONODAVSTVU SAD

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APSTRAKT

Rad analizira specifičnu pravnu prirodu američkog saveznog zakona JASTA (Justice Against Sponsors of Terrorism Act), sa fokusom na njegove krivičnopravne implikacije unutar građanskopravnih postupaka. Iako je primarni cilj zakona omogućavanje privatnih tužbi za naknadu štete protiv stranih država, on suštinski redefiniše standarde krivične odgovornosti, kroz institute pomaganja i podržavanja terorističkih akata. Analizom aktuelne sudske prakse iz 2025. i 2026. godine, rad istražuje, kako američki sudovi interpretiraju standard „svesnog i krivičnog učešća". Poseban osvrt je dat sukobu JASTA-e sa fundamentima međunarodnog javnog prava, prvenstveno principom suverenog imuniteta država, kao i potencijalnim recipročnim merama drugih država, koje bi mogle ugroziti pravnu sigurnost međunarodnih odnosa.

Ključne reči: JASTA, terorizam, suvereni imunitet, krivična odgovornost, SAD, međunarodno pravo.

UVOD - EVOLUCIJA KONCEPTA ODGOVORNOSTI ZA TERORIZAM

Dinamika međunarodnih odnosa u 21. veku je nametnula potrebu za redefinisanjem tradicionalnih pravnih instituta, među kojima je princip suverenog imuniteta država pretrpeo najznačajniju eroziju. Centralno mesto u tom procesu zauzima američki savezni zakon *Justice Against Sponsors of Terrorism Act* (JASTA) iz 2016. godine [1]. Iako formalno sistematizovan unutar građanskopravne sfere, JASTA suštinski predstavlja radikalan zahvat u sferu krivične odgovornosti suverenih država.

Istorijski posmatrano, američki *Foreign Sovereign Immunities Act* (FSIA) iz 1976. godine postavio je princip suverenog imuniteta kao pravilo, uz usko definisane izuzetke [2]. Čak i u slučajevima terorizma, tužbe su bile ograničene isključivo na države, koje je izvršna vlast SAD

zvanično proglasila „sponzorima terorizma“.[1] Međutim, usvajanjem JASTA-e, dolazi do suštinske promene paradigme [3]. Zakon ukida potrebu za prethodnom administrativnom klasifikacijom države, omogućavajući privatnim licima da pokrenu postupke protiv bilo koje strane države, ukoliko se dokaže njena povezanost sa terorističkim aktom na tlu SAD.

Teza ovog rada je, da JASTA funkcioniše kao instrument „privatizacije“ krivičnog progona. Kroz mehanizme civilnih parnica, žrtve i njihovi pravni zastupnici *de facto* preuzimaju ulogu javnog tužioca,[2] dok sudovi dobijaju mandat da ocenjuju elemente krivične odgovornosti, poput namere, pomaganja i podržavanja, koje su ranije bile u domenu međudržavnih sporova ili specijalizovanih krivičnih tribunalskih postupaka [4]. Ovakva, hibridna priroda zakona rezultira direktnom apsorpcijom krivičnopravnih standarda u građanskopravni proces, čime se svesno suspenduju fundamentalni principi međunarodnog poretka, zasnovanog na suverenoj jednakosti.

Od FSIA do JASTA: Erozija izvršnog monopola nad suverenim imunitetom

Evolucija američkog zakonodavstva u domenu suverenog imuniteta predstavlja put od stroge diplomatske zaštite do široke sudske nadležnosti nad stranim državama. Osnovu ovog poretka je decenijama činio *Foreign Sovereign Immunities Act* (FSIA) iz 1976. godine. Ovaj zakon je uspostavio generalno pravilo imuniteta stranih država pred sudovima SAD, dozvoljavajući samo restriktivno definisane izuzetke, poput onih, koji se odnose na komercijalne aktivnosti ili eksplicitnu podršku terorizmu. Međutim, čak i u slučajevima terorizma, sudska nadležnost je bila strogo uslovljena političkom odlukom. Država je mogla biti tužena samo ako se prethodno nalazila na zvaničnoj listi „država sponzora terorizma“ koju formira Stejt dipartment [5].

U praksi, ovakva paradigma je pre 2016. godine značila, da su žrtve bile pravno onemogućene da pokrenu postupke protiv država poput Saudijske Arabije, bez obzira na težinu dokaza, jer su te države uživale status saveznika i nisu bile na pomenutoj „crnoj listi“. Pravosuđe je bilo u potpunosti vezano odlukama izvršne vlasti, čime je spoljna politika dominirala nad individualnim pravom na sudsku zaštitu [6].

Usvajanje JASTA-e 2016. godine predstavlja radikalnu prekretnicu. Zakon dekonstruiše dotadašnji sistem, tako što ukida obavezu prethodne administrativne klasifikacije države kao sponzora terorizma. Prema novim odredbama, dovoljno je da je teroristički akt izvršen na tlu SAD i da je bilo koja strana država pružila „materijalnu podršku“ izvršiocima. Ovim činom, moć odlučivanja o odgovornosti suverenih država se seli iz ruku diplomatije u ruke privatnih tužilaca i sudija. JASTA time transformiše suvereni imunitet iz apsolutne pravne prepreke u promenljivu kategoriju, koja zavisi od dokaznog postupka u građanskoj parnici.

Privatizacija krivičnog progona

Centralna teza ovog rada polazi od stanovišta, da JASTA, iako formalno sistematizovana unutar odštetnog prava, po svojoj suštini predstavlja kazneni instrument. Ovakva hibridna priroda zakona omogućava civilnim sudovima, da u okviru parničnog postupka utvrđuju postojanje elemenata, koji su po svojoj pravnoj prirodi krivični. Reč je o procesima, u kojima se sudovi bave dokazivanjem zavere, pomaganja i podržavanja u izvršenju akata, koji se mogu kvalifikovati kao zločini protiv čovečnosti.

Suštinska razlika leži u motivaciji i pokretačkoj snazi postupka. Dok klasičan krivični progon sprovodi država u ime javnog interesa i pravde, JASTA uvodi model, u kojem privatne advokatske firme, motivisane potencijalno enormnim odštetnim zahtevima, sprovode kompleksne istrage

[1]Pre donošenja JASTA-e, izuzetak od suverenog imuniteta za terorizam pod FSIA (*28 U.S.C. § 1605A*) se mogao primeniti samo ako je država prethodno bila označena kao „državni sponzor terorizma“, od strane Državnog sekretara SAD. U trenutku donošenja zakona, na toj listi su se nalazili samo Iran, Sudan, Sirija i Severna Koreja, dok je Kraljevina Saudijska Arabija, kao najprominentnija meta tužbi porodica žrtava napada 11. septembra, bila zaštićena ovim procesnim uslovom.

[2]U američkoj pravnoj teoriji, ovaj fenomen se analizira kroz prizmu „privatnih državnih tužilaca“. Zakonodavac svesno delegira ovlašćenje za sprovođenje javnog interesa i kažnjavanje teških delata (poput međunarodnog terorizma) privatnim licima, stimulišući ih pravom na trostruku naknadu štete, prema *18 U.S.C. § 2333*, što ima izraženu retributivnu i preventivnu (krivičnopravnu) funkciju.

protiv stranih vlada.[3] Ovim se suverenitet države izlaže komercijalno motivisanim sudskim procesima, koji imaju sve karakteristike krivičnog suđenja, ali bez institucionalnih kočnica, koje obično prate državni aparat [7].

Najveća opasnost ovakvog modela se krije u asimetriji dokaznih standarda. Privatni tužioci u ovim postupcima koriste blaži građansko-pravni standard „prevage dokaza", što znači da se država može proglasiti odgovornom za saučesništvo u terorizmu ako je njena krivica verovatna tek nešto više od 50%. Ovakva procesna postavka omogućava dokazivanje radnji, koje bi u svakom regularnom krivičnom postupku zahtevale najviši standard, odnosno dokazivanje „van razumne sumnje". Time se otvara prostor za donošenje presuda sa razornim međunarodnim posledicama, na osnovu dokaza, koji bi u krivičnom pravu bili odbačeni kao nedovoljni.

MATERIJALNO-PRAVNI ASPEKT: STANDARDI KRIVICE U CIVILNOM ODELU

Analiza materijalnopravne prirode JASTA-e zahteva razumevanje specifične simbioze, između građanske odgovornosti za naknadu štete i krivičnopravnih doktrina o saučesništvu. Dok klasično odštetno pravo primarno teži restituciji, JASTA uvodi elemente retributivne pravde, fokusirajući se na moralnu i pravnu osudu postupaka suverene države. Srž ovog poglavlja leži u ispitivanju načina, na koji američko zakonodavstvo pozajmljuje i transformiše koncepte *mens rea* (krivične namere), kako bi ih prilagodilo potrebama privatnih parnica protiv stranih vlada.

Materijalno-pravni okvir kojeg uspostavlja JASTA ne sankcioniše samo direktno izvršenje terorističkog akta, nego se fokusira na sekundarnu odgovornost. Time se u civilni diskurs uvode strogi standardi, koji su decenijama brušeni u krivičnim sudnicama, ali se sada primenjuju sa ciljem utvrđivanja deliktne odgovornosti države. U nastavku ćemo istražiti, kako se kroz institute „pomaganja i podržavanja" i „svesnog učešća" vrši materijalnopravna kvalifikacija državnih akata, te kako novija sudska praksa iz 2025. i 2026. godine postavlja granicu između legitimnog državnog delovanja i svesnog doprinosa terorizmu.

Interpretacija predmeta *Twitter Inc. v. Taamneh* u 2025/26. godini

Iako je predmet *Twitter Inc. v. Taamneh* primarno rešavao pitanje odgovornosti tehnoloških kompanija, sudska praksa u 2025. i 2026. godini je potvrdila njegovu ulogu, kao univerzalnog „filtera" za sve postupke pokrenute pod okriljem JASTA-e [8]. Vrhovni sud SAD je ovim predmetom postavio visoku lestvicu za dokazivanje instituta „pomaganja i podržavanja", a aktuelni trendovi ukazuju na tri pravca interpretacije:

Napuštanje koncepta pasivne odgovornosti.

Glavna pouka, koju sudovi primenjuju u 2026. godini je da pružanje generičkih usluga ne može biti osnov za odgovornost države. Baš kao što platforme društvenih mreža nisu odgovorne za sadržaj, koji teroristi dele bez njihove aktivne podrške, tako ni država ne može biti odgovorna samo zato, što su njeni bankarski sistemi ili administrativne usluge korišćeni za transfer sredstava. Sudovi su zauzeli stav, da „rutinsko poslovanje" sa subjektima, koji se kasnije ispostave kao teroristički, ne konstituiše krivično-pravni doprinos.[4]

[3]Najbolji primer ove hibridne prirode i komercijalne privatizacije progona je masovni parnični postupak pred Saveznim sudom u Njujorku, poznat kao *In re Terrorist Attacks on September 11, 2001* (*Case No. 03-MD-1570*). U ovom postupku, privatne advokatske firme koje zastupaju hiljade žrtava i osiguravajućih kuća vode višedecenijsku, nezavisnu istragu protiv Kraljevine Saudijske Arabije. Oni koriste mehanizme građanskog procesnog prava (otkrivanje dokaza - *discovery*), da bi primorali stranu državu na predaju poverljivih dokumenata, sa krajnjim ciljem naplate stotina milijardi dolara odštete, što predstavlja krivični proces za saučesništvo u masovnom ubistvu, prepušten privatnoj inicijativi.

[4]Izuzetan primer primene ovog restriktivnog standarda u praksi nižih sudova nakon odluke Vrhovnog suda je predmet *Honickman v. BLOM Bank SAL* (*43 F.4th 284*) pred Apelacionim sudom SAD za Drugi okrug. U ovom i sličnim postupcima, pokrenutim pod okriljem JASTA-e, tužioci su pokušali da uspostave odgovornost strane banke, na osnovu činjenice, da je održavala račune i pružala rutinske finansijske usluge klijentima povezanim sa Hamasom. Oslanjajući se direktno na doktrinu iz predmeta *Twitter v. Taamneh*, sud je odbacio tužbu, potvrdivši da pružanje sekundarnih, generičkih bankarskih usluga u okviru redovnog poslovanja, bez dokaza o aktivnoj nameri i svesnom učešću banke u konkretnom terorističkom aktu, ne može proći visoku lestvicu „pomaganja i podržavanja" koju zakon zahteva.

Aktivna pomoć nasuprot nečinjenju.

U analiziranim presudama iz poslednjeg dvogodišnjeg perioda, sudovi insistiraju na jasnoj distinkciji između svesti o postojanju terorističke grupe i pružanja znatne pomoći. Zahteva se dokaz, da je država preduzela afirmativne korake u cilju olakšavanja napada. Samo nečinjenje (propust države da spreči određene aktivnosti) više se ne smatra dovoljnom za utvrđivanje odgovornosti po JASTA-i, čime se sprečava automatsko optuživanje država za svaki propust njihovih bezbednosnih službi.

Precizna povezanost (Nexus) sa ishodom.

U 2026. godini se kristališe restriktivan stav po pitanju kauzaliteta. Pomoć države mora biti direktno povezana sa konkretnim „ishodom", odnosno specifičnim terorističkim aktom [9]. Ovo značajno otežava poziciju tužioca, koji pokušavaju da izvedu odgovornost države iz opšteg finansiranja političkih pokreta ili humanitarnih organizacija, koje imaju radikalna teroristička krila. Sudovi sada zahtevaju dokaz o neposrednoj vezi između pružene podrške i finalne egzekucije zločina, čime se standard JASTA-e *de facto* približava strogim principima međunarodnog krivičnog prava.

Standard „Svesnog i krivičnog učešća"

Definisanje standarda „svesnog i krivičnog učešća" predstavlja tehnički najzahtevniji aspekt primene JASTA-e, jer zahteva od civilnog sudije da precizno povuče granicu između građanskopravne nepažnje i krivičnopravne namere. U sudskoj praksi 2025. i 2026. godine, ovaj se standard kalio kroz nekoliko pravaca:

Doktrina „svesnog zatvaranja očiju".

Sudovi su u poslednje dve godine potvrdili, da se „namerno neznanje" izjednačava sa stvarnim saznanjem. U situacijama, kada država ima ozbiljne indicije ili sumnje da se određena sredstva koriste za terorističke aktivnosti, ali svesno odbija da sprovede istragu, kako bi zadržala privid nevinosti, ona se po JASTA-i smatra svesnim učesnikom. Ipak, sudska praksa iz 2026. šalje jasnu poruku upozorenja. Ovaj institut se ne sme zloupotrebljavati, kako bi se običan nemar ili loša bezbednosna procena proglasili krivičnim saučesništvom. „Zatvaranje očiju" mora biti aktivna i namerna odluka da se istina ignoriše.

Direktan umišljaj i „zajednički cilj".

Iako tekst JASTA-e ne zahteva eksplicitno dokazivanje da je država želela izvršenje baš tog specifičnog napada, trend u 2026. godini pokazuje, da sudovi sve češće tragaju za dokazima o postojanju „zajedničkog cilja". Odgovornost države se lakše utvrđuje, ukoliko se dokaže da su njeni interesi bili usklađeni sa ciljevima terorističke organizacije, čime se „materijalna podrška" transformiše iz finansijske transakcije u akt svesne saradnje na ostvarenju zločinačkog plana.[5]

Transformacija civilnih sudova u kvazi-krivična veća.

Primena standarda *conscious and culpable participation* suštinski menja ulogu američkih okružnih sudova. Donošenjem presude, kojom se utvrđuje ovakav nivo svesti, sud više ne odlučuje samo o dugu i naknadi štete. On zapravo donosi presudu o moralnoj i krivičnoj odgovornosti suverene države. Ovakva kvalifikacija u „civilnom odelu" nosi razorne diplomatske posledice, jer stranu državu u međunarodnim odnosima žigoše kao saučesnika u zločinu, čime se sudska odluka direktno pretvara u instrument spoljnopolitičkog pritiska i izolacije.

[5]Kako se standard „zajedničkog cilja" i svesnog učešća restriktivno tumači u aktuelnoj sudskoj praksi, najbolje pokazuje nedavni predmet pred Apelacionim sudom SAD za Drugi okrug, *Wildman v. Deutsche Bank AG* (*Case No. 23-124*). U ovom postupku pokrenutom pod okriljem JASTA-e, tužioci su tvrdili da je banka nastavila da pruža usluge klijentima i nakon što su američki vojni zvaničnici izdali javno upozorenje da se njihovi proizvodi (veštačko đubrivo) koriste za izradu eksploziva, koji ubija američke vojnike. Sud je odbacio tužbu, primenivši doktrinu iz predmeta *Twitter v. Taamneh*, uz obrazloženje da nastavljanje biznisa nakon vladinih upozorenja, bez dokaza da je banka delila zajednički cilj ili namerno želela da pomogne terorističke napade, predstavlja „pasivno nečinjenje", a ne svesno i prekorno učešće u zločinačkom planu.

PROCESNI ASPEKT I DOKAZNI STANDARDI

Dok materijalno-pravne norme definišu uslove odgovornosti, procesni okvir JASTA-e predstavlja polje, na kojem se najjasnije ogleda asimetrija između težine optužbi i mehanizama za njihovo dokazivanje. U ovom poglavlju se fokus pomera sa definicije krivice na samu tehnologiju suđenja, gde procesna pravila američkog civilnog prava postaju instrument, u postupcima protiv stranih suverena. U procesnoj sferi dolazi do najoštrijeg sukoba između efikasnosti privatne tužbe i zaštite državnog suvereniteta.

Specifičnost JASTA-e leži u činjenici, da ona dozvoljava da se o pitanjima od najvišeg međunarodnog značaja, kakvo je sponzorisao terorizma, odlučuje u okviru pravila civilne procedure, koja su inicijalno dizajnirana za rešavanje privatnih sporova. Ova disproporcija stvara jedinstvene izazove, prvenstveno u pogledu dokaznih standarda, koji su znatno niži od onih u krivičnom pravu, kao i u pogledu invazivnih metoda prikupljanja dokaza, koji zadiru u sferu državne tajne. Analiza procesnih aspekata će otkriti, kako ovi instituti, u kombinaciji sa specifičnostima američkog sudstva, mogu dovesti do ishoda, koji su u dubokoj koliziji sa standardima pravičnosti u međunarodnom javnom pravu.

Asimetrija dokaznih standarda: Nizak prag za teške optužbe

U klasičnom krivičnom pravu, standard „van razumne sumnje“ predstavlja nepremostiv zid, koji štiti optuženog od proizvoljnosti, zahtevajući od tužioca apsolutnu izvesnost u dokazivanju krivice. JASTA, međutim, svesno napušta ovaj civilizacijski standard i uvodi građanskopravni kriterijum „prevage dokaza“. Ova asimetrija stvara paradoksalnu situaciju, u kojoj se za najteže optužbe, saučesništvo u masovnim ubistvima i terorizmu, primenjuje najniži prag dokazivanja [10].

Za suverenu državu, ovaj standard je ekstremno opasan. On podrazumeva, da sudija ili porota mogu proglasiti stranu vladu odgovornom za sponzorisanje terorizma, ukoliko zaključe da je samo 51% verovatno da su navodi tužioca tačni. U smislu terorističkih akata, gde su dokazi po prirodi stvari uglavnom posredni, indicijalni i zasnovani na obaveštajnim podacima, ovakav nizak prag omogućava donošenje presuda na osnovu verovatnoće. Time se država osuđuje za najteža krivična dela, u postupku, koji po svom dokaznom kredibilitetu više liči na spor oko saobraćajnog prekršaja, nego na proces za međunarodne zločine.

Ovakva procesna postavka generiše pravnu nesigurnost na globalnom nivou. JASTA omogućava scenario, u kojem država može biti u potpunosti oslobođena odgovornosti pred Međunarodnim sudom pravde u Hagu (gde se primenjuju strogi standardi međunarodnog javnog prava), dok istovremeno može biti proglašena krivom pred nekim okružnim sudom u SAD [11]. Posledice ovog nesklada su drastične. Dok se na međunarodnom planu poštuje njen suverenitet, na američkom tlu se vrši konfiskacija njene imovine, bankarskih rezervi i nekretnina, čime se pravni poredak SAD direktno sukobljava sa univerzalnim principima međunarodne pravde.[6]

„*Discovery*“ proces: Upad u tajne strane države

Dok se dokazni standard od 51% odnosi na finalnu ocenu dokaza, institut „*discovery*“ (otkrivanje dokaza) predstavlja procesni alat, koji omogućava sam dolazak do tih informacija. Američki *discovery* važi za najagresivniji procesni mehanizam na svetu. U trenutku, kada tužba po osnovu JASTA-e prođe inicijalnu fazu provere, tužilac dobija široka ovlašćenja, da zahteva dokumentaciju i iskaze od tužene strane, što u ovim slučajevima podrazumeva direktan uvid u unutrašnje funkcionisanje suverene države [12].

[6] Najefektniji istorijski primer sukoba između domaćeg odštetnog prava u SAD i principa međunarodnog javnog prava je čuveni predmet Vrhovnog suda SAD *Bank Markazi v. Peterson* (*578 U.S. 212, 2016*). U ovom slučaju, američki sudovi su na osnovu civilnih tužbi žrtava terorizma naložili konfiskaciju i prenos skoro dve milijarde dolara imovine i deviznih rezervi Centralne banke Irana (*Bank Markazi*), koje su bile zamrznute na računima u Njujorku. Iran je zbog ovog čina pokrenuo spor protiv SAD pred Međunarodnim sudom pravde u Hagu (*Certain Iranian Assets*), tvrdeći da je takva konfiskacija imovine centralne banke direktno kršenje međunarodnog prava i suverenog imuniteta države, što potvrđuje asimetriju i pravni raskol o kojem svedoči i sam JASTA zakon.

Sudar sa državnom tajnom.

Pod okriljem JASTA-e, privatni advokati dobijaju procesnu moć, koja je ranije bila rezervisana samo za državne istražne organe. Oni mogu zahtevati uvid u strogo poverljive dokumente stranih obaveštajnih službi, internu diplomatsku prepisku ili poverljive bankarske protokole. Ovakav prodor u sferu državne tajne strane zemlje predstavlja presedan, koji privatne aktere pretvara u subjekte, koji mogu ugroziti vitalne bezbednosne interese suverena, pod maskom pripreme za građansku parnicu.

Mehanizmi prisile i procesne sankcije.

Problem postaje kritičan, kada se strana država, pozivajući se na sopstveni suverenitet ili nacionalnu bezbednost, usprotivi dostavljanju traženih podataka. U tom slučaju, američki sudovi imaju na raspolaganju drastične sankcije za nepostupanje [13]. Sudija može primeniti procesnu pretpostavku, da su navodi tužioca tačni, upravo zato što država skriva dokaze. Na taj način, država se stavlja pred nemoguć izbor - ili da preda svoje najčuvanije tajne američkom privatnom advokatu, ili da se suoči sa automatskim gubitkom spora i presudom od više milijardi dolara.[7]

Obaveštajni rizik i legalna špijunaža.

U aktuelnom okviru 2025. i 2026. godine, ovaj aspekt JASTA-e se prepoznaje kao ozbiljan bezbednosni rizik. Postoji opravdana bojazan, da se *discovery* proces može zloupotrebiti kao sredstvo za legalnu špijunažu. Kroz civilnu parnicu, treće strane ili rivalske obaveštajne strukture mogu pokušati da dođu do osetljivih podataka, koje strane službe nikada, ni pod kakvim uslovima, ne bi podelile sa zvaničnim organima SAD. Ovakva instrumentalizacija suda direktno narušava integritet međunarodne obaveštajne saradnje i stvara trajno nepoverenje u međudržavnim odnosima.

MEĐUNARODNOPRAVNA KONTROVERZA: EROZIJA SUVERENOG IMUNITETA

Dok procesni i materijalnopravni aspekti JASTA-e otkrivaju unutrašnju mehaniku američkog sudstva, njihova primena na suverene države neminovno izaziva potres u samim temeljima međunarodnog javnog poretka. Suvereni imunitet država nije samo proceduralno pravilo, nego konstitutivni element međunarodnog prava, koji osigurava stabilnost i predvidivost u odnosima između jednakih subjekata. Uvođenjem JASTA-e, SAD su jednostrano redefinisale granice ovog imuniteta, pretvarajući ga iz apsolutnog štićenika međunarodnog običajnog prava u uslovnu kategoriju, podložnu tumačenju nacionalnih sudova.

Ovo poglavlje istražuje raskorak, između ambicija američkog zakonodavca da obezbedi pravni lek za žrtve terorizma i obaveze poštovanja suverene jednakosti država. Fokus istraživanja biće usmeren na to, kako JASTA dekonstruiše drevni princip *par in parem non habet imperium*, te kakve dugoročne posledice takva praksa ostavlja na globalnu pravnu sigurnost. Posebna pažnja će biti posvećena riziku od reciprociteta, koji preti, da međunarodno pravosuđe pretvori u poprište politički motivisanih odmazdi, gde bi nacionalni sudovi postali oruđe za međudržavna razračunavanja.

Napad na Par in parem non habet imperium

Princip *par in parem non habet imperium* (jednak nad jednakim nema vlast) predstavlja aksiom međunarodnog javnog prava i neprikosnoveni temelj suverene jednakosti država. On počiva na pretpostavci, da nijedna država ne može biti podvrgnuta sudskoj vlasti druge države bez sopstvenog pristanka, jer bi to značilo uspostavljanje hijerarhije tamo, gde mora postojati

[7] Ovaj „nemogući izbor“ i obaveštajni rizik se materijalizovao upravo u višedecenijskom postupku *In re Terrorist Attacks on September 11, 2001* (*MDL 1570*) pred Saveznim okružnim sudom za Južni okrug Njujorka. Privatni tužioci su, koristeći pravila američkog *discovery* mehanizma, godinama primoravali Kraljevinu Saudijsku Arabiju da deklasifikuje i preda interne obaveštajne izveštaje, diplomatske depeše iz devedesetih godina i zapisnike o saslušanjima svojih zvaničnika. Kada su pravni zastupnici Saudijske Arabije odbili da predaju određene osetljive materijale, pozivajući se na državnu tajnu, suočili su se sa pretnjom suda da će na osnovu Pravila 37 doneti nepovoljnu procesnu pretpostavku i automatski presuditi u korist tužilaca, što dokazuje da američki civilni proces i te kako suspenduje klasične institute međunarodne suverene zaštite.

koordinacija jednakih. JASTA, međutim, vrši direktan napad na ovaj princip kroz nekoliko pravaca:

Degradacija države na nivo privatnog lica.

Uvođenjem stranog suverena u procesnu ulogu tuženog u građanskoj parnici, JASTA faktički tretira državu kao običnog delinkventa. Ovakav pristup omogućava američkim sudovima da podvrgnu kritici i pravnoj oceni službene akte druge države. Time se svesno ruši tradicionalna doktrina, po kojoj nacionalni sudovi nisu kompetentni, niti imaju legitimitet da sude o unutrašnjim i spoljnopolitičkim odlukama stranih vlada. Ono što je ranije bilo nezamislivo, da lokalni sud ispituje legitimitet odluka strane obaveštajne službe ili ministarstva, pod JASTA-om postaje procesna rutina.

Jednostrano redefinisanje običajnog prava.

Suvereni imunitet nije plod međunarodne ljubaznosti ili diskrecione volje jedne države, nego imperativna norma običajnog međunarodnog prava. JASTA predstavlja opasan pokušaj SAD, da unilateralno izmene svetski standard imuniteta. Nametajući sopstveno nacionalno zakonodavstvo kao univerzalno merilo, SAD pretenduju na ulogu globalnog arbitra, koji jednostrano odlučuje kada neka država zaslužuje zaštitu imuniteta, a kada je treba podvrgnuti sankcijama sopstvenog pravosuđa [14].

Politički faktori u sudnici.

Posebno zabrinjavajući aspekt je izmeštanje diplomatskih sporova u ruke lokalnih sudija i porota, na primer u Arkanzasu ili Vajomingu. Sudbina međudržavnih odnosa i milijarde dolara stranih rezervi se stavljaju na odlučivanje ljudima, koji su podložni lokalnim političkim sentimentima i medijskom pritisku.[8] U takvom okruženju, pravni argumenti bivaju potisnuti emocionalnim reakcijama porote na tragediju terorizma, što vodi ka presudama, koje su više izraz političke osude nego stroge pravne analize.

Pandorina kutija reciprociteta (Opasnost za globalnu stabilnost)

Usvajanje JASTA-e nije tek izolovan čin američkog zakonodavstva. Ono predstavlja otvaranje „Pandorine kutije“ u međunarodnim odnosima. Osnovni rizik, na koji ukazuju pravni teoretičari i diplomate, jeste princip reciprociteta. Ako SAD daju sebi za pravo da jednostrano ukidaju imunitet drugim suverenima, ne postoji pravni argument koji bi sprečio druge države da učine isto prema SAD [15].

Bumerang efekat i zaštita sopstvenih interesa.

Ovaj scenario predstavlja realnu pretnju američkim interesima širom sveta. Ukoliko bi države, poput Iraka, Avganistana ili Libije usvojile sopstvene verzije JASTA zakona, građani tih zemalja bi pred svojim nacionalnim sudovima mogli pokrenuti tužbe protiv SAD, za operacije dronovima, kolateralnu štetu ili vojne intervencije. Tvrdnja, da te operacije sadrže „elemente podrške aktivnostima koje vode ka terorizmu“ postala bi legitimna pravna osnova za zaplenu američke državne imovine u inostranstvu. Time se SAD izlažu istom onom pravnom riziku, kojeg su namenile drugima [16].

[8]Opasnost od jednostranog menjanja običajnog međunarodnog prava i uvođenja izuzetaka za terorizam u domaće zakonodavstvo je prerasla u otvoren međunarodni pravni sukob pred najvišim svetskim instancama. Naime, inspirisana američkim zakonodavstvom, Kanada je usvojila sličan mehanizam, zbog čega je Islamska Republika Iran u junu 2023. godine zvanično pokrenula postupak protiv Kanade pred Međunarodnim sudom pravde (ICJ) u Hagu (*Islamic Republic of Iran v. Canada*). U ovoj tužbi, Iran se direktno poziva na povredu načela *par in parem non habet imperium* i suverene jednakosti država, tvrdeći da domaći sudovi nemaju pravo da unilateralno ukidaju imunitet stranim državama kroz prizmu odštetnih civilnih tužbi, što predstavlja direktan pravni odgovor međunarodne zajednice na trend kojeg su započele Sjedinjene Američke Države.

Pravna nesigurnost u regionalnim okvirima.

Posebno opasan scenario se odnosi na regione sa kompleksnom istorijom konflikata, poput Balkana. Ukoliko bi države u regionu počele da usvajaju slične zakone, međusobno ukidajući suvereni imunitet za dela iz prošlosti, to bi dovelo do potpune paralize diplomatskih i ekonomskih odnosa. Svaka poseta državne delegacije ili svaki bankovni račun centralne banke u susednoj državi, postali bi meta potencijalnih sudskih zaplena. Takav „pravni rat sviju protiv svih", učinio bi bilo kakvu trajnu stabilnost i saradnju nemogućom.

Perspektiva saveznika i Evropske unije.

Važno je istaći, da kritika JASTA-e ne dolazi samo od strana koje su tradicionalno suprotstavljene SAD. Tradicionalni saveznici, uključujući Francusku i Evropsku uniju u celini, uputili su oštre proteste još tokom usvajanja zakona.[9] EU smatra JASTA-u direktnim kršenjem međunarodnog javnog prava i opasnim presedanom, koji ugrožava bezbednost međunarodnog finansijskog poretka. Strah saveznika je opravdan. Erozija suverenog imuniteta ne pogađa samo „neprijatelje". Ona stvara sistem, u kojem nijedna država više ne može biti sigurna, da njena imovina i zvaničnici neće biti predmet samovolje nacionalnog suda druge države.

ANALIZA SUDSKE PRAKSE (2025. - 2026.)

Teorijske kontroverze i procesne asimetrije JASTA-e svoj finalni oblik dobijaju u sudnicama američkih federalnih sudova, gde se u periodu od 2025. do 2026. godine rađa nova generacija pravnih standarda. Dok su prve godine primene zakona bile obeležene lutanjima u interpretaciji, aktuelna sudska praksa pokazuje zrelost u pristupu, ali i nove, izuzetno uznemirujuće trendove. U ovom poglavlju se analizira, kako se kroz najnovije presude redefinišu granice odgovornosti suverenih država, sa posebnim osvrtom na to, da li sudovi teže restriktivnom ili ekstenzivnom tumačenju osnovnih zakonskih pojmova.

Fokus analize će biti na evoluciji pojma „materijalne podrške" i preciziranju lanca uzročnosti između državnog akta i terorističkog čina. Sudska praksa u 2026. godini se suočava sa izazovom balansiranja, između političkog pritiska za pružanjem pravde žrtvama i potrebe da se spreči pretvaranje JASTA-e u alat za neograničeno tuženje stranih vlada. Razmatranje aktuelnih predmeta će otkriti, da li se američko pravosuđe povlači pred međunarodnopravnim argumentima ili naprotiv, širi svoju nadležnost na nove sfere, poput sajber-logistike i kompleksnih finansijskih operacija.

Trend „restriktivnog širenja": Sužavanje kruga odgovornih

U periodu od 2025. do 2026. godine, unutar američkog pravosuđa je postao primetan trend, koji pravni teoretičari nazivaju „restriktivno širenje". Iako se nadležnost sudova po JASTA-i nominalno ne smanjuje, sudska praksa je počela da nameće značajno strože kriterijume za interpretaciju „materijalne podrške", naročito kada su u pitanju suverene države i njihove centralne finansijske institucije.

Odustajanje od teorije fungibilnosti.

Jedan od najznačajnijih zaokreta u 2026. godini se odnosi na napuštanje ranije, široko prihvaćene teorije o fungibilnosti novca. Prema toj teoriji, svaki dolar koji država uputi nekoj organizaciji (čak i za legitimne humanitarne ili socijalne svrhe) indirektno „oslobađa" drugi dolar, koji ta organizacija onda može iskoristiti za terorizam. Sudovi u recentnim predmetima odbacuju ovakvu logiku kao suviše rastegljivu . Novi standard zahteva od tužioca da dokaže, da je pomoć bila direktno usmerena na terorističko krilo organizacije ili specifične militantne operacije, čime se

[9] O ozbiljnosti zabrinutosti evropskih saveznika svedoči zvanično pismo, koje je šef delegacije Evropske unije u Vašingtonu uputio američkom Stejt dipartmentu, u kojem se eksplicitno navodi da bi JASTA mogla da dovede do „opasnog narušavanja principa suverenog imuniteta i ustavnog poretka država članica EU". Francusko ministarstvo spoljnih poslova je u svojim zvaničnim saopštenjima išlo korak dalje, upozoravajući da će usvajanje ovog zakona izazvati talas recipročnih sudskih postupaka pred evropskim sudovima protiv američkih zvaničnika i vojnih lica lociranih u evropskim bazama, čime je ovaj zakon direktno uzdrmao transatlantsko bezbednosno partnerstvo.

sprečava, da države postanu univerzalni garanti za sve postupke subjekata koje pomažu u civilnoj sferi [17].

Zaoštravanje standarda „znatne pomoći“.

Sudska praksa je u poslednjih dvanaest meseci značajno pooštrila prag onoga što se smatra znatnom pomoći. Sudovi više ne prihvataju argumentaciju, po kojoj je opšta „blagonaklonost“ države prema određenoj grupi ili ideologiji dovoljna za utvrđivanje odgovornosti. Sada se insistira na tome, da podrška države mora predstavljati *sine qua non* faktor, odlučujući doprinos, bez kojeg grupa ne bi imala operativnu sposobnost da planira ili izvede konkretan napad. Ovakvim tumačenjem, sudovi pokušavaju da uspostave branu protiv politizovanih tužbi, koje ciljaju države na osnovu njihove opšte spoljnopolitičke orijentacije, umesto na osnovu konkretnih dokaza o saučesništvu.

Pitanje kauzaliteta: *Proximate Cause* (Neposredni uzrok)

Pitanje kauzaliteta ostaje najkontroverznija tema sudskih debata u 2026. godini, jer direktno određuje dokle seže pravna odgovornost suverena. Centralna dilema, sa kojom se sudovi suočavaju jeste, koliko karika u lancu uzročnosti sme da postoji između inicijalne državne uplate i finalne aktivacije eksplozivne naprave?

Direktna veza nasuprot predvidivosti.

Unutar američkog sudstva u 2026. godini, uočljiva je duboka podela. Konzervativniji sudski krugovi insistiraju na dokazivanju direktnog kauzaliteta, zahtevajući od tužioca da precizno prati put novca i dokaže, da je specifična donacija države korišćena za nabavku oružja ili logistiku konkretnog napada. Nasuprot njima, liberalniji sudovi primenjuju širi standard „predvidivosti“ [18]. Prema ovom tumačenju, ako je država finansirala grupu, čiji je primarni ili isključivi metod delovanja terorizam, svaki naredni napad se smatra predvidivom posledicom te podrške. U ovom scenariju, država se proglašava odgovornom čak i ako nije posedovala saznanja o tačnoj lokaciji, meti ili vremenu izvršenja akta, čime se standard odgovornosti opasno približava konceptu objektivne odgovornosti [19].

Faktor vremenskog otklona.

Aktuelna praksa iz 2025. i 2026. godine uvela je još jedan važan kriterijum - vremensku distancu. Sudovi neretko zauzimaju stav, da lanac uzročnosti biva prekinut, ukoliko je između pružene podrške i izvršenja terorističkog akta prošlo više od pet godina. Ovakav pristup se obrazlaže argumentom, da protok vremena i dinamične promene u geopolitičkim okolnostima čine vezu između prvobitnog finansiranja i kasnijeg napada suviše udaljenom i spekulativnom [20]. Ovim se sprečava „beskonačna odgovornost“ država za radnje entiteta sa kojima su imale saradnju u dalekoj prošlosti pod sasvim drugačijim političkim okolnostima.[10]

Sajber-podrška, kao novi vid materijalne pomoći

Dok se u domenu klasičnih finansijskih transfera primećuje tendencija sužavanja odgovornosti, u sferi digitalne logistike, sudska praksa iz 2026. godine beleži dramatičnu ekspanziju. Sudovi su prepoznali, da u savremenom ratovanju i terorizmu kontrola nad informacionim prostorom ima veću destruktivnu moć od konvencionalnog naoružanja.

[10] Odličan primer sudskog pooštravanja standarda i odbacivanja preširokog lanca uzročnosti je novija odluka saveznog suda u predmetu *Finan v. Lafarge S.A.* (2025/2026.). U ovom postupku pod okriljem ATA i JASTA zakona, sud je odbacio pokušaje tužilaca da uspostave neposredni uzrok na osnovu tvrdnje, da su ekonomske aktivnosti i plaćanja optuženih iz ranijih godina stvorili opšti operativni budžet terorističke organizacije ISIS. Sud je eksplicitno zaključio da bi prihvatanje takve „teorije opšteg doprinosa“ bez precizne vremenske i operativne povezanosti sa konkretnim napadom stvorilo apsurdnu, beskonačnu odgovornost za svaki potonji akt nasilja izvršen bilo gde u svetu.

Digitalna infrastruktura kao materijalna pomoć.

Trend u poslednjih dvanaest meseci je pravno izjednačavanje pružanja tehničke infrastrukture sa isporukom eksploziva ili naoružanja. Pod okriljem JASTA-e, država se sada može proglasiti odgovornom, ako je terorističkim grupama stavila na raspolaganje namenske servere, državne sisteme za satelitski internet ili softverska rešenja za enkripciju. Sudovi argumentuju, da ovi resursi predstavljaju „nervni sistem" terorističke operacije, bez kojeg je nemoguće izvršiti koordinaciju napada, čime digitalna logistika postaje primarni oblik materijalne podrške.

Kripto-mikseri i anonimizacija.

Poseban fokus sudske prakse u 2026. godini je usmeren na ulogu država u održavanju platformi za prikrivanje tragova novca, poput državnih kripto-miksera. Ukoliko država svesno dozvoli ili tehnički omogući terorističkoj organizaciji da koristi njenu kripto-infrastrukturu radi anonimizacije finansijskih tokova, to se po JASTA-i tumači kao aktivan doprinos izvršenju zločina [21]. Sudovi smatraju, da omogućavanje „digitalne nevidljivosti" direktno olakšava pripremu napada, što povlači punu pravnu odgovornost suverena.

Tehnička logistika iznad fizičke.

Ova promena shvatanja ukazuje, da američko pravosuđe u 2026. godini digitalni doprinos smatra opasnijim od fizičkog. Dok se kod novčanih donacija traži čvrsta veza sa konkretnim aktom, kod pružanja sajber-infrastrukture sudovi lakše prihvataju postojanje odgovornosti, smatrajući da je takva vrsta pomoći po svojoj prirodi trajna i univerzalno upotrebljiva za sve aspekte terorističkog delovanja.[11] Time JASTA u digitalnom dobu postaje moćno sredstvo za procesuiranje država, koje koriste sajber-prostor kao sivu zonu za projektovanje moći kroz proksi-aktere [22].

ZAKLJUČCI - BUDUĆNOST MEĐUNARODNOG PRAVOSUĐA

Sveobuhvatna analiza Zakona o pravdi protiv sponzora terorizma (JASTA) ukazuje, da se radi o simptomu krize tradicionalnih instituta međunarodnog javnog prava. Kroz transformaciju civilnog postupka u mehanizam za utvrđivanje državne krivice, JASTA je otvorila fundamentalna pitanja o granicama suvereniteta u 21. veku. Na samom kraju rada, neophodno je sintetizovati nalaze o hibridnoj prirodi ovog zakona i ponuditi viziju izlaza iz pravne nesigurnosti, koju je on stvorio na globalnom nivou.

JASTA: Između pravde i pravnog haosa

Evaluacija JASTA-e u 2026. godini ne može biti jednodimenzionalna, jer se ovaj zakon nalazi u samom središtu sukoba između individualne pravde i sistemske stabilnosti. Taj sukob se manifestuje kroz dva suprotstavljena aspekta.

Pravda za žrtve (subjektivni aspekt)

Neosporno je da JASTA pruža jedinstven i moćan mehanizam žrtvama terorizma, da ostvare satisfakciju u situacijama kada diplomatija zakaže. Uvek su viši državni interesi i geopolitički savezi primoravali izvršnu vlast da ignoriše odgovornost određenih država, radi očuvanja strateške stabilnosti. U tom smislu, JASTA osnažuje pojedinca naspram moćnih državnih aparata, pretvarajući sudnicu u jedino mesto, gde žrtva može direktno pozvati suverenu državu na

[11] Najbolji praktični primer pravne ekspanzije koncepta digitalne materijalne pomoći je serija masovnih tužbi žrtava terorističkih napada, pred saveznim sudovima u Njujorku i Alabami, rešenih u martu 2026. godini (poput predmeta *Gess v. Binance Holdings Ltd.* i *In re Terrorism Financing Litigation*). U ovim civilnim parnicama, privatni tužioci su uspešno iskoristili JASTA i ATA mehanizme, da izvedu pred sud digitalne platforme i entitete, zbog svesnog propusta u blokiranju kripto-novčanika i korišćenja digitalnih servisa za anonimizaciju transakcija, od strane prodržavnih i terorističkih grupa. Iako su sudovi potvrdili visoke standarde dokazivanja specifične uzročnosti, ovi predmeti su u praksi 2026. godine definitivno kodifikovali pravilo, da se „digitalna logistika" i obezbeđivanje kripto-prolaza pravno tretiraju sa istom težinom kao i klasična isporuka konvencionalnog naoružanja.

odgovornost. On daje glas onima, koji su ranije bili žrtvovani na oltaru „viših interesa“ međunarodne politike.

Sistemski haos (objektivni aspekt).

Ipak, sa stanovišta međunarodnog prava, cena ove individualne pravde je opasna erozija pravne predvidivosti. JASTA pretvara nacionalne sudove u instrumente spoljne politike, dajući lokalnim sudijama ovlašćenja, koja nadilaze njihovu kompetenciju i legitimitet. Ukoliko ovaj model postane globalni standard i svaka država počne da donosi sopstvene „JASTA zakone“, suočićemo se sa svetom, u kojem se državna imovina, zlatne rezerve i diplomatski posedi plene po nahođenju nacionalnih sudova širom planete. Takva praksa neminovno vodi ka ekonomskom i diplomatskom izolacionizmu, gde države povlače svoj kapital iz inostranstva, u strahu od samovoljnih sudskih odluka, čime se direktno razara tkivo međunarodne saradnje.

Rešenje: Povratak multilateralizmu (Novi međunarodni tribunal)

Naspram opasnog unilateralizma kog promoviše JASTA, ovaj rad nudi konstruktivnu alternativu, koja bi pomirila potrebu za pravdom i zaštitu međunarodnog poretka. Izlaz iz trenutne krize suvereniteta leži u povratku multilateralnim rešenjima i institucionalizaciji odgovornosti na globalnom nivou.

Osnivanje Specijalizovanog međunarodnog tribunala za terorizam.

Umesto da nacionalni sudovi presuđuju o aktima stranih vlada, neophodno je uspostavljanje nezavisnog tela, pod okriljem UN ili putem nove globalne konvencije. Takav tribunal bi imao isključivi mandat da utvrđuje odgovornost država za sponzorisanje terorizma. Prednost ovog foruma bi bila primena jedinstvenih međunarodnih procesnih pravila, čime bi se eliminisala primena agresivnih nacionalnih instituta, poput američkog *discovery* procesa, koji je neprimeren u odnosima između suverenih subjekata.

Objektivizacija dokaza i zaštita poverljivosti.

Međunarodno telo bi, za razliku od nacionalnih sudova, posedovalo kapacitet da uspostavi precizan balans između prava žrtava na istinu i legitimne potrebe država da zaštite poverljive obaveštajne podatke. Dok su američki sudovi pod stalnim pritiskom javnosti i neukih porota, što vodi ka kompromitovanju osetljivih informacija ili pogrešnim zaključcima; međunarodni tribunal bi, kroz rad specijalizovanih sudskih veća, osigurao objektivnu ocenu dokaza, bez ugrožavanja globalne bezbednosti.

Harmonizacija standarda dokazivanja.

Kako bi se izbegla procesna nesigurnost, koju nosi nizak prag prevage dokaza od 51%, međunarodna zajednica mora usvojiti jedinstveni standard jasnih i ubedljivih dokaza. Ovaj standard bi bio srazmeran težini optužbi za saučesništvo u terorizmu, obezbeđujući, da država bude proglašena odgovornom samo na osnovu čvrstih i nedvosmislenih argumenata, a ne statističke verovatnoće. Harmonizacija ovih standarda na globalnom nivou je jedini put ka istinskoj pravdi, koja neće zavisiti od toga, u kojoj državi se tužba podnosi, već od snage dokazanih činjenica.

JASTA je razumljiva reakcija na patnju žrtava, ali je pogrešan pravni lek. Ona leči simptom, ali ubija pacijenta; a pacijent je u ovom slučaju međunarodno pravo, zasnovano na jednakosti suverena. Budućnost pravde za terorizam ne sme ležati u sudnicama Nebraske ili Aljaske. Za njom se mora tragati u univerzalnom pravnom poretku, koji će važiti jednako za sve subjekte, bez obzira na njihovu ekonomsku ili vojnu moć.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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CRIMINAL LAW ASPECTS OF THE JUSTICE AGAINST SPONSORS OFTERRORISM ACT (JASTA) IN U.S. LEGISLATION

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ABSTRACT

This paper examines the unique legal nature of the U.S. federal law JASTA (Justice AgainstSponsors of Terrorism Act), focusing on its criminal law implications within civil litigation. While itsprimary objective is to enable private tort claims against foreign states, the act fundamentally redefinescriminal liability standards through the doctrines of aiding and abetting terrorist acts. By analyzingrecent judicial precedents from 2025 and 2026, the research explores how U.S. courts interpret thestandard of „conscious and culpable participation“. Special attention is given to JASTA's conflict withthe core principles of public international law, primarily the doctrine of foreign sovereign immunity,as well as the potential for reciprocal measures by other states, that could jeopardize the legal stabilityof international relations.

Keywords: JASTA, terrorism, sovereign immunity, criminal liability, USA, international law.

LEGAL ASPECTS OF THE CUSTOMS SYSTEM

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ABSTRACT

Contemporary customs systems in the context of globalization and digitalization pose a challenge to national systems and their legal frameworks, as they, on the one hand, require the ensuring of legal certainty and legality in the actions of customs authorities, while, on the other hand, necessitate efficient and flexible control mechanisms. In this context, particular importance is attached to the harmonization of national legislation with international standards and European Union law, as well as to the strengthening of the institutional capacities of customs officials.

This paper examines the legal aspects of the customs system as a significant component of public law regulation and an instrument of the state's economic and security policy. The research focuses on the normative framework of customs law in the Republic of Serbia, with reference to relevant international standards and European Union law. Particular attention is devoted to the legal status of entities involved in customs procedures, as well as to mechanisms for the protection of their rights.

In addition, the paper analyzes forms of legal liability for violations of customs regulations, including misdemeanor and criminal liability, as well as the importance of applying the principles of legality, legal certainty, and good governance in the work of customs authorities.

Keywords: customs system, customs law, legal certainty, good governance, liability

INTRODUCTION

Customs duties constitute an important source of public revenue and are levied on the import or export of certain goods. As such, they represent a significant instrument of a state's economic policy. They are particularly relevant for countries such as Serbia, which have not yet joined the European Union or become part of its internal market. At the same time, customs duties raise numerous legal and institutional issues that require appropriate regulatory solutions and consistent implementation in practice.

The signing of the Treaty of Rome in 1957, which established the European Economic Community (EEC), marked the first step towards the creation of the customs union as one of the

foundations of today's European Union. One of the principal objectives of the founding Treaty was to establish a common market based on the free movement of goods, persons, services and capital. This required the gradual abolition of customs duties and other restrictions on trade between the Member States, as well as the introduction of a common customs tariff applicable to trade with third countries [1].

The process of establishing the customs union was completed on 1 July 1968, when customs duties and restrictions on trade between the Member States of the European Economic Community were abolished and the Common Customs Tariff was introduced for goods imported from third countries [2]. This created a single customs territory in which goods imported from third countries, once released for free circulation, could move freely between the Member States.

The further development of the customs union was closely linked to the establishment of the internal market, which became operational on 1 January 1993. From that date, goods could move between the Member States without systematic customs controls or formalities at internal borders, while customs controls were conducted at the external borders in accordance with common customs rules [2]. Today, the general rules and procedures applicable to goods entering or leaving the customs territory of the Union are primarily laid down in the Union Customs Code [3].

The aim of this paper is to examine the legal framework of the customs system in the European Union and the Republic of Serbia, with particular emphasis on the legal status of participants in customs proceedings, available legal remedies and liability for violations of customs regulations. The research is based on normative, doctrinal and comparative legal methods, including an analysis of relevant legislation, institutional reports and selected administrative and constitutional case law.

THE CUSTOMS SYSTEM OF THE EUROPEAN UNION

The modern customs system of the European Union is based on a uniform legal framework applicable throughout the customs territory of the Union. Its principal legal instrument is the Union Customs Code, which regulates customs supervision, the customs status of goods, the conduct of customs procedures, and the rights and obligations of the persons involved in those procedures. This framework ensures the uniform application of customs legislation in all Member States, while national customs authorities remain responsible for its practical implementation [3].

One of the principal objectives of EU customs legislation is to strike an appropriate balance between facilitating legitimate international trade and ensuring effective customs supervision. Particular importance is therefore attached to the simplification of customs procedures, electronic data exchange and the development of information systems that enable more efficient communication between customs authorities and economic operators. At the same time, the customs system contributes to protecting the financial interests of the European Union, preventing fraud and unlawful trade, and controlling goods that may pose a risk to the safety and security of citizens, public health, the environment or the internal market.

Consequently, the role of customs is no longer limited to the assessment and collection of customs duties. It also encompasses ensuring the legality of international trade in goods, implementing the common commercial policy and protecting the economic and security interests of the Union. The development of uniform customs legislation reflects the increasing complexity of international trade and the need for the customs authorities of all Member States to operate in accordance with common rules and standards.

The principal legal instrument in this field is the Union Customs Code (UCC), established by Regulation (EU) No 952/2013. The Regulation entered into force on 30 October 2013, while most of its provisions became applicable on 1 May 2016. It lays down the general rules and procedures applicable to goods brought into or taken out of the customs territory of the Union [3].

One of the main objectives of the Union Customs Code is the transition to an electronic customs environment. The exchange of information between economic operators and customs authorities, as well as between customs authorities themselves, is generally conducted by means of electronic data-processing techniques. Replacing paper-based procedures with electronic systems is intended to accelerate the movement of goods, reduce administrative burdens and ensure more efficient and reliable customs controls [3].

The Union Customs Code distinguishes between Union goods and non-Union goods and regulates the conditions under which goods acquire or lose their customs status. It also governs the lodging of customs declarations, the presentation and temporary storage of goods, release for free circulation, export and re-export. In addition, it lays down rules governing special procedures, which include transit, storage, specific use and processing. Under the prescribed conditions, these procedures allow economic operators to defer the payment of import duties or benefit from other customs advantages, thereby facilitating business activities and enhancing the competitiveness of the European economy [3].

A significant part of the Union Customs Code concerns the incurrence of a customs debt, the identification of the persons liable for its payment and the provision of a guarantee to secure its collection. It also regulates the time limits and methods of payment, as well as the conditions under which import or export duties may be repaid or remitted. The Code contains rules on determining the customs value and origin of goods and on their tariff classification, which provide the basis for calculating customs duties and applying the relevant commercial policy measures. Customs value is primarily based on the transaction value, namely the price actually paid or payable for goods when sold for export to the customs territory of the Union [3].

A particularly important role is assigned to the status of Authorised Economic Operator (AEO). This status may be granted to economic operators that satisfy the prescribed criteria concerning compliance with customs and taxation rules, the maintenance of appropriate commercial records, financial solvency, professional competence and, where applicable, security and safety standards. Depending on the type of authorisation granted, Authorised Economic Operators may benefit from certain simplifications and more favourable treatment in relation to customs controls, including fewer physical and documentary controls [3].

Customs controls are primarily based on risk analysis and risk management. This approach allows available resources to be directed towards consignments, goods and economic operators in relation to which there is a higher risk of irregularities. At the same time, it facilitates the movement of goods for operators that conduct their activities lawfully and reliably. Customs authorities thus perform control, fiscal, security and trade-facilitation functions simultaneously [3].

The provisions of Regulation (EU) No 952/2013 are further elaborated by Commission Delegated Regulation (EU) 2015/2446 and Commission Implementing Regulation (EU) 2015/2447. The Delegated Regulation supplements certain elements of the Union Customs Code, including rules relating to the origin and customs value of goods, guarantees, special procedures and Authorised Economic Operator status [4]. The Implementing Regulation lays down detailed procedural rules, including those governing the lodging of customs declarations, the exchange of information and the practical conduct of customs authorities [5]. Together, these acts contribute to the consistent implementation of common customs rules throughout the Member States.

Since not all the electronic systems required for the full implementation of the Union Customs Code were available when the Code became applicable, the EU legislature introduced a transitional regime. In this context, Commission Delegated Regulation (EU) 2016/341 established transitional rules permitting the use of means other than electronic data-processing techniques until the relevant information systems became operational [6]. This Regulation played an important role during the transition to an electronic customs environment by ensuring the continuity of customs procedures and safeguarding legal certainty for the persons involved.

Council Regulation (EEC) No 2658/87 on the tariff and statistical nomenclature and on the Common Customs Tariff also constitutes an important part of the legal framework. It established the Combined Nomenclature (CN), which provides for the uniform tariff classification of goods throughout the Member States. Tariff classification serves as the basis for determining applicable customs duties, implementing commercial policy measures and compiling external trade statistics. Closely related to this system is TARIC, the integrated tariff of the European Union, which brings together information on customs duties, tariff measures, prohibitions, restrictions and other measures applicable to the import and export of goods [7].

The customs system of the European Union is based on the principles of legality, legal certainty, proportionality and transparency, as well as on the protection of the rights of persons involved in customs procedures. One of its defining characteristics is the effort to reconcile the

effective protection of the Union's financial and security interests with the facilitation of legitimate trade. Harmonised legal rules, electronic customs systems, standardised procedures and cooperation between the customs administrations of the Member States all contribute to achieving this objective.

One of the most significant challenges in the application of customs legislation is preventing the evasion of customs duties. Unlawful conduct may take the form of smuggling goods in order to circumvent customs supervision, but it may also involve abuses committed within a formally initiated customs procedure. Such abuses include the provision of inaccurate information concerning the nature, quantity, value, tariff classification or origin of goods for the purpose of reducing customs liability or improperly obtaining a customs advantage. Since these forms of unlawful conduct are often interconnected, their detection and prevention require effective control mechanisms, the exchange of information, international cooperation and the consistent application of effective, proportionate and dissuasive penalties laid down by the Member States in accordance with EU customs legislation [3], [8].

THE CUSTOMS SYSTEM OF THE REPUBLIC OF SERBIA

The principal legal act governing the customs system of the Republic of Serbia is the Customs Law. It lays down the general rules and procedures applicable to goods brought into or taken out of the customs territory of the Republic of Serbia. The Law regulates the rights and obligations of persons involved in customs procedures, the powers of customs authorities, customs procedures, customs debt, the customs value and origin of goods, tariff classification, special procedures and legal remedies. Its principal objectives are to protect the financial interests of the Republic of Serbia, protect the country from unfair and unlawful trade while supporting legitimate business activities, ensure the safety and security of the country and its citizens, and maintain an appropriate balance between customs controls and the facilitation of legitimate trade. The current Customs Law is largely aligned with the Union Customs Code, representing an important step in Serbia's EU integration process [9].

Another significant legal act is the Law on Customs Service, which regulates the organisation and scope of activities of the Customs Administration, as well as the rights, duties, powers and responsibilities of customs officers. The activities of the customs service are carried out in accordance with the principles of professionalism and integrity, openness, service to the public, accountability, and consistency in the application of the law and the exercise of statutory powers. The Law also regulates the powers of customs officers to control goods, passengers and means of transport, as well as their status within the public administration system [10].

The Customs Tariff Law also constitutes an important source of Serbian customs law. It regulates the tariff classification of goods and provides the legal basis for determining the rates of customs duty applicable to goods imported into the Republic of Serbia. The Serbian tariff system is based on the International Convention on the Harmonized Commodity Description and Coding System and is aligned with the Combined Nomenclature of the European Union [11]. This ensures a high degree of compatibility between the Serbian tariff system and international and European standards. The correct tariff classification of goods provides the basis for calculating customs duties, applying commercial policy measures and compiling external trade statistics.

The customs system of the Republic of Serbia is based not only on national legislation but also on international agreements binding on the country. Particularly important instruments include the Stabilisation and Association Agreement between the European Communities and their Member States, of the one part, and the Republic of Serbia, of the other part [12], the Convention on a Common Transit Procedure [13], and the Convention on the Simplification of Formalities in Trade in Goods [14]. Instruments developed within the framework of the World Customs Organization and the World Trade Organization are also relevant. These sources facilitate the harmonisation of Serbian legislation with EU law and international standards, contribute to the simplification of international trade and promote cooperation between customs administrations.

THE LEGAL STATUS OF PARTICIPANTS IN CUSTOMS PROCEEDINGS IN THE REPUBLIC OF SERBIA

The legal status of participants in customs proceedings in the Republic of Serbia is governed by the Customs Law, the implementing regulations adopted pursuant to it, and the rules of general administrative procedure [9], [15]. In addition to the customs authorities, participants in customs proceedings include importers, exporters, declarants, customs representatives, carriers, holders of the procedure, holders of goods, customs debtors, and other natural and legal persons whose rights or obligations may be affected by a decision of the customs authority.

A declarant is a person who lodges a customs declaration in their own name or the person in whose name such a declaration is lodged. Any person may appoint a customs representative to perform the acts and formalities required under customs legislation in dealings with the customs authorities. Representation may be direct, where the representative acts in the name and on behalf of another person, or indirect, where the representative acts in their own name but on behalf of another person. A customs representative must state the person represented and specify whether the representation is direct or indirect. At the request of the customs authority, the representative must also provide evidence of the relevant authorisation [9].

Participants may request information from the customs authorities concerning the application of customs legislation. The customs authority must provide the requested information to the interested person within 30 days of the submission of the request, provided that the request concerns an activity genuinely envisaged in connection with international trade in goods. Participants are also entitled to express their views on the facts and circumstances relevant to the adoption of a decision and to receive a reasoned decision. Before adopting a decision that would adversely affect a person, the customs authority must, as a rule, communicate the grounds on which it intends to base its decision and provide that person with an opportunity to express their views within the prescribed period [9].

On the other hand, persons directly or indirectly involved in the completion of customs formalities or the performance of customs controls are required to provide the customs authorities with the necessary documents and information and to render any assistance required for the completion of the procedure or the performance of the control. A person lodging a customs declaration, notification or application is responsible for the accuracy and completeness of the information provided, the authenticity, accuracy and validity of the supporting documents, and compliance with the obligations arising from the relevant customs procedure [9].

The protection of participants' rights is ensured through the availability of legal remedies. An appeal against a first-instance decision of a customs authority may be lodged with the ministry responsible for finance, while a second-instance decision may be challenged by initiating an administrative dispute before the competent court. As a rule, an appeal does not suspend the enforcement of the decision. However, the first-instance customs authority may suspend its enforcement, in whole or in part, where the evidence and facts presented indicate that the decision is contrary to customs legislation and that its enforcement could cause serious damage to the person concerned. Where the contested decision concerns the assessment of import or export duties, suspension is, as a rule, conditional upon the provision of an appropriate guarantee. No guarantee is required where providing one would impose a disproportionate burden or cause serious economic harm to the debtor [9].

The legal status of participants in customs proceedings therefore comprises both procedural rights and statutory obligations. The rights to information, representation, the opportunity to be heard and access to legal remedies contribute to the protection of the parties, while the obligation to provide accurate information and authentic supporting documents facilitates the lawful and efficient conduct of customs proceedings [9], [15].

It is particularly important to ensure that decisions are adopted within a reasonable time and to prevent prolonged legal uncertainty in customs matters. An illustrative example from the case law of the Constitutional Court is Decision Už-3097/2016, concerning the post-clearance assessment of a customs liability imposed on a sole proprietorship. In 2008, the Kragujevac Customs Office amended the information contained in a customs declaration and ordered the importer to pay an additional amount of customs debt. The importer appealed against that decision,

but the second-instance administrative authority did not decide on the appeal until more than one year later. Following the initiation of an administrative dispute, the Administrative Court took more than four years to deliver its first judgment, by which it annulled the second-instance decision and remitted the case for reconsideration [16].

The proceedings lasted approximately six and a half years, although the Constitutional Court found that neither the facts of the case nor the legal issues involved were particularly complex. The Court concluded that the excessive duration of the proceedings was primarily attributable to the conduct of the second-instance administrative authority and the Administrative Court. At the same time, it took into account the fact that the applicant had not used the procedural remedies available in cases of administrative silence, which could have contributed to the more expeditious completion of the proceedings. Notwithstanding that circumstance, the Constitutional Court upheld the constitutional appeal in the part concerning the duration of the proceedings, found a violation of the right to a trial within a reasonable time, and awarded the applicant EUR 500 in compensation for non-pecuniary damage [16].

This case demonstrates that the formal availability of an appeal and the possibility of initiating an administrative dispute are insufficient if decisions on those remedies are not taken within a reasonable time. Prolonged uncertainty concerning the amount of a customs liability may seriously affect the business operations of an economic operator. Improvements to customs proceedings should therefore include more efficient second-instance decision-making, more consistent compliance with and monitoring of statutory time limits, and the proper and complete establishment of the relevant facts in order to reduce the need for cases to be remitted for reconsideration. Such improvements would bring domestic practice closer to European standards of effective legal protection, legal certainty and good administration [16], [17].

LIABILITY FOR VIOLATIONS OF CUSTOMS REGULATIONS

Violations of customs regulations may constitute either a misdemeanour or a criminal offence, depending on whether the conduct in question fulfils the statutory elements of a particular misdemeanour or criminal offence [9], [18], [19]. The Customs Law prescribes specific customs misdemeanours, while the Law on Misdemeanours regulates the concept of a misdemeanour, the general conditions for misdemeanour liability, the system of misdemeanour sanctions, and the rules governing misdemeanour proceedings [9], [18]. Natural persons, entrepreneurs, legal entities, and responsible persons within legal entities may be held liable for customs misdemeanours [9], [18].

Customs misdemeanours include, inter alia, failure to declare goods brought into or taken out of the customs territory of the Republic of Serbia, the provision of inaccurate or false information, the submission of false or unreliable documents, the removal of goods from customs supervision, failure to fulfil obligations arising from special customs procedures, and the import or export of goods in breach of the prescribed prohibitions and restrictions. These misdemeanours are punishable by fines, the amount of which depends on the type of misdemeanour, the status of the offender and, in certain cases, the value of the goods constituting the subject matter of the misdemeanour [9], [18].

In addition to fines, the Customs Law provides for protective measures. Pursuant to Article 271, goods constituting the subject matter of a misdemeanour referred to in Article 265 of the Customs Law shall be confiscated, even if they are not owned by the offender. Such goods shall be temporarily retained and remain under customs supervision until the completion of the misdemeanour proceedings. Where the goods cannot be found or cannot be confiscated for any other reason, the offender shall pay their value, as determined in accordance with the Customs Law, and separate proceedings shall be instituted for the collection of the duties and charges payable upon the import or export of the goods [9].

Under the specific conditions prescribed by law, a means of transport used to carry goods constituting the subject matter of a misdemeanour under Article 265 of the Customs Law shall also be confiscated. Such a means of transport shall be confiscated if the value of the goods exceeds one third of its value and its owner knew or could have known that it would be used to transport goods constituting the subject matter of a misdemeanour. Irrespective of the respective value of the

goods and the means of transport, the latter shall be confiscated if it has been specially constructed, adapted, modified, or otherwise adjusted for the purpose of concealing goods [9].

An illustrative case occurred on 23 February 2026 at the Preševo border crossing. During the inspection of a vehicle leaving Serbia, customs officers discovered an undeclared collection of valuables and numismatic items estimated to be worth more than EUR 30,000. The discovered items included gold jewellery, 186 silver coins dating from different periods, 60 silver rings, 37 used watches, and a pearl necklace. Customs officers also discovered 1,250 cannabis seeds, as well as smaller quantities of amphetamine and ecstasy, which were handed over to the police and the public prosecutor's office for further action. According to the Customs Administration, the competent misdemeanour court ordered the permanent confiscation of the undeclared goods and the vehicle, while the driver was fined [20].

This case demonstrates that a single factual event may disclose indications of both a customs misdemeanour and a criminal offence. Failure to declare the valuables and numismatic items may constitute a customs misdemeanour, while the discovery of amphetamine and ecstasy may indicate that the statutory elements of a criminal offence have also been fulfilled. Whether a criminal offence has been committed must be determined by the police, the public prosecutor's office, and the competent court in the appropriate criminal proceedings. However, the discovery of different categories of undeclared or prohibited goods during the same inspection does not automatically establish both misdemeanour and criminal liability. The legal classification of each act depends on the established facts, the nature and quantity of the discovered items, the manner in which they were transported, the offender's culpability, and the fulfilment of all statutory elements of the relevant punishable offence [9], [18], [19].

More serious forms of unlawful conduct may constitute the criminal offence of smuggling. Under Article 236 of the Criminal Code, this offence is committed, inter alia, by anyone who engages in transporting goods across the customs line while evading customs supervision measures or who, while evading such measures, transports goods across the customs line while armed, as a member of a group, or by using force or threats. The offence also encompasses certain forms of selling, distributing, and concealing goods that have not been cleared through customs, as well as the organisation of a network of resellers or intermediaries. In addition to imprisonment and a fine, the Criminal Code provides for the confiscation of the goods and, under the conditions prescribed by law, of the means of transport or other means used to commit the criminal offence [19].

The distinction between a customs misdemeanour and a criminal offence must be based on the statutory elements of the conduct in question, with consistent application of the principles of legality, proportionality, legal certainty, and the individual assessment of liability. It is particularly important to determine whether the conduct identified in connection with a single incident consists of separate acts fulfilling the statutory elements of different punishable offences or constitutes the same punishable conduct.

Where legally and factually distinct acts fulfil the statutory elements of different punishable offences, they may, in principle, give rise to separate misdemeanour and criminal proceedings. Nevertheless, the ne bis in idem principle must be respected. Pursuant to Article 8 of the Law on Misdemeanours, misdemeanour proceedings may not be instituted against a person who has been found guilty by a final judgment in criminal proceedings of a criminal offence that also encompasses the elements of the misdemeanour in question. If such misdemeanour proceedings have already been instituted or are pending, they may not be continued or completed [18]. The proper distinction between misdemeanour and criminal liability is important for protecting the financial interests of the state, effectively combating smuggling and safeguarding the procedural rights of persons against whom proceedings are conducted.

AREAS FOR FURTHER IMPROVEMENT AND HARMONISATION WITH EU LAW

An important direction for further reform is the continuous professional development of customs officers, the strengthening of the administrative and technical capacities of the Customs Administration, and improved cooperation with other state authorities and economic operators. In its 2025 Serbia Report, the European Commission assessed that Serbia has a good level of preparation in the area of the customs union, but that it made only limited progress. The

Commission identified the integration of risk management into all customs procedures, the further development of the national customs IT system to enable interconnection and interoperability with the EU electronic customs environment, and the upgrading of the national component of the New Computerised Transit System (NCTS) to Phase 6 as key priorities [21]. Their implementation would contribute to greater legal certainty, more effective customs controls and Serbia's fuller integration into the customs system of the European Union.

It is also necessary to ensure consistent practice among all organisational units of the Customs Administration, more rigorous observance of the parties' right to be heard, and the adoption of better-reasoned customs decisions. Particular attention should be paid to improving the effectiveness of legal remedies, especially by reducing the duration of appeal proceedings and ensuring the clear and consistent application of the conditions under which the enforcement of a customs decision may be suspended. The publication of administrative guidelines and relevant administrative practice could further contribute to the transparency, consistency and predictability of decision-making.

In addition to legislative alignment, the further development of the customs system should focus on the comprehensive digitalisation of customs procedures, more effective data exchange between competent authorities, and the reduction of the administrative burden imposed on economic operators. Particular attention should be given to strengthening the risk management system, further developing the Authorised Economic Operator programme and expanding the use of simplified customs procedures. These measures would enable customs controls to focus on high-risk consignments while facilitating legitimate trade and accelerating the movement of goods.

The development of a modern customs system requires more than the replacement of traditional procedures with electronic tools. Customs authorities must simultaneously facilitate the lawful movement of goods and apply controls necessary to protect fiscal interests, public health and security. This task has become increasingly complex due to changes in global trade, the expansion of digital commerce and the effects of geopolitical tensions and rapidly changing tariff measures. Accordingly, further reform should promote adaptable risk-based controls and encourage economic operators to strengthen their internal compliance procedures. Such an approach could improve the effectiveness of customs supervision without creating unnecessary obstacles for businesses that consistently comply with customs regulations [22].

Further reform should also strengthen the transparency and accountability of customs authorities. Economic operators should have access to clear, timely and consistent guidance on the application of customs legislation. At the same time, effective internal control and anti-corruption mechanisms should be developed, accompanied by the consistent application of the principles of legality, proportionality, legal certainty and good administration. The uniform application of customs legislation and the predictability of customs decisions are particularly important for protecting the legitimate expectations of participants and strengthening confidence in the Customs Administration.

CONCLUSION

The analysis indicates that the principal challenge facing Serbia's customs system no longer lies solely in insufficient normative alignment with EU law, but in the gap between formally adopted legal standards and their practical implementation. Consequently, further reform should not be limited to the transposition of additional EU rules; it should also encompass the development of consistent administrative practice, improvements in the quality of customs decisions, more effective legal protection, and consistent respect for the rights of participants in customs proceedings. Only when normative harmonisation is accompanied by adequate institutional capacity and predictable conduct on the part of customs authorities can a proper balance be achieved between effective customs control, protection of the public interest, and the unhindered conduct of lawful international trade.

Ultimately, the success of customs reform should not be assessed solely on the basis of the formal alignment of Serbian legislation with the EU acquis, but also in light of its effective, consistent and uniform implementation in practice. Shorter proceedings, properly reasoned decisions, effective legal remedies, predictable administrative practice and the efficient facilitation

of international trade should therefore serve as the principal indicators of progress. The proper distinction between customs misdemeanours and criminal offences, together with consistent observance of the ne bis in idem principle, is also essential for effective enforcement and the protection of the procedural rights of the persons concerned. Achieving these objectives would contribute to the establishment of a modern customs system capable of protecting the fiscal and security interests of the state while simultaneously safeguarding the rights of participants in customs proceedings.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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ENVIRONMENTAL CRIME AS A BARRIER TO SUSTAINABILITY TRANSITIONS

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ABSTRACT

Environmental crime represents a significant barrier to the global sustainability transition by compromising environmental integrity, economic stability, and social well-being. The study assesses the multifaceted impacts of illegal activities, including wildlife trafficking, illegal logging, pollution, and illicit waste disposal, on sustainable development pathways. Utilizing interdisciplinary perspectives from environmental economics, criminology, and sustainability science, the analysis explores how environmental crime disrupts resource efficiency, weakens institutional frameworks, and erodes public trust in governance systems. Drawing on case studies from the European Union, the analysis places particular emphasis on regulatory gaps, corruption, and transnational networks that enable these activities, thereby complicating enforcement and policy implementation. The study highlights the economic consequences of environmental degradation, including biodiversity loss, diminished ecosystem services, and long-term financial burdens on governments and communities. The research findings indicate that addressing environmental crime is essential for effective and equitable sustainable development, necessitating coordinated action among policymakers, businesses, and civil society to mitigate risks and strengthen resilience. Strengthening institutional capacity, enhancing cross-border cooperation, and leveraging technological innovations such as environmental monitoring systems are essential for effective prevention and enforcement. Furthermore, integrating anti-crime measures into sustainability strategies can enhance policy coherence and reinforce long-term economic and environmental resilience.

Keywords: Environmental crime, sustainable development, transition, European Union, prevention.

INTRODUCTION

The transition to sustainable development is a central policy objective of the twenty-first century, shaping international agreements, national strategies, and corporate governance frameworks. However, environmental crime increasingly threatens the pursuit of sustainability and remains underrepresented in mainstream economic and policy discourse [1]. Encompassing wildlife trafficking, illegal logging, unauthorized pollution, and illicit waste disposal, environmental crime is among the most profitable and rapidly expanding forms of transnational criminal activity. It generates illicit proceeds estimated at tens of billions of euros annually and impacts nearly every ecosystem and economic sector [2].

Unlike conventional crime, environmental crime rarely produces an immediately identifiable individual victim. Its harms are diffuse, cumulative, and often irreversible, including biodiversity loss, soil and water contamination, depleted fish stocks, and degraded carbon sinks [3]. Considering that these harms develop gradually and span jurisdictions and generations, environmental crime has historically received less priority than other forms of organized crime, despite having equally severe consequences for sustainable development. Environmental crime should therefore be recognized as a structural barrier to sustainability transitions, as it interacts with and exacerbates weaknesses in institutional governance, economic incentives, and international cooperation mechanisms [1], [3].

This study employs an interdisciplinary approach, integrating environmental economics, criminology, and sustainability science. Environmental economics provides tools to analyze how environmental crime distorts markets, externalizes costs, and undermines the valuation of natural capital. Criminology offers frameworks for examining the actors, networks, and enforcement dynamics that enable environmental harm to persist despite formal prohibitions. Sustainability science introduces a systems perspective, positioning environmental crime within the broader context of the Sustainable Development Goals (SDGs) and the European Green Deal. This approach facilitates tracing how localized illegal acts evolve into systemic barriers to climate, biodiversity, and social equity objectives. The study seeks to demonstrate that environmental crime is a structural barrier to sustainability transitions and to identify necessary institutional, economic, and cooperative changes to remove this barrier, using the EU as a case study.

The remainder of the article is structured as follows. Section 2 develops a conceptual framework situating environmental crime within sustainability transition theory and examines the main typologies of environmental crime. Section 3 analyzes the institutional and governance conditions, regulatory gaps, corruption, transnational criminal networks that facilitate environmental crime, as well as assesses the economic consequences of environmental degradation linked to criminal activity. Section 4 presents case studies from the European Union (EU). Section 5 discusses policy responses and prevention strategies and concludes with recommendations for coordinated action among policymakers, businesses, and civil society.

THEORETICAL BACKGROUND OF ENVIRONMENTAL CRIME WITHIN SUSTAINABILITY TRANSITIONS

Sustainability transitions are long-term, multidimensional processes in which societies shift from unsustainable production and consumption patterns toward systems that protect ecological integrity, economic viability, and social equity. Transition theory, particularly the multi-level perspective, conceptualizes these shifts as resulting from interactions among niche innovations, dominant socio-technical regimes, and broader landscape pressures [4]. Environmental crime disrupts each of these levels. At the regime level, it reinforces unsustainable practices, such as illegal logging that supplies informal timber markets, by making these products cheaper and more accessible than legally compliant alternatives, thereby hindering the adoption of sustainable substitutes. At the landscape level, the cumulative ecological damage from environmental crime, including biodiversity loss and greenhouse gas emissions from illegal deforestation, intensifies the very pressures that sustainability transitions seek to address [5].

A critical distinction must be made between environmental crime and broader environmental harm. Not all ecologically damaging activities are criminalized, and not all environmental crimes result in catastrophic or visible harm. Environmental crime is characterized by the intentional violation of legal prohibitions, domestic or international, governing the protection of species, habitats, air, water, or waste management, typically for financial gain [6]. This legal-economic dimension is significant for sustainability analysis, given that environmental crime often reflects a rational response to misaligned incentives: when the expected profit from illegal exploitation exceeds the anticipated costs of detection and sanctions, actors are structurally incentivized to offend [7]. Sustainability transitions that fail to address this incentive imbalance will continue to permit opportunities for criminal exploitation, regardless of the ambition of their formal targets.

Institutional erosion is fundamental to understanding why environmental crime constitutes a barrier, rather than a mere side effect, to sustainability transitions. Effective sustainability governance depends on robust regulatory institutions, credible enforcement, and public trust in the fairness and efficacy of environmental regulations. Environmental crime undermines each of these pillars. It exposes regulatory gaps and enforcement deficiencies, diminishing the perceived legitimacy of environmental law among both compliant and non-compliant actors. When legally operating firms observe competitors profiting by evading environmental obligations with minimal risk of sanction, their incentives to invest in genuine sustainability practices are reduced [8]. As a result, environmental crime creates a corrosive feedback loop: it exploits existing institutional weaknesses while simultaneously intensifying them, making each subsequent policy intervention more difficult to implement effectively.

Environmental crime comprises various illegal activities, each characterized by specific actors, market structures, and sustainability impacts. The primary categories of environmental crime include wildlife trafficking, illegal logging and deforestation, pollution, and illicit waste disposal [5], [6], [9], [10].

Wildlife trafficking, which includes the illegal trade in live animals, plants, and derivative products such as ivory, timber species, and traditional medicine ingredients, is among the most profitable forms of environmental crime and clearly illustrates its impact on biodiversity-related sustainability targets. The depletion of keystone and endangered species through poaching and illegal trade destabilizes ecosystems, reduces genetic diversity, and can trigger cascading effects throughout food webs. Beyond ecological harm, wildlife trafficking undermines local livelihoods dependent on legal ecotourism and sustainable resource use, and it has increasingly been linked to public health risks, including the transmission of zoonotic pathogens through unregulated wildlife markets.

Illegal logging encompasses the harvesting, transportation, processing, or trading of timber in violation of national or international laws, including breaches of harvesting quotas, encroachment into protected areas, falsification of permits, and mislabeling of species. The sustainability consequences are substantial: deforestation resulting from illegal logging is a major driver of biodiversity loss, disrupts hydrological cycles, and is one of the largest anthropogenic sources of carbon emissions from land-use change, directly undermining climate mitigation objectives. Illegally sourced timber frequently enters legal supply chains through document fraud and complex intermediary networks, a process known as timber laundering, which allows it to reach EU markets despite due-diligence regulations. Economically, the persistent influx of illegal timber undercuts legally and sustainably managed forestry operations, whose compliance costs place them at a competitive disadvantage compared to illegally sourced, artificially cheaper timber.

Illicit waste disposal and unauthorized pollution, including the dumping of hazardous, electronic, and municipal waste, illegal shipment of waste to jurisdictions with weaker enforcement, and unpermitted industrial emissions, constitute also the major typology of environmental crime. These activities are primarily driven by cost avoidance: legal waste treatment and emissions abatement are expensive, and illegal disposal allows firms to externalize

these costs onto surrounding communities and ecosystems. The consequences include soil and groundwater contamination, air quality degradation, and, in the case of illegal transboundary waste shipments, the transfer of environmental burdens from wealthier to less-resourced regions, directly contradicting the principles of environmental justice central to sustainability frameworks. Within the EU, illegal waste shipment networks have been documented moving materials labeled as recyclable but effectively unprocessable to destination countries with limited capacity for safe treatment, creating long-term contamination liabilities beyond the point of origin.

Across these main typologies, a consistent structural pattern emerges: environmental crime systematically shifts environmental costs that legitimate market participants and public budgets are intended to internalize onto ecosystems and communities least able to resist or recover from the resulting harm. This cost-shifting function is the primary reason environmental crime constitutes a barrier to sustainability transitions, rather than merely representing a limited category of illegal activity. It actively undermines the internalization of environmental externalities that sustainable development strategies require [11].

INSTITUTIONAL, GOVERNANCE, AND ECONOMIC DIMENSIONS

The persistent prevalence of environmental crime, despite comprehensive legal prohibitions, indicates underlying governance deficiencies that generate high economic costs. This section examines four interconnected dimensions: regulatory gaps, corruption, transnational criminal networks, and the broader economic consequences resulting from their persistence.

Regulatory frameworks for environmental protection are frequently fragmented across jurisdictions, sectors, and levels of government, creating exploitable gaps for criminal actors. Inconsistent definitions between national legal systems regarding what constitutes a criminal environmental offense, as opposed to an administrative infraction, impede cross-border investigations and prosecutions. In many jurisdictions, sanctions for environmental crime remain disproportionately low relative to the financial gains, resulting in inadequate deterrence. Monitoring and inspection capacities are often under-resourced compared to the scale of regulated activities, particularly in sectors such as waste management and maritime transport, where shipment volumes far exceed the capacity of customs and environmental authorities to conduct comprehensive inspections [12], [13].

Corruption is a key enabling factor for environmental crime, particularly within permitting, customs clearance, and law enforcement processes. Bribery of officials responsible for issuing extraction permits, certifying legal timber or wildlife products, or inspecting waste shipments allows illegal activities to appear legitimate and enter formal supply chains and markets. Corruption further undermines prosecutorial and judicial processes, resulting in low conviction rates and lenient sentencing even when investigations are successful. The relationship between corruption and environmental crime is mutually reinforcing: environmental crime generates substantial illicit profits that sustain corrupt networks, while corruption reduces the operational risks and costs of continued offenses, creating a self-perpetuating cycle that is difficult to disrupt through enforcement alone [12], [14], [15].

Environmental crime increasingly operates through sophisticated *transnational networks* that resemble the organizational structures of other serious and organized crimes. These networks include compartmentalized supply chains, the use of shell companies and complex ownership structures, and integration with money-laundering mechanisms. They exploit jurisdictional fragmentation by routing goods through countries with weaker enforcement or lower detection risks before reaching final destination markets [16]. The transnational nature of these networks renders unilateral enforcement by a single state insufficient. Without coordinated cross-border cooperation, criminal networks can reroute activities through jurisdictions with minimal resistance. This dynamic demonstrates that environmental crime cannot be addressed solely as a domestic law enforcement issue and presents a unique challenge for sustainability governance frameworks, which are often designed and implemented at national or regional levels.

The economic costs of environmental crime extend beyond the immediate value of illegally extracted or traded resources, imposing long-term and diffuse burdens on public budgets, ecosystem services, and future economic productivity [17]. Biodiversity loss from wildlife trafficking and habitat destruction associated with illegal logging reduces the availability of ecosystem services such as pollination, water purification, and climate regulation, which are essential for agricultural and broader economic activity. Considering that these services are often unpriced or undervalued in conventional economic accounting, their degradation is not immediately reflected in standard economic performance measures, even though it undermines the natural capital base critical for sustained productivity [18], [19]. Governments and communities face significant direct financial burdens due to environmental crime, including costs for remediating contaminated sites from illegal waste disposal, restoring degraded forest and marine ecosystems, and strengthening infrastructure and public health systems affected by pollution. Remediation costs typically exceed those associated with prevention, indicating that insufficient investment in enforcement capacity often results in a net economic loss, even when considered solely in fiscal terms [20], [21], [22]. Additionally, environmental crime distorts competition within legitimate industries, as firms adhering to legal and sustainability standards incur higher operating costs than non-compliant competitors. This disparity can discourage investment in sustainable production methods and hinder the broader transition of affected sectors. At the macroeconomic level, persistent environmental crime generates reputational and market-access risks, particularly as international trade increasingly requires sustainability-linked conditions such as due diligence and traceability for commodities associated with deforestation or illegal extraction. Regions or supply chains with high levels of environmental crime may be excluded from markets enforcing these requirements, resulting in long-term competitiveness costs that compound the immediate fiscal and ecological burdens previously described [23].

CASE STUDIES FROM THE EU

Environmental crime poses a significant obstacle to sustainability transitions by undermining environmental protection, public health, institutional trust, and the implementation of circular economy principles. The EU offers a valuable context for analyzing environmental crime as a barrier to sustainability transitions, given its advanced regulatory framework. Key instruments include the Environmental Crime Directive, the Timber Regulation and its successor deforestation-related due-diligence framework, and the Waste Shipment Regulation [24], [25]. Despite these measures, persistent enforcement challenges underscore the limitations of formal legal harmonization.

One of the most prominent examples of environmental crime in Europe, based on the European Union Action to Fight Environmental Crime – EFFACE [26] is the illegal disposal and burning of hazardous waste in the Campania region of southern Italy, commonly referred to as the "Land of Fires" (Terra dei Fuochi). For decades, organized criminal networks, particularly the Camorra mafia, illegally transported and disposed of industrial and hazardous waste originating from various Italian regions. Waste was frequently buried on agricultural land or openly burned, releasing toxic substances into the air, soil, and groundwater. The environmental consequences have been severe, including widespread soil contamination, groundwater pollution, biodiversity degradation, and reduced agricultural productivity. Numerous epidemiological studies have also suggested increased incidences of cancer and other health problems among local populations. Economically, the contamination damaged the reputation of agricultural products from Campania, reducing market competitiveness and affecting rural livelihoods. From a sustainability perspective, this case demonstrates how environmental crime directly contradicts the objectives of the circular economy by replacing regulated waste management with illegal disposal practices. It also illustrates the importance of strong environmental governance, effective monitoring systems, and coordinated law enforcement. The case highlights that sustainability transitions cannot succeed

where organized crime exploits weaknesses in environmental regulation and institutional capacity [27].

Another significant EU case study on environmental crime concerns the illegal shipment of electronic waste (e-waste) from EU Member States to China despite international regulations prohibiting the export of hazardous waste [28]. Large quantities of discarded computers, televisions, mobile phones, and other electronic devices were falsely declared as reusable second-hand products to circumvent customs controls and avoid the higher costs associated with environmentally sound recycling within Europe. Once transported to informal recycling centers in China, electronic waste was dismantled using primitive techniques, including open burning of cables and acid extraction of valuable metals. These practices generated substantial environmental pollution and exposed workers and local communities to toxic substances such as lead, mercury, cadmium, and brominated flame retardants. The case demonstrates the global dimension of environmental crime and reveals how illegal international waste trade undermines the EU's circular economy ambitions. Instead of recovering valuable secondary raw materials within Europe, criminal networks externalized environmental costs to countries with weaker enforcement capacity.

The ILVA steel plant in Taranto represents one of Europe's largest examples of corporate environmental non-compliance [29]. For many years, industrial operations emitted excessive quantities of dioxins, heavy metals, particulate matter, and other hazardous pollutants into the surrounding environment. Investigations revealed repeated failures to comply with environmental regulations despite the known risks to human health and ecosystems. The environmental impacts included extensive air, soil, and marine pollution, while nearby residents experienced elevated rates of respiratory diseases and certain cancers. The case generated significant legal proceedings concerning corporate criminal liability, environmental accountability, and the balance between industrial production and environmental protection. Unlike environmental crimes committed by organized criminal groups, the ILVA case illustrates that environmental crime may also result from systematic corporate negligence and regulatory failures. It demonstrates that sustainable industrial transformation requires not only technological innovation but also effective environmental compliance mechanisms, transparent monitoring, and credible sanctions. The case has become an important example in discussions regarding corporate environmental responsibility within the European Green Deal framework.

Illegal logging remains one of the most profitable forms of environmental crime affecting global forest ecosystems while also challenging European regulatory systems. This case study examined how illegally harvested timber entered European markets through complex supply chains involving document fraud, money laundering, and insufficient coordination between enforcement authorities responsible for the EU Timber Regulation (EUTR), the Convention on International Trade in Endangered Species (CITES), and financial crime investigations [30]. Illegal logging contributes to deforestation, biodiversity loss, carbon emissions, and ecosystem degradation, directly conflicting with climate neutrality objectives and sustainable forest management principles. The economic consequences include unfair competition against legally operating forestry companies and substantial losses of public revenues in producing countries. This case highlights that sustainability transitions depend not only on environmental legislation but also on integrated enforcement across customs, environmental authorities, financial intelligence units, and judicial institutions. The study recommends stronger due diligence requirements, improved international information exchange, and enhanced financial investigations targeting organized criminal networks involved in timber trafficking.

The Aznalcóllar tailings dam failure in Spain (1998) and the Kolontár red mud spill in Hungary (2010) are examples of environmental harm linked to failures in industrial risk management and corporate responsibility [31]. Although differing in legal circumstances, both incidents raised important questions regarding criminal liability for environmental damage. In Spain, the collapse of a mining waste reservoir released millions of cubic meters of toxic sludge

into the Guadiamar River, threatening the nearby Doñana National Park. Similarly, the failure of a red mud reservoir in Hungary released highly alkaline industrial waste that caused fatalities, injuries, widespread ecological damage, and long-term contamination of rivers and agricultural land. These cases demonstrate that environmental crime extends beyond deliberate illegal acts and includes serious breaches of environmental safety obligations where negligence results in catastrophic environmental harm. They illustrate the necessity of rigorous environmental risk assessment, continuous monitoring of industrial facilities, effective inspection systems, and criminal accountability where operators fail to prevent foreseeable environmental disasters. Such governance mechanisms are essential for ensuring that industrial development remains compatible with sustainability transitions and environmental resilience.

DISCUSSION AND CONCLUSION

The evidence presented in the preceding sections substantiates the central argument that environmental crime constitutes a structural, rather than incidental, barrier to sustainability transitions. Environmental crime operates at multiple levels: ecologically, by directly depleting biodiversity and natural resources; economically, by externalizing costs and distorting competitive dynamics; and institutionally, by eroding regulatory legitimacy and diminishing public trust in governance systems. These dimensions are mutually reinforcing. Institutional weaknesses enable the proliferation of environmental crime, which in turn generates economic distortions that undermine incentives for compliance. The resulting ecological degradation further increases the challenges and costs associated with achieving sustainability transitions.

Another significant implication is the distributional impact of environmental crime. Its ecological and economic costs are often shifted onto communities and regions with limited capacity to resist or recover, such as through the illegal shipment of waste to under-resourced countries or the depletion of resources vital to local livelihoods. Consequently, environmental crime raises environmental justice concerns that intersect directly with the equity dimension of sustainable development. Transitions that overlook these distributional effects risk perpetuating the very inequities they aim to resolve. Evidence from the EU indicates that the primary constraint on progress is not legislative ambition, given the extensive regulatory framework, but rather the capacity for implementation and effective cross-border coordination. This finding underscores a broader lesson for sustainability governance: comprehensive legal commitments to environmental protection are insufficient unless accompanied by adequate investment in enforcement capacity, anti-corruption measures, and international cooperation mechanisms capable of addressing the transnational nature of environmental crime networks.

Addressing these challenges requires coordinated, multi-layered responses. Strengthening institutional capacity involves increasing resources for environmental regulatory and enforcement authorities and enhancing the coherence of legal definitions and sanctioning regimes across jurisdictions. Penalties must be proportionate to the financial scale and ecological harm of offenses to restore deterrence. Additional measures include investing in specialized training for judicial and law enforcement personnel and embedding anti-corruption safeguards, transparency requirements, and independent audit mechanisms within permitting and inspection processes to reduce regulatory capture. Given the transnational nature of environmental crime, domestic reforms must be complemented by enhanced cooperation among national enforcement agencies, customs authorities, and international organizations. This includes shared intelligence systems, harmonized data standards for tracking shipments and supply chains, and joint operational task forces capable of intercepting criminal activity across borders. Within the EU, deeper integration of national environmental crime units with shared enforcement infrastructure would help close jurisdictional gaps exploited by transnational networks.

Technological innovation provides an additional, complementary means of prevention at a scale beyond the capacity of manual inspection. Satellite-based remote sensing enables near real-time identification of illegal deforestation and land-use change. Blockchain-based supply-chain verification increases the difficulty of falsifying origin documentation. Automated monitoring

networks for air, water, and waste facilities enhance detection of unauthorized pollution and illegal disposal while reducing dependence on resource-intensive physical inspections. However, these measures will not be effective unless anti-crime strategies are explicitly integrated into broader sustainability policies rather than pursued separately. Incorporating environmental crime risk assessments into sustainability-linked trade agreements, corporate due diligence requirements, and development finance conditions helps ensure that resources allocated to sustainability transitions are not undermined by unaddressed criminal exploitation of the same resources and ecosystems.

In summary, environmental crime represents a significant and often overlooked barrier to global sustainability transitions, undermining environmental integrity, economic stability, and social well-being through activities such as wildlife trafficking, illegal logging, pollution, and illicit waste disposal. The persistence of environmental crime reflects deeper governance weaknesses, regulatory gaps, corruption, and transnational criminal networks, which complicate enforcement and policy implementation even in jurisdictions with advanced legal frameworks, as demonstrated by case studies from the EU. Effective responses require coordinated action among policymakers, businesses, and civil society, including strengthened institutional capacity, enhanced cross-border cooperation, and the integration of technological innovations such as environmental monitoring systems directly into sustainability strategies. As sustainability transitions accelerate in response to climate and biodiversity imperatives, safeguarding the resources and ecosystems central to these transitions from criminal exploitation will be essential to achieving equitable and lasting sustainable development outcomes.

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The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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GESTALT PSIHOLOGIJA I VIZUELIZACIJA PRAVA U ERI VJEŠTAČKE INTELIGENCIJE

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ABSTRACT

Upotreba sistema vještačke inteligencije (AI) u pravnoj profesiji je praćena jednim posebnim izazovom. Više nego u nekim drugim profesijama, pravnici bi trebalo da razumiju kako sistemi AI odlučuju i da kritički ocijene usklađenost tih odluka sa osnovnim društvenim vrijednostima, kao što su moral, pravda, vladavina prava, itd. Ovaj izazov implicira teška hermeneutička pitanja: kako posredovati u komunikaciji između ljudskog iskustva i kompjuterske formalne logike, kako prevesti ljudske riječi u pravnim normama na jezik brojeva blizak mašinskom odlučivanju, i kako obezbijediti da te odluke ne pređu granice koje društvene vrijednosti postavljaju. U ovom radu se predlaže korišćenje algoritamske vizualizacije prava primjenom metoda Gestalt psihologije kao učinkovitog sredstva komunikacije podjednako bliskog i čovjeku i kompjuteru. U interdisciplinarnom pristupu u kome se kombinuju metodi psihologije i pravne nauke objašnjava se kako Gestalt psihologija može da bude koristan alat u vizualizaciji prava. Dalje, objašnjava se kako vizualizacija prava putem algoritama doprinosi boljoj ljudskoj komunikaciji i kontroli automatskog odlučivanja, a sa druge strane može da pomogne koliko praktikantima prava u ubjedljivijoj argumentaciji, toliko i teoretičarima prava i legislatorima u logičkom struktuiranju pravnih normi. Zato se uključivanje algoritamske vizualizacije primjenom metoda Gestalt psihologije u pravnu edukaciju može smatrati korisnom pripremom za buduće izazove primjene vještačke inteligencije u pravnoj teoriji i praksi.

Ključne riječi: Gestalt psihologija, vizualizacija prava, algoritmi, Fuzzy logika, pravna hermeneutika

UVOD

Narastajuća ponuda nedavno razvijenih sistema vještačke inteligencije (AI) na globalnom tržištu izaziva veliku pažnju javnog mnjenja, a njena primjena je sve primjetnija u svim sferama društvenog života koje su inače već duže vrijeme u procesu digitalizacije. Sistemi AI su tako pronašli svoje mjesto i u svijetu prava, otvarajući brojne nove mogućnosti efikasnijeg pribavljanja i obrade podataka i odlučivanja. Sa druge strane, polazište u narastajućem javnopravnom okviru za regulaciju AI je zabrinutost zbog prijetnji ugrožavanja osnovnih društvenih vrijednosti, kao što su ljudska prava, demokratija i vladavina prava [1].

Ignorisanje izazova AI od strane pravne nauke nije prihvatljivo, jer je digitalizacija prava ionako već dovela do pada verbalizacije i porasta programiranja u svakodnevnoj komunikaciji. Zato je izazov AI pravnoj struci i nauci aktuelna tema, jer treba što prije artikulisati odgovore na pitanja kako pripremiti buduće pravnike, pravne profesionalce i edukatore za projektovanje, održavanje, testiranje i kontrolu sistema AI koji digitalnom obradom podataka ishoduju odluke čija primjena ima pravne posljedice. Ovo pogotovo iz razloga što je pravna edukacija na fakultetima kod nas uglavnom ostala ograničena na tradicionalne nastavne metode verbalizacije (učenja i rada na tekstu), dok su moderni metodi koji podrazumijevaju vizuelizaciju i interaktivnu nastavu rijetkost. Ova tradicionalna metodika se pokazuje nedostatnom, jer sa jedne strane ne doprinosi razvoju logičkog mišljenja i argumentacije, a sa druge strane na teorijskom nivou ne približava pravničko rezonovanje jeziku na kom kompjuter funkcionišu [2].

Ovaj rad upućuje na dobro poznato edukativno sredstvo - vizuelizaciju prava, kao odgovor na pitanje korisne i bezbjedne digitaizacije i posljedične upotrebe AI u pravnoj profesiji. Ovaj, već odavno dobro poznati edukativni alat zasnovan na principima Gestalt psihologije, može da bude prvi korak u neizbježnom procesu prolagođavanja i plodonosne kooperacije pravnika i kompjutera. To bi trebalo da bude korisno posjećanje na dobro poznatu alternativu u nastavi, jer je ovaj alat u pravoj edukaciji kod nas, za razliku od pravničkih velesila, ostao zanemaren.

Za ovakvo podsjećanje je nužan interdisciplinarni pristup, koji spaja saznanja iz teorije psihologije, edukacije, kibernetike i prava. U prvom dijelu rada se izlažu osnovni pojmovi vizuelizacije i načela Geštalt psihologije, a u drugom se pronalaze putevi da se ti principi primijene u pravnoj edukaciji, nauci i praksi. U trećem dijelu se provjerava korisnost ovog pristupa u nekoliko praktičnih ogleda.

GESTALT PSIHOLOGIJA I SAVREMENO OBRAZOVANJE

Teorijski pravac u psihologiji pod nazivom Geštalt psihologija nastaje početkom 20. vijeka prilikom istraživačkih procesa Vilhelma Vundta (Wilhelm Maximilian Wundt). Vundt je smatrao da oblast psihologije treba biti zainteresovana za trenutne procese, odnosno mentalne promjene i vezu između percepcije, spoznaje, emocija i volje. Ti procesi se mogu odrediti kao „neposredna realnost događaja u psihološkom iskustvu“. Kao odgovor na Vundtovo analiziranje psiholoških procesa i iskustava u istraživanjima ljudske percepcije i ponašanja nastala je Geštalt psihologija, koja vodi porijeklo iz perceptivnih teorija Ernsta Maha (Ernst Mach) i Kristijana fon Ehrenfelsa (Christian von Ehrenfels). Oni su se bavili istraživanjima prostornih i slušnih formi i oblika (kvadrat, krug i jednostavna melodija) i u svojim istraživanjima su zaključili da ti oblici i forme imaju kvalitete koji su različiti od njihovih sastavnih elemenata. Definicija same riječi geštalt dolazi iz njemačke riječi Gestalt, a koja označava cjelinu, oblik, sklop, konfiguraciju, strukturu, integrisanu i organizovanu cjelinu čija se posebna svojstva ne mogu dobiti sabiranjem elemenata. Osnovna postvaka Geštalt psihologije ogleda se u shvatanju da karakteristike cjeline nije moguće objasniti karakteristikama pojedinih elemenata ili njihovim jednostavnim sabiranjem. U početku je primarno područje interesa Geštalt psihologije bila percepcija ali se interes ubrzo proširio i na druga psihološka područja kao što su pamćenje, učenje, mišljenje i rješavanje problema [3, 4].

Glavni principi geštalt sistema su:

- Pojavljivanje: na slici se neki lik ne doživljava dio po dio već se doživljaj cjeline pojavljuje odjedanput.

- Konkretizacija: konstruktivni ili generativni aspekt percepcije, prema kojem doživljena percepcija sadrži više eksplicitnih specijalnih informacija nego sam senzorni podražaj na kojem se bazira.
- Multistabilnost: tendencija nejasnih perceptivnih iskustava prema izmjeni između dvije ili više alternativa.
- Nepromjenjivost: jednostavni geometrijski oblici doživljavaju se identično nezavisno o položaju, rotaciji, uglu, osvjetljenju i slično.

Ovi principi nisu odvojeni modaliteti, već predstavljaju različite aspekte jednog dinamičkog mehanizma.U Geštalt teoriji postoji sedam principa kojima se opisuje uticaj na perceptivnu organizaciju elemenata.

- Princip dobrog oblika. Temeljni princip geštalt percepcije je princip dobrog oblika, prema kojem će čovjek organizovati podražaje kao dobre figure što je god više moguće. Čine ga četiri geštalt principa, i to principi kontinuiranosti, simetričnosti, zatvorenosti i kretanja. Prema Wertheimeru, kada se stvari doživljavaju kao cjeline, minimalna količina energije ulaže se u razmišljanje.
- Princip blizine. Blizak raspored elemenata se koristi da bi se stvorila grupna povezanost između njih. Princip blizine objašnjava vrstu integracije pojedinačnih komponenti u nadređenu cjelinu, u kojoj elementi imaju tendenciju da se percipiraju kao agregirani u grupe ako su bliže jedan drugome. Pažnja može dati doprinos figuralnoj percepciji, ali je većinom njena uloga ograničena: nije pažnja ta koja stvara oblike, već oblici, organizovani u skladu s Geštalt načelima privlače pažnju.
- Princip zatvorenosti. Tendencija ljudskog oka da vidi zatvorene oblike. Čovjekov um često ignoriše kontradiktorne informacije i ispunjava praznine u informacijama. Po principu zatvorenosti dodajemo elemente kojih nema i zatvaramo oblike koji nisu zatvoreni. Elementi imaju tendenciju grupisanja zajedno ako su dio zatvorene figure.
- Princip sličnosti. Po principu sličnosti čovjekov um grupiše slične elemente i oblike na način da ih razumije kao jednu cjelinu. Princip sličnosti može se primijeniti kroz oblike, boju, sjenke ili druge grafičke elemente.
- Princip simetričnosti. Simetrija označava srazmjernost (proporcionalnost) elemenata neke cjeline u veličini, obliku, intenzitetu, vrijednosti ili nekoj drugoj karakteristici. Po ovom principu simetrično raspodijeljene elemente čovjekov um percipira grupisano, kao jednu cjelinu, formirajući ih oko središnje ose. Kompozicija ne treba da stvara osjećaj poremećaja ili neuravnoteženosti, jer u suprotnom posmatrač gubi vrijeme pokušavajući da pronađe nedostajući element ili da riješi problem, umjesto da se fokusira na poruku.
- Princip kontinuiteta ili istog pravca. Čovjekov um često percipira odvojene elemente koji slijede jedan drugog u obliku smjera ili obrasca koji se nastavlja. Elementi objekta imaju tendenciju da se grupišu, ako su ujednačeni sa nekim objektom, integrišu se u percepcijske cjeline. Ukoliko postoji tačka presjeka između objekata, oko teži da percipira jednu kontinuiranu sliku duž određenog puta ili linije.
- Princip kretanja ili zajedničke sudbine. Elemente koji se kreću zajedno u istom smjeru čovjekov um percipira kao jedinstvenu cjelinu. Elementi se percipiraju kao da imaju trendove kretanja, koji ukazuju na putanju u kojoj je objekat uključen [5].

Wertheimer je predložio korištenje gestalt načela u obrazovanju. On je suprotstavio produktivno razmišljanje i učenje napamet, koje se događa bez razumijevanja. Rješavanje problema predstavlja učenje s razumijevanjem koristeći geštalt načela, čime se podstiče dugoročno pamćenje i primjena naučenog. Geštaltisti predlažu da oni koji uče treba da budu ohrabreni da otkriju kompletnu prirodu veze između elemenata problema. S obzirom da ljudski um funkcioniše u skladu s navedenim geštalt principima, nastavni program bi trebao biti zasnovan na blizini, zatvorenosti, sličnosti i jednostavnosti [5]. Principi Geštalt teorije uspješno se koriste u marketingu, grafičkom dizajnu, umjetnosti i vizualizaciji kognitivnih elemenata.

VIZUELIZACIJA PRAVA U PRAVNOJ TEORIJI, EDUKACIJI I PRAKSI

U ovom dijelu rada se nalazi o vizuelizaciji po principima Gestalt psihologije primjenjuju na teorijska i doktrinarna saznanja koja pripadaju pravnoj edukaciji, profesiji i nauci. O tome se kod nas malo pisalo i govorilo, iako je korisnost vizuelizacije već mnogo puta dokazana i potvrđena u raznim edukacijskim i naučnim disciplinama. Međutim, u savremenom obrazovanju pravnika kod nas njena primjena je izuzetno rijetka: Autori ovog rada su našli tek dva primjera: prvi je monografija Pojam prava Nikole Viskovića, u kome autor putem dijagrama uspješno demonstrira složene strukture pojmova koji čine suštinu prava [6], a drugi udžbenik Nasledno pravo Olivera B. Antića u kome se ne samom kraju shematski prikazuju nasledni redovi [7].

Sa druge strane, u uporednim pravnim sistemima, posebno kod pravničkih velesila, vizuelnost se koristi kao korisno sredstvo za razumevanja društvene funkcije prava već nekoliko decenija, i to ne samo od strane pravnika. Tako npr. čuveni filozof Mišel Fuko je analizama slika starih majstora slikanja demonstrirao važnost vizuelnog materijala za razumijevanje prava i društva [8]. A u pravnoj misli, vizuelizacija je primijećena kao velika prilika za reafirmaciju vrednosti klasične retorike i etike, koja je u modernom dobu potisnuta dominacijom naučnog rezonovanja i instrumentalne racionalnosti. Naime, ona može da postane izdanak integralne retorike koji pokušava da harmonizuje estetske i etičke aspekte jurisprudencije [9]. Da bi se to i postiglo, treba odgovoriti na tri krupna pitanja: kako da se tok slika podvede pod jurisprudenciju riječi, kako da se povjeruje vizualnom koje uvek kombinuje stvarno i nestvarno, i kako obezbijediti da presude na koje utiče popularna vizuelna kultura ostanu pravične [10]. Sljedeći iskorak u primjeni vizuelizacije je načinjen u u pravnoj heremenutici: Argumentuje se da struktuirani vizelni formati mogu da značajno unaprijede analitičko rezonovanje, koje čini suštinu tumačenja prava. Vizuelizacijom se mogu na ljudskom umu i kompjuteru prijemčiv način opisati implicitni odnosi između različitih pravila, pojmova i dokumenata tako što se struktuiraju njihove kompleksnosti i postavljaju u odgovarajući situacioni okvir [11]. Dalje, kao prednosti vizuelizacije ističu: da unapređuje učinkovitost komunikacije o kompleksnim pojmovima široj publici, jer može da „učini ono što je nerazumljivo razumljivim, i interesantnim ono što je neinteresantno. Naime, ljudi pretećno uče individualno pošto je vid dominantno čulo koje angažuje do polovine resursa mozga - slike bolje pamte od reči, a kombinacija slike i reči je još efektivnija [12].

Vizuelizacija primenom Gestalt psihologije i tzv. pravni dizajn (Legal design) su naročito popularni u njemačkoj pravnoj školi, gdje se koriste kao važno eksplikativno sredstvo u pravnoj hermeneutici i obrazovanju, za prikazivanje strukture sudijske hijerarhije, tokova postupaka po pravnim lekovima, hijerarhije normi, itd. Slično tome, i u SAD predlažu takvu vizuelizaciju prava kao alat za bolje razumevanje šablona i i veza koje nisu jasno vidljive, poboljšavanja komunikacije, pomoći praktikantima prava da se usredsrede na bitne aspekte slučaja i unapređivanje rešavanja problema i odlučivanja [13].

Najvažnija prednost vizuelizacije ka edukativnog i heremeneutičkog alata se sastoji u njenoj pogodnosti kompjuterskom kodiranju, jer se njime ne omogućuje samo bolje razumijevanje prava, nego se i olakšava njegova digitalizacija i kodiranje u informatičke sisteme, uključujući AI [14]. Naime, strukturna vizuelizacija pravnih normi se najbolje može postići algoritamskim opisima procesa tumačenja, a ti algoritmi su pogodni za automtaozovanu primjenu u kompjuterskim sistemima [15]. Za to su naročito pogodni geometerijski oblici koji čine unifikovani jezik modelovanja (Unified Modeling Language - UML), jer su precizniji i jasniji u odnosu na verbalno i pisano izražavanje. Tako vizuelizovani modeli su pogodni za prevođenje zakonskog teksta u algoritme kojima se predložena zakonska rešenja mogu virtuelno validirati i verifikovati od strane komjutera koji mogu da procesuiraju znatno više informacija od ljudskog uma [16]. Drugim riječima, vizuelna analitika se može integrisati u jursprudenciju u sučeljavanju sa izazovima kompleksnosti, formalnosti i hijerarhijske prirode norme, tako da se proces tumačenja prava može prikazati kao dijagram toka (flowchart) pogodan za mašinsko kodiranje koji bi kontrolisali i usmjeravali ljudi [17].

Kao metod algoritamske vizuelizacije je prepoznata tzv. Fuzzy logika, koja je razvijena kao matematička teorija i najviše primijenjena u teoriji menadžerskog odlučivanja, koje je inače

obilježeno neizvjesnostima zbog manjka informacija, znanja, kao i mogućih nepredvidivih situacija. Ona se svodi na primjenu formalne logike i binarnog odlučivanja (DA ili NE kao mogući ishodi obrade podataka, i sl.) da bi se konstruisale logičke veze između pojmova koje čine jedan složen sistem, a u svrhu procesa odlučivanja u kome se ljudske misli izražene riječima prevode u brojeve pogodne za kompjutersko procesuiranje [18]. Primjenom principa Gestalt psihologije kao što su sličnost, kontinuitet, bliskost i sl., matematički ishodi kompjuterske obrade podataka se mogu bolje tumačiti outem intuitivnih vizelnih shema, kao što su dijagrani toka (flowcharts), dijagrami odlučivanja (decision tree u teoriji menadžmenta), i sl. Drugim riječima, ovi Gestalt principi mogu da budu u funkciji saznajnog posredovanja između Fuzzy logike i ljudskog mišljenja, jer mogu pomoći u tumačenju AI generisanih rezultata putem strukturne vizuelizacije pravnih instituta i procesa kao koherentnih cjelina, preglednijeg prikazivanja toka procesa i kategorizacije sličnih pojmova odgovatajućom vizuelizacijim (npr. pomoću UML). Ovakvom spajanjem AI sistema sa Gestalt psihologijom, pravnom hermeneutikom i Fuzzy logikom se postiže kognitivna jasnoća i logička fleksibilnost koja omogućuje da se egzaktne matematičke operacije AI prilagode konkretnim pravnim problemima.

Za ulazak Fuzzy logike u svijet pravne teorije zaslužan je japanski pravnik Hajime Yoshino, koji je pre skoro pola veka zaokružio teorijski sistem logičke jurisprudencije koja je spojila Kelzenovu čistu teoriju prava sa ovom matematičkom disciplinom. Primjenjivost ove teorije je dokazana na Konvenciji o međunarodnom prometu robe [19]. Da je to moguće pokazano je i u domaćoj literaturi, na primjeru objašnjavanja sudske prakse Evropskog suda za ljudska prava u predmetima ograničavanja ljudskih prava. U tom primjeru je neodređeni verbalni pravnodogmatski iskaz o praksi Suda u ovoj vresti predmeta preveden u jezik blizak kompjuterima, tj. definisan je egzaktan algoritam – dijagram toka koji je zatim kodiran u programskom jeziku Python [20].

Dakle, algoritamska vizuelizacija prava može da bude etablirana u studije prava kao korisno didaktičko i hermeneutičko sredstvo sredstvo saznavanja prava i njegovog prevođenja u virtuelni svet mašinskog odlučivanja. Ovaj metod, koji je atabliran u samim počecima digitalizacije prava, se čini neizbežnim u sučeljavanju sa izazovima AI, jer je pogodan za prilagođavanje pravne hermenuetike kodiranju i programiranju sistema AI, kao i boljem razumevanju kako AI procesuira informacije i zaključuje u konkretnim slučajevima. Zato bi algoritamsku vizuelizaciju prava trebalo smatrati putem izdizanja pravne profesije iznad zahteva puke informatičke pismenosti, u pravcu sticanja punog paketa sposobnosti za sigurno i korisno projektovanje, upotrebu i nadzor sistema AI. U narednom dijelu slijedi nekoliko primjera koji potvrđuju ove nalaze.

NEKOLIKO OGLEDA O VIZUELIZACIJI PRAVA

U ovom dijelu se u nekilo primjera pokazuje kako bi izgledala vizelizacija prava putem algoritama baziranih na fuzzy logici i ocjenjuje korisnost ovog pristupa.[1] Vizuelizacija je osmišljena kroz dijagram toka (flowchart), primjenom gore pomenutog unifikovanog jezika modelovanja (UML) i fuzzy logike. Da bi se postigli zadovoljvajući rezultati, potrebno je da tumač prava vešto koristi sve metode tumačenja i teorijska znanja, da iz smisla norme identifikuje i izrazi njene elemente u formi pitanja na koje se može odgovoriti sa DA/NE i posledice u formi iskaza ako-onda (IF/THEN), te da jasno prepozna i izrazi logičke odnose između pojedinih elemenata.

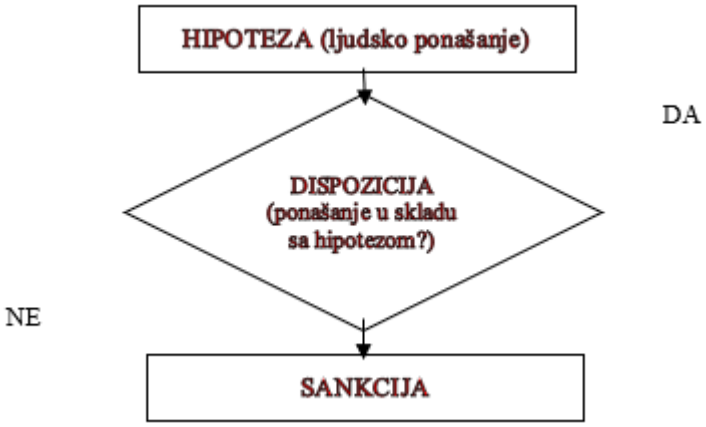
Sledi nekoliko primera poredanih stepenovano, od onih jednostavnih prema komplikovanijim. Prva dva su iz opšte pravne teorije. Struktura pravne norme, koju Kelzen izražava kao u obliku jeste – treba [21, 22], odnosno hipoteza- dispozicija – sankcija, može se vizuelizovati sledećim algoritimom baziranim na fuzzy logici. Na slici 1. slijedi vizuelizacija izražena pomoću UML.

Baveći se istim pravnoteorijskim pitanjem, gore pomenuti Nikola Visković je predložio i uspešno algoritamski izrazio složeniju strukturu pravne norme u obliku šeme čiji su elementi: „(1) uvjetujuća situacija ili primarna hipoteza (H) (2) pasivni subjekt (S1) (3) obveza (Ob) (4)objekt obveze (O) (5) aktivan subjekt (S2) (6) ovlaštenje (Ov) (7) prekršaj ili sekundarna hipoteza (P) (8)

[1] Primjeri su preuzeti i prerađeni iz [2].

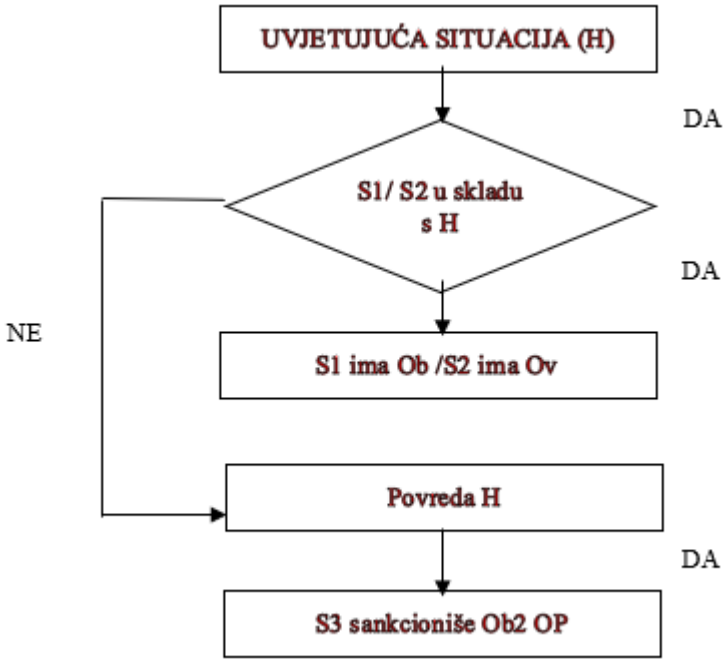
subjekt sankcije (S3) (9) obveza subjekta sankcije (Ob2) (10) objekt-prisila obveze subjekta sankcije (OP).“ Dokazujući da ponekad i riječi mogu da budu dovoljno precizne, Visković jasno i precizno definiše njihove međusobne odnose „formulom dvostruko hipotetičkog suda u disjunktivnom sudu:

Ako H treba S1 Ob O i S2 Ov, ili ako P (ne-Ob) treba S3 Ob2 OP [6].“



Slika 1. Struktura pravne norme

Odnos između pojedinih elemenata je objašnjen i rečima, ali je ova komlikovana i kompleksna struktura pogodna i za vizuelizaciju putem algoritma koji koristi fuzzy logiku na sl.2.



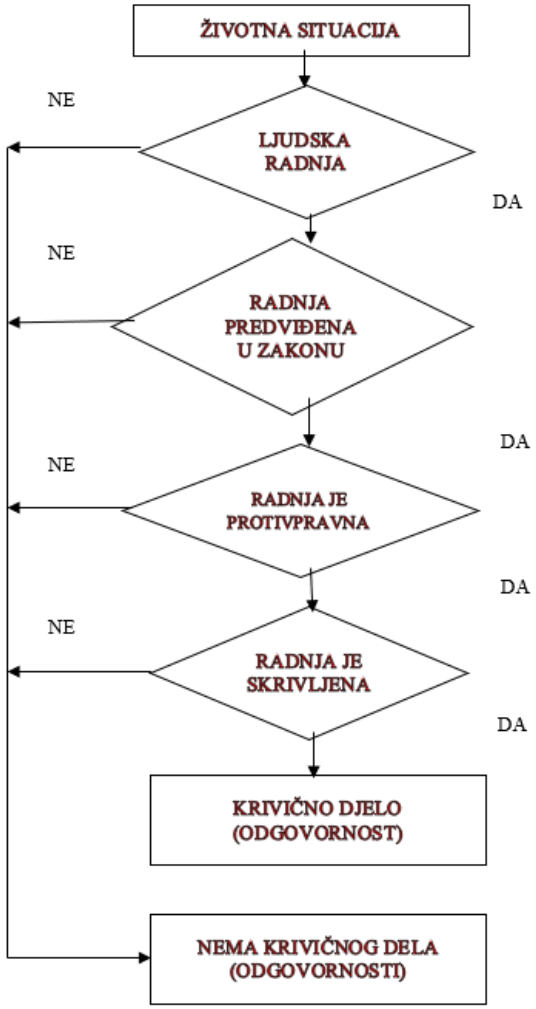
Slika 2. Struktura pravne norme po Viskoviću

Vizuelno algoritamsko prikazivanje odnosa između elemenata strukture pravne norme omogućuje jasnije sagledavanje posledica ne/poštovanja norme, a time i načina na koji ona upravlja ljudskim ponašanjem: ljudska mogućnost izbora da se ponaša u skladu sa normom ili ne, je izražena kao disjunkcija, a alternativa u vidu nepoštovanja uzročno-posledično stavlja u pogon državnu prisilu u vidu sankcije.

Sledeći ogled je iz krivičnog prava. Dobar primer preciznog i jasnog pravnog izražavanja je definicija pojma krivičnog dela prof. Zorana Stojanovića:

„Krivično delo je radnja koja je u zakonu previđena kao krivično delo, koja je protivpravna i koja je skrivljena ... redosled pojedinih elemenata nije da proizvoljno i on se ne može menjati, a da se ne dođe do neprihvatljivih teoriskih i praktičnih posledica. Naime, postepenost u utvrđivanju ostvarenosti navedena četiri elementa je veoma važna ... četiri obavezna elementa u pojmu krivičnog dela istovremeno predstavljaju četiri stepena ili nivoa kroz koja se mora proći da bi se na kraju moglo konstatovati da je učinjeno krivično delo [23].“

Dakle, odnos između elementa je jasno definisan u vidu stepenaste kumulacije kriterijuma, koji se odnosu sa prethodnim kriterijumom postavljaju akcesorno supsidijarno (tj. slede prethodni kriterujum pod uslovom da je odgovor na prethodni krierijum DA, a u protivnom se i ne postavljaju). Tako se postupak utvrđivanja krivične odgovornosti može pojednostavljeno vizuelizirati algoritamski uz upotrebu fuzzy logike na sl. 3.



Slika 3. Struktura pojma krivičnog dela

Navedena vizuelizacija je svakako korisna za brže i bolje razumevanje pojma krivičnog dela i postupka utvrđivanja krivične odgovornosti, jer jasno definiše korake koje tumač krivičnog prava treba da načini da bi određeno ljudsko ponašanje kvalifikovao kao krivično delo. Time se minimizuju greške u mišljenju koje često prate ovaj proces.

U navedenim primjerima je pokazano da se pravne norme izražene riječima mogu uspješno vizuelizirati u algoritme primjenom Fuzzy logike i da su pri tome principi Gestalt psihologije važno sredstvo saznajnog posredovanja između virtuelnog svijeta formane logike i znatno kompleksnijeg ljudskog mišljenja. Radi se o intelektualno zahtjevnom poduhvatu koji isključuje svaku površnost, jer podrazumeva ne samo teorijska i doktrinalna znanja nego i vještinu i pažnju tumačenja svih detalja strukture pravnih insitituta i procesa. Gestalt principi su važni i za intepretaciju matematičkih rezultata, jer Fuzzy logika nalaže formu binarnih ishoda (DA/NE i sl.).

Naravno, treba postaviti pitanje u kojoj je mjeri ovaj poduhvat koristan, jer su mnoge savremene pravne torije pokazale da primjena matematičkih formula i formalne logike na neizmjeno komplikovane i neizvjesne životne situacije ne daje zadovoljavajuće rezultate [24]. Ovaj prigovor gubi težinu ako se zadrži primat ljudskog pravnog odlučivanja, a kompjuteri ostanu kao pomoćno sredstvo, što je inače izražena namjera u prvim pozitivnopravnim aktima koji regulišu AI [25]. Osim toga, treba imati u vidu da se nalazimo u eri rapidnog razvoja sistema AI, čija kompleksnost i komplikovanost već počinje da nadmašuje sposobnosti ljudskog mozga. Da bi se ti sistemi mogli da projektuju, upotrebljavaju i kontrolišu, nužno je da budući pravnici ovladaju barem ovako pojednostavljenom načinu vizuelizacije njihovog funkcionisanja da bi spriječili sasvim moguće zloupotrebe. Ako to ne budu u stanju, opasnost od osamostaljivanja AI od ljudske kontrole je iminentna. Na kraju, ne treba zanemariti ni mogući hermeneutički benifit: tumač prava u poduhvatu vizuelizacije algoritma stiče produbljena znanja i veštine logičkog tumačenja koje su mašinski proverljive, a korišćenje te mogućnosti će ga/nju svakako učiniti boljim pravnikom.

ZAKLJUČAK

Geštalt psihologija predstavlja značajan teorijski okvir za razumijevanje načina na koji ljudi organizuju, interpretiraju i usvajaju informacije. Njena osnovna pretpostavka da se cjelina percipira kao više od prostog zbira pojedinačnih elemenata ima posebno važnu primjenu u obrazovanju, gdje se naglašava učenje s razumijevanjem umjesto mehaničkog memorisanja sadržaja. Primjenom geštalt principa moguće je kreirati materijale koji podstiču pojednice da prepoznaju odnose među pojmovima, razvijaju kritičko mišljenje i lakše usvajaju nova znanja kroz organizovane i smislene cjeline. Poseban potencijal Geštalt teorije ogleda se u vizualizaciji informacija, gdje principi blizine, sličnosti, zatvorenosti, kontinuiteta i dobrog oblika omogućavaju jasnije predstavljanje složenih sadržaja. Organizovanjem sadržaja prema Geštalt principima moguće je povećati preglednost, smanjiti kognitivno opterećenje i unaprijediti proces učenja i donošenja odluka.

U svijetu prava, vizuelizacija primjenom principa Gestalt psihologije nije doživjela potpunu elaboraciju i afirmaciju, iako su razvijeni ubjedljivi teorijski modeli koji omogućuju smislenu upotrebu kompjutera u pravnoj edukaciji i praksi. Međutim, u eri AI je nužno da se informatička pismenost pravnika izdigne na nivo koji je potreban za projektovanje, upotrebu i kontrolu sistema AI.

U ovom radu su izneseni ubjedljivi teorijski argumenti o potrebi algoritamske vizuelizacije prava u sadašnjem trenutku razvoja AI, koji otvara neslućene mogućnosti efikasnijeg pravnog odlučivanja, ali istovremeno prijeti ostvarivanju osnovnih vrijednosti demokratskog društva. Ona podrazumijeva interdisiciplinaran pristup na više nivoa, počevši od principa Gestalt psihologije, preko Fuzzy logike kao matematičke discipline do pravne hermeneutike. Ti argumenti se svode na potrebu da se pravničko mišljenje približi virtuelnom svijetu mašina, ili da se barem bolje razumije kako AI fukcioniše, koje su prednosti i mane mašinskog odlučivanja i koje su odgovornosti pravnika u procesima koji uključuju projektovanje, upotrebu i nadzor nad sistemima AI.

U praktičnim ogledima u trećem dijelu je pokazano da vizuelizacija prava može da bude korisno sredstvo pravne edukacije i hermeneutike, jer ne samo da uspješno posreduje između

čovjeka i kompjutera nego i razvija praktične vještine pravno-logičkog mišljenja i tako unaprjeđuje ubjedljivost pravne argumentacije.

Zato autori predlažu i predviđaju reformu pravničkog obrazovanja primjenom ovdje predložene metodologije, jer će se na taj način budući pravnici pripremiti da se suoče sa izazovom AI.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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GESTALT PSYCHOLOGY AND THE VISUALIZATION OF LAW IN THE ERA OF ARTIFICIAL INTELLIGENCE

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ABSTRACT

The use of artificial intelligence (AI) systems in the legal profession is accompanied by a particular challenge. More than in some other professions, legal professionals should understand how AI systems make decisions and critically assess whether those decisions are aligned with fundamental social values such as morality, justice, the rule of law, and others. This challenge implies difficult hermeneutic questions: how to mediate communication between human experience and formal computer logic, how to translate human language embedded in legal norms into a numerical language suitable for machine decision-making, and how to ensure that such decisions do not exceed the boundaries established by social values.

This paper proposes the use of algorithmic visualization of law through the application of Gestalt psychology methods as an effective means of communication that is equally accessible to both humans and computers. Through an interdisciplinary approach combining methods from psychology and legal science, the paper explains how Gestalt psychology can serve as a useful tool in the visualization of law. Furthermore, it explains how the algorithmic visualization of law contributes to better human communication and greater control over automated decision-making, while also helping both legal practitioners in developing more persuasive arguments and legal theorists and legislators in logically structuring legal norms. Therefore, the inclusion of algorithmic visualization through the application of Gestalt psychology methods in legal education may be considered a useful preparation for future challenges related to the application of artificial intelligence in legal theory and practice.

Keywords: Gestalt psychology, visualization of law, algorithms, fuzzy logic, legal hermeneutics

TEHNOLOŠKA ISKLJUČENOST I OSTVARIVANJE LJUDSKIH PRAVA U DIGITALIZOVANOJ SOCIJALNOJ ZAŠTITI

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APSTRAKT

Digitalizacija socijalne zaštite sve češće se predstavlja kao instrument unapređenja efikasnosti, dostupnosti i transparentnosti javnih usluga. Međutim, kada pristup socijalnim pravima postane dominantno posredovan digitalnim platformama, elektronskim procedurama, bazama podataka i automatizovanim oblicima odlučivanja, mogu nastati novi oblici isključenosti. Rad analizira tehnološku isključenost kao pitanje ostvarivanja ljudskih prava u digitalizovanim sistemima socijalne zaštite. U središtu analize nalaze se korisnici koji nemaju dovoljne digitalne vještine, stabilan pristup internetu, odgovarajuće uređaje, pristupačne digitalne servise ili institucionalnu podršku u korišćenju digitalnih procedura. Posebna pažnja usmjerena je na starije osobe, osobe sa invaliditetom, siromašne, ruralno stanovništvo, migrante i druge socijalno ranjive grupe. Rad razmatra odnos između administrativne modernizacije i stvarnog ostvarivanja ljudskih prava, posebno načela jednakosti, nediskriminacije, pristupačnosti, privatnosti, transparentnosti i prava na djelotvoran pravni lijek. Osnovna teza rada jeste da digitalizacija ne smije zamijeniti stvarnu dostupnost socijalne zaštite, već treba da funkcioniše kao dodatni i socijalno osjetljiv kanal ostvarivanja prava. Rad zaključuje da digitalizovana socijalna zaštita zahtijeva zaštitne mehanizme zasnovane na ljudskim pravima, nedigitalne alternative i institucionalne garancije koje sprečavaju da tehnološka isključenost preraste u novi oblik socijalne nejednakosti.

Ključne riječi: socijalna zaštita, ljudska prava, tehnološka isključenost, digitalizacija, socijalna prava

UVOD

Digitalizacija javnih usluga sve snažnije mijenja odnos između građana i institucija. U tom procesu posebno osjetljivo mjesto zauzima socijalna zaštita, jer se ona ne odnosi samo na

administrativnu obradu zahtjeva, vođenje evidencija i isplatu davanja, već na ostvarivanje prava neposredno povezanih sa ljudskim dostojanstvom, socijalnom sigurnošću i zaštitom od siromaštva. Zbog toga digitalizacija socijalne zaštite ne može biti posmatrana samo kao tehničko pitanje modernizacije javne uprave. Ona istovremeno otvara pitanje da li nove digitalne procedure proširuju stvarnu dostupnost prava ili, pod određenim uslovima, proizvode dodatne prepreke za korisnike kojima je podrška sistema najpotrebnija [1], [2].

Digitalne tehnologije danas se koriste u gotovo svim fazama ostvarivanja prava: od informisanja građana, elektronskog podnošenja zahtjeva i provjere identiteta, preko povezivanja baza podataka i utvrđivanja ispunjenosti uslova, do obračuna davanja, digitalnih isplata i otkrivanja mogućih nepravilnosti. Digitalni sistemi socijalne zaštite sve češće uključuju digitalne identitete, socijalne registre, interoperabilne baze, elektronska plaćanja i automatizovane oblike administrativne obrade [1], [2], [3], [4]. Njihova primjena može ubrzati postupke, smanjiti administrativne troškove, unaprijediti koordinaciju institucija i olakšati pristup pravima korisnicima koji raspolažu odgovarajućim uređajima, internetom i digitalnim vještinama. U tom smislu, digitalizacija može predstavljati značajan instrument unapređenja socijalne zaštite, naročito u sistemima obilježenim sporim, nepovezanim i administrativno opterećujućim procedurama [2], [3], [5].

Problem, međutim, nastaje kada se digitalni kanal podrazumijeva kao neutralan, univerzalno dostupan i za sve korisnike jednako upotrebljiv. Pristup digitalizovanoj socijalnoj zaštiti zavisi od niza međusobno povezanih uslova: odgovarajućeg uređaja, stabilnog interneta, digitalnih vještina, funkcionalne pismenosti, razumljivosti jezika, pristupačnosti digitalnog interfejsa i mogućnosti dobijanja neposredne pomoći. Kada ovi uslovi nisu ispunjeni, digitalizacija ne djeluje kao proširenje pristupa, nego kao novi filter između građanina i njegovih prava. Upravo se u tom prostoru tehnološka isključenost pojavljuje kao savremeni oblik socijalne isključenosti [6], [7], [8], [9].

Posljedice takvog procesa posebno osjećaju grupe koje su već izložene socijalnim rizicima: starije osobe, osobe sa invaliditetom, siromašni, nezaposleni, migranti, ruralno stanovništvo, osobe nižeg obrazovanja i korisnici bez stabilnog stanovanja. Za njih digitalizacija može značiti dodatno udaljavanje od sistema, naročito ako se neposredni kontakt sa službenikom, papirni obrasci, telefonska podrška i terenski rad potiskuju kao zastarjeli oblici komunikacije. Tada formalno pravo nastavlja da postoji, ali njegovo stvarno ostvarivanje postaje uslovljeno tehnološkom sposobnošću korisnika. Istraživanja pokazuju da digitalizacija javnih i socijalnih usluga može dodatno opteretiti upravo one građane koji se već nalaze na rubu institucionalne podrške [6], [7], [8].

Ovaj problem prevazilazi pitanje digitalnog jaza i neposredno ulazi u područje socijalne politike i ljudskih prava. Pravo na socijalnu sigurnost, socijalnu pomoć i socijalne usluge ne podrazumijeva samo njihovo formalno priznavanje, već i mogućnost da korisnik bude informisan, razumije postupak, dobije potrebnu podršku, ospori nepovoljnu odluku i ne bude diskriminisan zbog okolnosti koje su izvan njegove kontrole. Komitet za ekonomska, socijalna i kulturna prava naglašava da pravo na socijalnu sigurnost obuhvata pristup i održavanje davanja bez diskriminacije, uz posebnu pažnju prema grupama koje se tradicionalno suočavaju sa teškoćama u njegovom ostvarivanju [10]. Evropski socijalni standardi na sličan način pravo na socijalnu sigurnost, socijalnu i medicinsku pomoć, socijalne službe i zaštitu od siromaštva posmatraju kao dio stvarno dostupne socijalne zaštite, a ne samo kao formalno-pravni katalog prava [11], [12].

Dodatnu složenost unosi sve veća upotreba podataka, automatizovanih procjena i algoritamskih sistema. Digitalizovana socijalna zaštita više se ne iscrpljuje u elektronskoj prijavi ili digitalnoj evidenciji, već obuhvata i profilisanje korisnika, procjenu rizika, klasifikaciju potreba i automatsku ili poluautomatsku podršku odlučivanju. Takvi sistemi mogu povećati efikasnost, ali mogu proizvesti i netransparentnost, institucionalnu distancu i nejednako postupanje. Posebno je problematično kada korisnik ne zna koji su podaci korišćeni, kako je odluka donesena, da li je u postupku učestvovao algoritamski sistem i kome se može obratiti ako smatra da je oštećen. U tom

slučaju digitalizacija ne mijenja samo tehniku rada institucije, već i samu prirodu odnosa između države i građanina [1], [13], [14], [15], [16].

Cilj rada je da analizira tehnološku isključenost kao prepreku ostvarivanju ljudskih prava u digitalizovanoj socijalnoj zaštiti. Polazi se od pretpostavke da digitalizacija nije sama po sebi ni socijalno progresivna ni regresivna. Njeni efekti zavise od toga da li se digitalne procedure uspostavljaju kao dodatni, pristupačni i socijalno osjetljivi kanali ostvarivanja prava ili kao dominantni, tehnički zatvoreni i nedovoljno podržani mehanizmi pristupa sistemu. Osnovna teza rada jeste da digitalizacija može unaprijediti socijalnu zaštitu samo ako je praćena standardima ljudskih prava, nedigitalnim alternativama, pristupačnim dizajnom, ljudskom podrškom, transparentnošću odlučivanja i djelotvornim mehanizmima žalbe [10], [17], [18], [19], [20]. Rad stoga digitalizaciju ne razmatra isključivo kroz prizmu administrativne efikasnosti, već kroz pitanje stvarne dostupnosti prava i položaja korisnika koji se nalaze na presjeku socijalne, ekonomske i tehnološke ranjivosti. Tehnološka isključenost se time prepoznaje ne kao sporedna posljedica digitalne transformacije, već kao jedno od važnih pitanja savremene socijalne politike.

Metodološki okvir rada

Rad je zasnovan na kvalitativnoj analizi naučne literature, međunarodnih izvještaja, dokumenata javnih politika i relevantnih normativnih izvora koji se odnose na digitalizaciju socijalne zaštite, tehnološku isključenost, algoritamsko odlučivanje i ostvarivanje ljudskih prava u digitalnom okruženju. Istraživanje nije usmjereno na prikupljanje primarnih empirijskih podataka, već na povezivanje teorijskih, institucionalnih i normativnih uvida. Takav pristup omogućava da se digitalizovana socijalna zaštita ne posmatra samo kao tehničko-administrativna reforma, nego kao proces koji mijenja uslove pristupa socijalnim pravima.

Analizirani izvori obuhvataju četiri međusobno povezane cjeline. Prvu čine radovi i izvještaji o digitalnoj državi blagostanja i digitalizaciji socijalne zaštite, uključujući elektronske procedure, digitalne registre, sisteme isporuke davanja i automatizovane oblike upravljanja [1], [2], [14], [3], [23], [4]. Drugu cjelinu čine istraživanja tehnološke isključenosti i njenog uticaja na starije osobe, osobe sa invaliditetom, siromašne, migrante, ruralno stanovništvo i druge socijalno ranjive grupe [6], [7] , [8], [9]. Treću čine izvori o algoritamskom odlučivanju, obradi podataka, profilisanju korisnika i institucionalnoj odgovornosti u digitalizovanoj socijalnoj zaštiti [13], [15], [24], [16].

Četvrtu cjelinu čine međunarodni i evropski normativni dokumenti o pravu na socijalnu sigurnost, jednakosti i nediskriminaciji, pristupačnosti, zaštiti podataka i djelotvornoj zaštiti prava [10], [11], [12], [17], [21], [22], [18], [19], [25], [20]. U metodološkom smislu, primijenjena su tri povezana postupka. Prvi je pregled i selektivna analiza literature radi identifikovanja osnovnih pojmova, pristupa i rasprava o digitalizovanoj socijalnoj zaštiti i tehnološkoj isključenosti. Drugi je normativna analiza, kojom se pitanja dostupnosti, jednakosti, nediskriminacije, pristupačnosti, zaštite podataka i djelotvornog pravnog lijeka povezuju sa međunarodnim i evropskim standardima ljudskih i socijalnih prava. Treći postupak je tematska sinteza, kojom su nalazi organizovani u nekoliko analitičkih cjelina: digitalna modernizacija socijalne zaštite, tehnološka isključenost korisnika, rizici po ostvarivanje prava, algoritamsko odlučivanje i institucionalne garancije.

Osnovni kriterijum izbora izvora bila je njihova neposredna relevantnost za odnos digitalizacije, socijalne zaštite i ljudskih prava. Prednost je data izvorima koji digitalnu transformaciju razmatraju iz perspektive korisnika i stvarne dostupnosti prava, a ne samo administrativne efikasnosti. Istovremeno su uključeni i izvori koji ukazuju na pozitivne potencijale digitalizacije, jer cilj rada nije njeno jednostrano osporavanje, već utvrđivanje uslova pod kojima ona može biti socijalno pravedna, pristupačna i usklađena sa standardima ljudskih prava. Ograničenje ovakvog pristupa proizlazi iz činjenice da rad ne donosi neposredne empirijske nalaze o funkcionisanju digitalizovane socijalne zaštite u konkretnoj državi ili instituciji. Njegov doprinos je prvenstveno teorijsko-analitički i normativan: sistematizuju se ključni rizici i pokazuje zbog čega tehnološka isključenost nije samo tehnički problem, već pitanje stvarne dostupnosti socijalne zaštite i ostvarivanja ljudskih prava. Na toj osnovi, u nastavku rada razmatraju se glavne dimenzije

digitalizovane socijalne zaštite i uslovi pod kojima ona može proširiti, a ne ograničiti, pristup socijalnim pravima.

Tehnološka isključenost kao prepreka ostvarivanju socijalnih i ljudskih prava

Tehnološka isključenost u digitalizovanoj socijalnoj zaštiti ne može se svesti samo na nedostatak pristupa internetu ili digitalnim uređajima. Ona nastaje na presjeku socijalne ranjivosti, digitalnih nejednakosti, institucionalnog dizajna i načina organizovanja javnih usluga. Zbog toga nije samo posljedica individualnih ograničenja korisnika, već i pokazatelj da sistem nije prilagođen različitim životnim okolnostima. Kada se digitalna procedura oblikuje prema pretpostavci da korisnik raspolaže znanjem, opremom, vremenom, jezičkom sigurnošću i sposobnošću samostalnog snalaženja, ona već u svom dizajnu može isključiti one koji od takvog modela odstupaju [7], [9].

U socijalnoj zaštiti ovaj problem ima posebnu težinu. Siromaštvo, bolest, invaliditet, starost, nezaposlenost, porodična nestabilnost, migracijsko iskustvo, niže obrazovanje ili život u udaljenim područjima mogu otežati razumijevanje procedure, prikupljanje dokumentacije, praćenje rokova i reagovanje na institucionalne zahtjeve. Kada se postojećem socijalnom riziku doda obaveza savladavanja digitalne procedure, korisnik se suočava sa dodatnim tehnološkim pragom koji mora preći da bi došao do podrške. Digitalizacija tako može nenamjerno proizvesti novu administrativnu selekciju [6], [8]. Starije osobe posebno su izložene zbog nižeg nivoa digitalnih vještina, straha od greške, nepovjerenja u elektronske procedure, ograničenih prihoda i veće potrebe za neposrednom komunikacijom. Digitalni servisi mogu im olakšati pristup informacijama i smanjiti potrebu za odlascima u institucije. Međutim, ako se papirni obrasci, telefonsko informisanje i pomoć službenika zamijene isključivo online procedurama, stariji korisnici postaju zavisni od članova porodice, komšija, nevladinih organizacija ili drugih posrednika. Pravo tada više nije neposredno dostupno korisniku, već se ostvaruje posredstvom digitalnih sposobnosti drugih lica [6], [2].

Digitalizacija može povećati samostalnost osoba sa invaliditetom samo ako su platforme pristupačne, razumljive i kompatibilne sa asistivnim tehnologijama. Elektronski obrazac koji nije prilagođen čitačima ekrana, nejasna navigacija, izostanak alternativnog načina komunikacije ili zahtijevanje radnji koje korisnik ne može samostalno izvršiti pretvaraju digitalni servis u novu institucionalnu barijeru. Pristupačnost zato nije tehnički dodatak, već uslov jednakog ostvarivanja prava [20]. Siromaštvo neposredno ograničava mogućnost korišćenja digitalnih usluga. Korisnici sa niskim prihodima često nemaju stabilan internet, odgovarajuće uređaje, mogućnost štampanja i skeniranja dokumenata niti siguran prostor za sprovođenje elektronske procedure. Čak i naizgled jednostavni zahtjevi, poput posjedovanja e-mail adrese, pamćenja lozinke, pristupa mobilnom telefonu, učitavanja dokumenata ili praćenja elektronskih obavještenja, mogu zahtijevati dodatni trošak, vrijeme i pomoć drugih lica. Za korisnike čiji su životni resursi već ograničeni, takvi zahtjevi nisu neutralni [13], [7], [9].

Ruralno stanovništvo i osobe u udaljenim područjima suočavaju se sa povezivanjem prostorne i tehnološke udaljenosti. Digitalizacija može smanjiti potrebu za fizičkim dolaskom u instituciju, ali samo ako postoje stabilna internet infrastruktura, odgovarajući uređaji i dostupna lokalna podrška. Kada ti uslovi izostanu, digitalni servis ne prevazilazi udaljenost od institucije, već joj dodaje novu prepreku [3], [8].

Poseban problem predstavlja slaba vidljivost tehnološke isključenosti. Institucija može smatrati da je usluga dostupna zato što postoji digitalna platforma, elektronski obrazac ili online uputstvo. Međutim, podaci o korišćenju servisa često ne pokazuju ko nije uspio da pristupi sistemu, ko je odustao od zahtjeva, napravio grešku, propustio obavještenje ili nije imao kome da se obrati za pomoć. Tako nastaje kategorija „nevidljivih“ korisnika koji formalno imaju pravo, ali se ne pojavljuju u evidencijama jer nisu uspjeli da savladaju digitalni prag pristupa [2], [7]. Na tom mjestu tehnološka isključenost povezuje se sa problemom neostvarivanja prava. Dio građana ni u tradicionalnim sistemima ne koristi prava koja im pripadaju zbog neinformisanosti, stigme, nepovjerenja, složenih procedura ili administrativnih prepreka. Digitalizacija može ovaj problem ublažiti jednostavnijim informisanjem i podnošenjem zahtjeva, ali ga može i produbiti ako je

procedura tehnički složena, komunikacija nerazumljiva ili podrška nedostupna. U takvim okolnostima tehnološka isključenost postaje jedan od savremenih mehanizama neostvarivanja socijalnih prava [3], [9]. Značaj ovog problema iz perspektive ljudskih prava proizlazi iz činjenice da socijalna prava ne mogu biti svedena na formalnu normu. Pravo na socijalnu sigurnost, socijalnu pomoć i socijalne usluge podrazumijeva djelotvoran pristup, jednak tretman, razumljivu proceduru i mogućnost zaštite prava. Ako naizgled neutralna digitalna pravila nesrazmjerno pogađaju korisnike koji nemaju potrebne resurse, vještine ili pristupačne uslove korišćenja, postavlja se pitanje indirektne diskriminacije. Namjera da se određena grupa isključi nije neophodna da bi posljedice sistema bile diskriminatorne [10], [11], [12]. Tehnološka isključenost utiče i na dostojanstvo i privatnost korisnika. Osoba koja ne može samostalno koristiti digitalnu proceduru često mora trećim licima otkriti lične, zdravstvene, porodične ili finansijske podatke kako bi podnijela zahtjev ili pratila postupak. Time se povećava zavisnost korisnika, smanjuje njegova autonomija i otvara mogućnost neprimjerenog pristupa osjetljivim informacijama. Pravo se tada ne ostvaruje kroz neposredno dostupnu institucionalnu podršku, već uz neformalno posredovanje drugih lica [18] [9].

Tehnološku isključenost zato treba razumjeti kao višedimenzionalnu prepreku. Ona ima materijalnu dimenziju, povezanu sa uređajima, internetom i infrastrukturom; kompetencijsku, povezanu sa digitalnim i administrativnim vještinama; komunikacijsku, koja se odnosi na razumljivost jezika i procedura; prostornu, povezanu sa mjestom stanovanja; institucionalnu, koja zavisi od dostupnosti podrške; i pravnu dimenziju, jer utiče na mogućnost ostvarivanja i zaštite prava. Posmatrane zajedno, ove dimenzije pokazuju da tehnološka isključenost nije sporedni problem digitalne transformacije, već jedno od centralnih pitanja digitalizovane socijalne zaštite. Uspješnost digitalne transformacije zato treba procjenjivati prema njenom uticaju na korisnike koji su najizloženiji riziku isključenja, a ne samo prema administrativnoj efikasnosti. Sistem koji dobro funkcioniše za digitalno kompetentne građane, ali dodatno opterećuje starije osobe, osobe sa invaliditetom, siromašne, migrante ili stanovnike ruralnih područja, nije stvarno, već selektivno dostupan. Socijalna zaštita ne smije biti dostupna u zavisnosti od digitalne sposobnosti korisnika.

Osnovni izazov zato nije izbor između digitalne i nedigitalne socijalne zaštite, već oblikovanje sistema u kojem digitalni alati proširuju prostor ostvarivanja prava. To podrazumijeva višekanalni pristup, ljudsku podršku, razumljiv jezik, pristupačan dizajn, mogućnost ispravljanja grešaka, jasna obavještenja, zaštitu privatnosti i zadržavanje nedigitalnih alternativa. Bez takvih uslova administrativna modernizacija može postati nova granica između građana koji mogu i onih koji ne mogu pristupiti socijalnoj zaštiti.

Ljudska prava u digitalizovanoj socijalnoj zaštiti

Digitalizovana socijalna zaštita mora se posmatrati u širem okviru ljudskih prava, jer se pristup socijalnoj zaštiti ne iscrpljuje u administrativnoj mogućnosti podnošenja zahtjeva. Ona je povezana sa pravom na socijalnu sigurnost, zaštitom od siromaštva i socijalne isključenosti, pravom na socijalne usluge, jednakošću i nediskriminacijom, pristupačnošću, privatnošću i djelotvornom zaštitom prava. Zbog toga se digitalizacija ne može vrednovati samo prema brzini obrade, smanjenju troškova ili broju elektronski podnesenih zahtjeva, već i prema tome da li korisnicima omogućava stvarno lakši, sigurniji i jednak pristup pravima [10], [11], [12], [25].

Međunarodni okvir ekonomskih, socijalnih i kulturnih prava polazi od neposredne povezanosti socijalne sigurnosti sa ljudskim dostojanstvom. Pravo na socijalnu sigurnost obuhvata pristup i održavanje davanja, u novcu ili naturi, bez diskriminacije, radi zaštite od rizika kao što su bolest, invaliditet, nezaposlenost, starost, nedostatak prihoda i nedovoljna porodična podrška [10]. Socijalna sigurnost u tom smislu nije samo instrument preraspodjele, već i sredstvo sprečavanja siromaštva, ublažavanja socijalne isključenosti i omogućavanja društvenog učešća. Prenesen na digitalno okruženje, ovaj standard zahtijeva da digitalni sistemi obezbijede ne samo formalno postojanje prava, nego i njegovu stvarnu dostupnost. Stvarna dostupnost predstavlja ključnu vezu između digitalizacije i ljudskih prava. Pravo koje postoji u propisu, ali se teško ostvaruje zbog tehničkih prepreka, složenih elektronskih procedura, nepristupačnih platformi ili nedostatka

institucionalne podrške, nije u potpunosti dostupno. Digitalna dostupnost ne znači samo da je obrazac objavljen na internet stranici ili da postoji elektronski servis. Ona podrazumijeva da korisnik može razumjeti informacije, pristupiti sistemu bez nesrazmjernog opterećenja, dobiti potrebnu pomoć, zaštititi privatnost, pratiti postupak i osporiti odluku. Digitalni kanal zato treba da bude dio šire dostupnosti socijalnih prava, a ne njena zamjena. Evropski okvir socijalnih prava potvrđuje takav pristup. Revidirana evropska socijalna povelja prepoznaje pravo na socijalnu sigurnost, socijalnu i medicinsku pomoć, korišćenje socijalnih službi, nezavisnost i učešće osoba sa invaliditetom, socijalnu zaštitu starijih osoba, kao i zaštitu od siromaštva i socijalne isključenosti [11]. Ova prava pokazuju da se socijalna zaštita ne može svesti na isplatu davanja i vođenje evidencija. Ona obuhvata savjetovanje, ličnu pomoć, socijalne usluge, podršku porodici i institucionalne mehanizme koji sprečavaju da građanin u stanju potrebe ostane sam pred sistemom. U digitalnom okruženju to znači da elektronska procedura ne smije potisnuti sadržajnu podršku koja čini suštinu socijalne zaštite.

Posebno je značajan princip nediskriminacije. Digitalna procedura može djelovati neutralno zato što se primjenjuje jednako na sve korisnike, ali jednakost u formalnom postupanju ne znači nužno jednakost u stvarnim efektima. Isti digitalni zahtjev ne predstavlja jednako opterećenje za korisnika sa stabilnim internetom i razvijenim digitalnim vještinama i za stariju osobu, korisnika sa invaliditetom ili osobu koja nema odgovarajući uređaj. Problem tada nije u različitom formalnom tretmanu, već u tome što sistem ne prepoznaje različite mogućnosti korisnika. Naizgled neutralna digitalna pravila mogu zato nesrazmjerno pogoditi one koji su već socijalno, ekonomski ili zdravstveno ranjivi i proizvesti indirektnu diskriminaciju [10], [12]. Pristupačnost je posebno važna za osobe sa invaliditetom. Ona nije tehnički dodatak digitalnom sistemu, već uslov jednakog ostvarivanja prava. Platforma koja nije kompatibilna sa čitačima ekrana, ne nudi alternativne načine komunikacije ili zahtijeva radnje koje određeni korisnici ne mogu samostalno izvršiti premješta postojeće prepreke u digitalni prostor. Digitalna socijalna zaštita zato mora biti razvijana u skladu sa principima univerzalnog dizajna, razumnog prilagođavanja i odgovarajuće podrške [20].

Sličan zahtjev odnosi se i na starije osobe. Evropski socijalni standardi naglašavaju njihovo pravo na dostupne informacije i usluge, očuvanje dostojanstva i autonomije i učešće u odlučivanju o pitanjima koja ih se tiču [11], [12]. Digitalizacija može smanjiti potrebu za fizičkim odlascima u institucije i ubrzati ostvarivanje prava. Međutim, ako se uvodi bez podrške i nedigitalnih alternativa, može povećati zavisnost starijih osoba od drugih lica i umanjiti njihovu samostalnost. Digitalna reforma zato mora biti usklađena sa njihovim pravom na socijalnu zaštitu, a ne samo sa administrativnom logikom racionalizacije troškova.

Evropski stub socijalnih prava socijalnu zaštitu povezuje sa socijalnom uključenošću, minimalnim prihodom, zdravstvenom zaštitom, uključivanjem osoba sa invaliditetom, dugotrajnom njegom, stanovanjem i pristupom osnovnim uslugama [21]. Njegov Akcioni plan ukazuje da digitalna tranzicija mora biti praćena socijalnom osjetljivošću i prilagođavanjem javnih politika potrebama građana [22]. Digitalizacija koja nije ugrađena u takav okvir može biti tehnički uspješna, ali socijalno nedovoljna.

U digitalizovanoj socijalnoj zaštiti posebno mjesto zauzimaju privatnost i zaštita ličnih podataka. Institucije obrađuju podatke o prihodima, zaposlenju, porodičnim okolnostima, zdravlju, invaliditetu, stanovanju, djeci i drugim osjetljivim aspektima života korisnika. Njihovo povezivanje kroz registre, baze i platforme može ubrzati odlučivanje, ali istovremeno povećava rizike prekomjerne obrade, netransparentnosti, pogrešnog povezivanja, nadzora i sekundarne upotrebe podataka [18]. Korisnik se pritom često nalazi u slabijoj poziciji, jer mu je institucionalna podrška potrebna i nema stvarnu mogućnost da odbije obradu podataka bez posljedica po ostvarivanje prava. Zaštita podataka zato nije samo tehničko-pravno pitanje, već i pitanje odnosa moći između korisnika i države. Jednako su važni pravo na informaciju i razumljiva procedura. Korisnik mora znati koja prava postoje, koje uslove treba ispuniti, koje podatke institucija obrađuje, kako se odluka donosi i šta može učiniti ako je ona nepovoljna. U digitalnom sistemu ova obaveza dobija dodatnu težinu, jer se komunikacija često odvija putem standardizovanih

obrazaca, automatskih obavještenja i uputstava koja ne ostavljaju dovoljno prostora za razgovor i pojašnjenje. Sistem koji je formalno informativan, ali nerazumljiv korisniku, ne omogućava njegovo stvarno učešće u postupku.

Djelotvorna zaštita prava podrazumijeva mogućnost osporavanja odluke, razumijevanje razloga zbog kojih je zahtjev odbijen ili pravo umanjeno, uvid u relevantne podatke i obraćanje nadležnom organu ili nezavisnom tijelu. Ova pitanja postaju posebno važna kada se koriste automatizovani sistemi i algoritamske procjene. Ako korisnik ne zna da je algoritamski sistem učestvovao u odlučivanju, koji su kriterijumi primijenjeni i ko je odgovoran za grešku, mogućnost žalbe postaje oslabljena. Digitalizovana socijalna zaštita zato zahtijeva odluke koje su objašnjive, provjerljive i podložne osporavanju [16], [19].

Ključno pitanje, dakle, nije da li socijalna zaštita treba da koristi digitalne tehnologije. Njihova primjena je opravdana kada povećava dostupnost, ubrzava postupke, smanjuje administrativne prepreke i unapređuje koordinaciju podrške. Odlučujuće je, međutim, da li digitalizacija ostaje u funkciji prava ili se prava podređuju logici digitalnog sistema. Kada se od korisnika zahtijeva da se prilagodi platformi, dok platforma nije prilagođena njegovim mogućnostima i potrebama, digitalizacija gubi svoju socijalnu funkciju. Digitalizovana socijalna zaštita zato mora biti oblikovana kao sistem usmjeren na ostvarivanje prava. Digitalni servisi treba da budu dostupni, pristupačni, razumljivi, sigurni i nediskriminatorni, uz očuvanu ljudsku podršku i alternativne kanale pristupa. Standardi ljudskih prava u tom procesu nisu prepreka digitalizaciji, već njen korektiv i uslov legitimnosti. Bez njih digitalizacija može biti efikasna, ali nepravedna; brza, ali nerazumljiva; tehnički moderna, ali socijalno isključujuća. Tehnološka isključenost stoga nije samo posljedica nedovoljnih digitalnih vještina korisnika, već pokazatelj neusklađenosti sistema sa standardima dostupnosti, jednakosti, pristupačnosti, privatnosti i djelotvorne zaštite prava. Ako je socijalna zaštita dio obaveze države da štiti dostojanstvo i socijalnu sigurnost građana, digitalna transformacija mora biti oblikovana tako da prvenstveno štiti one koji su najizloženiji riziku isključenja. Tek pod tim uslovom ona može predstavljati socijalnu modernizaciju, a ne samo tehničku reformu javne administracije.

Algoritamsko odlučivanje, podaci i institucionalna odgovornost

Digitalizacija socijalne zaštite ne završava se elektronskim obrascima, digitalnim evidencijama i elektronskom komunikacijom između korisnika i institucija. Sve veći značaj dobijaju sistemi koji podatke koriste za provjeru uslova, klasifikaciju potreba, otkrivanje rizika i nepravilnosti, predviđanje ponašanja i podršku odlučivanju. Digitalizovana socijalna zaštita tako prelazi iz faze elektronske administracije u fazu upravljanja zasnovanog na podacima. Ne mijenja se samo način podnošenja zahtjeva, već i način na koji institucije sagledavaju korisnika, procjenjuju njegov položaj i odlučuju o pristupu pravima [1], [2], [14]. Podaci u socijalnoj zaštiti imaju posebnu osjetljivost jer se odnose na prihode, zaposlenost, imovinu, porodične odnose, zdravstveno stanje, invaliditet, stanovanje, obrazovanje i ranije institucionalne kontakte korisnika. Njihovo povezivanje kroz registre, elektronske evidencije i interoperabilne baze može omogućiti bržu provjeru činjenica i efikasnije odlučivanje. Međutim, istovremeno se povećava kapacitet države da korisnike nadzire, klasifikuje, profiliše i automatski upoređuje sa unaprijed definisanim kriterijumima. Digitalni podaci zato nisu samo administrativni resurs, već i instrument institucionalne moći [1], [13], [18]. Posebno osjetljivo pitanje predstavlja upotreba algoritamskih sistema za procjenu rizika, utvrđivanje ispunjenosti uslova i usmjeravanje korisnika prema određenim pravima ili uslugama. Takvi sistemi mogu obrađivati veliki broj podataka i prepoznavati obrasce koje službenik ne bi mogao lako uočiti. Problem, međutim, nastaje kada odluke o ljudskim i socijalnim pravima zavise od modela čiji kriterijumi nisu dovoljno poznati, razumljivi, provjerljivi ili podložni osporavanju [16], [19]. Asimetrija između institucije i korisnika tada postaje još izraženija. Građanin koji traži socijalnu pomoć, naknadu, uslugu ili drugi oblik podrške najčešće ne zna koji su podaci korišćeni, iz kojih baza su preuzeti, da li su tačni i ažurni, kako su povezani i na koji način su uticali na odluku. Institucija raspolaže sistemom, podacima i

tehničkim znanjem, dok korisnik često raspolaže samo ishodom postupka koji ne razumije u potpunosti [1], [16].

Slučaj holandskog sistema SyRI pokazuje zbog čega je algoritamsko odlučivanje u socijalnoj sferi posebno osjetljivo iz perspektive ljudskih prava. Sistem je bio namijenjen identifikovanju mogućih prevara u oblasti socijalnih davanja i drugih javnih obaveza, ali je njegova primjena otvorila pitanja zakonitosti, privatnosti, transparentnosti, proporcionalnosti i diskriminatornih efekata. Posebno je problematično bilo povezivanje procjene rizika sa područjima u kojima žive grupe nižeg socioekonomskog statusa i migrantskog porijekla. Ovaj slučaj pokazuje da netransparentnost algoritamskog sistema ne ugrožava samo privatnost, već slabi i sposobnost korisnika da razumije, ospori i djelotvorno zaštiti svoja prava [16].

Algoritamski sistem ne mora formalno donositi konačnu odluku da bi snažno uticao na njen ishod. Dovoljno je da korisnika označi kao rizičnog, generiše upozorenje, preporuči dodatnu kontrolu ili usmjeri pažnju institucije prema određenoj grupi. Takva oznaka može promijeniti način na koji službenik posmatra korisnika, intenzitet kontrole kojoj ga izlaže i spremnost da njegov zahtjev razmatra sa početnim povjerenjem. Algoritam tako može stvarno učestvovati u oblikovanju odluke i onda kada formalna odgovornost ostaje na službeniku. Rizik je posebno izražen kada se algoritamski modeli oslanjaju na istorijske podatke koji već odražavaju društvene i institucionalne nejednakosti. Ako su siromašne, migrantske, manjinske ili prostorno marginalizovane zajednice ranije bile češće predmet nadzora i institucionalne sumnje, podaci nastali iz takve prakse mogu reprodukovati isti obrazac. Algoritam tada ne otkriva neutralnu stvarnost, već preuzima tragove ranije selektivne kontrole [13], [16]. Diskriminatorni efekti ne moraju nastati samo korišćenjem izričito zabranjenih osnova razlikovanja, kao što su etnička pripadnost, invaliditet ili starost. Oni mogu proizaći i iz zamjenskih varijabli, poput adrese stanovanja, tipa naselja, obrazovnog ili porodičnog statusa, istorije korišćenja davanja i učestalih promjena zaposlenja. Ako se na osnovu takvih podataka pojedine grupe češće označavaju kao rizične, algoritamski sistem može proizvesti indirektnu diskriminaciju iako se formalno oslanja na neutralne kriterijume [16], [19]. Sljedeći problem odnosi se na transparentnost. U administrativnom postupku korisnik bi morao znati na osnovu kojih činjenica i pravnih pravila je donesena odluka. U algoritamski podržanom sistemu ta veza može postati nejasna. Korisnik može dobiti odluku, ali ne i razumljivo objašnjenje načina obrade podataka, razloga zbog kojih mu je pripisan određeni rizik ili kriterijuma zbog kojih je njegov slučaj označen kao sporan. Ako institucija ne može objasniti logiku algoritamske procjene, prava na informaciju i žalbu postaju ozbiljno oslabljena [16], [18].

Odgovornost se dodatno komplikuje zbog broja aktera uključenih u digitalizovani sistem: javne institucije, dobavljača softvera, obrađivača podataka, drugih organa i tehničkih stručnjaka. Službenik može tvrditi da slijedi preporuku sistema, institucija da koristi rješenje razvijeno izvan nje, a dobavljač da nije odgovoran za njegovu primjenu u konkretnom postupku. Za korisnika je, međutim, presudno da zna ko odgovara za odluku koja utiče na njegovo pravo. Bez jasno utvrđene odgovornosti nastaje prostor u kojem je šteta stvarna, ali se njeno institucionalno porijeklo teško utvrđuje [17], [19].

Digitalni sistemi mogu smanjiti slučajne administrativne propuste, ali mogu i proširiti posljedice grešaka kroz povezane baze. Netačan podatak o prihodima, zaposlenju, adresi ili porodičnom statusu može se prenijeti u više evidencija i uticati na različite postupke. Ako korisnik ne zna da greška postoji, iz koje baze potiče i kome se može obratiti, mogućnost ispravke postaje ozbiljno ograničena. Pojedinačna greška tada može prerasti u sistemski problem koji se ponavlja kroz različite institucije [24], [18]. Važno pitanje predstavlja i logika sumnje. Kontrola zakonitosti korišćenja javnih sredstava legitimna je funkcija socijalne zaštite. Međutim, ako se digitalizacija dominantno razvija oko otkrivanja zloupotreba, a ne oko olakšavanja pristupa pravima, mijenja se institucionalni odnos prema korisniku. On se sve manje posmatra kao nosilac prava, a sve više kao potencijalni rizik. Takav pomak može pojačati stigmu, nepovjerenje i nadzor nad siromašnima, posebno kada se sličan intenzitet digitalne kontrole ne primjenjuje na druge oblike javne potrošnje i privilegija [1], [13]. Zbog toga treba razlikovati digitalnu administraciju od digitalnog nadzora. Prva može korisniku olakšati podnošenje zahtjeva, dostavljanje dokumentacije i pristup pravima.

Drugi podatke koristi radi praćenja, provjeravanja, klasifikovanja i sankcionisanja korisnika. U praksi se ove funkcije često prepliću: isti sistem može omogućiti bržu isplatu davanja i istovremeno intenzivniju kontrolu. Ključno pitanje zato nije samo koja se tehnologija koristi, već koja socijalnopolitička logika određuje njenu namjenu [1], [14]. Evropski regulatorni okvir sve jasnije prepoznaje ove rizike. Akt Evropske unije o vještačkoj inteligenciji svrstava među visokorizične i sisteme koji se koriste pri procjeni ispunjenosti uslova, priznavanju, smanjenju, ukidanju ili povratu prava iz oblasti javne pomoći i socijalne zaštite. Time se potvrđuje da algoritamski sistemi u ovoj oblasti nisu obični administrativni alati, već tehnologije koje mogu ozbiljno uticati na osnovna prava i položaj ranjivih grupa [19]. Okvirna konvencija Savjeta Evrope o vještačkoj inteligenciji takođe zahtijeva da aktivnosti tokom životnog ciklusa ovih sistema budu usklađene sa ljudskim pravima, demokratijom i vladavinom prava [17]. Regulacija, međutim, mora biti prevedena u institucionalnu praksu. Potrebna su jasna pravila o tome kada se algoritamski sistemi mogu koristiti, ko ih odobrava, kako se procjenjuju rizici i diskriminatorni efekti, ko ima pravo uvida i kako se obezbjeđuju ljudski nadzor i mogućnost žalbe. To uključuje prethodne procjene uticaja na ljudska prava, nezavisne provjere, učešće korisnika i stručnjaka iz oblasti socijalne politike, kao i zabranu da se najosjetljivije odluke prepuste potpuno automatizovanom postupku bez stvarne ljudske odgovornosti. Uloga stručnih radnika ne smije se svesti na tehničko potvrđivanje zaključaka koje je sistem već unaprijed oblikovao. Socijalna zaštita zahtijeva razumijevanje životnog konteksta, stručnu procjenu potreba, komunikaciju i prepoznavanje okolnosti koje se ne uklapaju lako u standardizovane kategorije. Ako digitalni sistem previše suzi prostor stručnog rasuđivanja, socijalna zaštita može izgubiti svoju ljudsku i profesionalnu dimenziju. Stručni radnik tada postaje produžetak sistema, umjesto korektiva njegovih ograničenja. Algoritamske sisteme i tehnologije zasnovane na podacima ipak ne treba unaprijed odbaciti. Oni mogu pomoći u planiranju usluga, ranijem prepoznavanju potreba, smanjenju administrativnih grešaka, boljoj koordinaciji institucija i bržem ostvarivanju prava. Njihova upotreba, međutim, mora biti ograničena, objašnjiva i podložna kontroli. Tehnologija u socijalnoj zaštiti treba da podržava odgovorno odlučivanje, a ne da zamijeni odgovornu instituciju. Njena svrha mora biti povećanje sposobnosti sistema da pomogne korisniku, a ne samo da ga nadzire. Ključni uslov legitimne digitalizacije jeste da korisnik ne ostane sam pred nevidljivim sistemom. On mora imati pravo na informaciju, razumljivo objašnjenje, ispravku podataka, ljudski kontakt, žalbu i nezavisnu provjeru odluke. Odgovorna upotreba podataka podrazumijeva da se prikupljaju samo podaci koji su nužni, da se koriste za jasno određene svrhe, da korisnici budu obaviješteni o njihovoj obradi i da postoji stvarni ljudski nadzor. Bez takvih mehanizama digitalizacija može postati snažna prema korisniku, a slaba u pogledu vlastite odgovornosti. Algoritamsko odlučivanje pokazuje da tehnološka isključenost nije jedini rizik digitalizovane socijalne zaštite. I korisnik koji uspije pristupiti digitalnom sistemu može biti izložen netransparentnoj obradi podataka, skrivenim kriterijumima i procjenama koje ne razumije. Digitalna dostupnost zato mora biti povezana sa pravnom sigurnošću u digitalnom okruženju. Pristup platformi nije dovoljan ako korisnik nema pristup razlozima odluke, korišćenim podacima i djelotvornim mehanizmima zaštite. Digitalizovana socijalna zaštita može biti socijalno opravdana samo ako istovremeno obezbjeđuje dostupnost, objašnjivost, odgovornost i zaštitu prava.

Socijalno osjetljiva digitalizacija kao uslov zaštite prava

Ako digitalizacija socijalne zaštite može proizvesti nove oblike tehnološke isključenosti, odgovor na taj rizik ne može biti odbacivanje digitalnih tehnologija. Takav pristup ne bi bio ni realan ni poželjan, jer digitalni sistemi mogu unaprijediti pristup informacijama, ubrzati postupke, smanjiti administrativno opterećenje i omogućiti bolju koordinaciju institucija. Ključno pitanje nije da li socijalna zaštita treba da bude digitalizovana, već pod kojim uslovima digitalizacija može biti socijalno pravedna, pristupačna i usklađena sa ljudskim pravima. Digitalizacija nije cilj sama po sebi, nego sredstvo koje ima opravdanje samo ako doprinosi stvarnom ostvarivanju prava [2], [3]. Socijalno osjetljiva digitalizacija polazi od činjenice da korisnici socijalne zaštite nisu homogena grupa. Oni se razlikuju prema prihodima, obrazovanju, digitalnim vještinama, zdravstvenom

stanju, invaliditetu, starosti, jeziku, mjestu stanovanja, porodičnim okolnostima i sposobnosti da samostalno prate administrativne postupke. Digitalni sistem koji je jednostavan za jednog korisnika može predstavljati ozbiljnu prepreku za drugog. Socijalna zaštita zato mora biti oblikovana prema stvarnim korisnicima, a ne prema zamišljenom prosječnom korisniku koji raspolaže uređajem, stabilnim internetom, vremenom, znanjem i sigurnošću da bez pomoći koristi elektronsku proceduru [6], [7], [9].

Prvi uslov socijalno osjetljive digitalizacije jeste višekanalni pristup i očuvanje nedigitalnih alternativa. Digitalni kanal treba razvijati kao dodatnu mogućnost, a ne kao zamjenu za sve druge oblike komunikacije. Korisniku mora ostati dostupna mogućnost da se informiše, podnese zahtjev, dopuni dokumentaciju i dobije objašnjenje neposredno u instituciji, telefonom, poštom, preko mobilnih timova, lokalnih punktova ili uz podršku stručnog radnika. Višekanalnost nije ostatak zastarjele administracije, već uslov jednakog pristupa u društvu u kojem građani nisu jednako digitalno uključeni [10], [3]. Nedigitalna alternativa posebno je važna za korisnike koji zbog nedostatka opreme, nepismenosti, invaliditeta, starosti, bolesti, beskućništva, gubitka dokumenata, nedostatka privatnosti ili drugih životnih okolnosti ne mogu koristiti elektronske procedure. Institucija ih zbog toga ne smije tretirati kao problematične ili nedovoljno prilagođene modernizaciji. Njena je odgovornost da obezbijedi stvaran put do prava i onda kada digitalni kanal nije dostupan ili primjeren konkretnom korisniku. Nedigitalni oblici pristupa zato nisu izuzetak od modernizacije, već njen neophodan korektiv [10], [2], [25].

Drugi uslov jeste dostupna ljudska podrška. Digitalizovana socijalna zaštita ne smije pretpostaviti da svaki korisnik može samostalno savladati proceduru. Što je sistem digitalniji, to je važnije da postoji jasna, dostupna i stručna pomoć za one koji imaju teškoće u njegovom korišćenju. Takva podrška ne bi smjela biti prepuštena isključivo porodici, komšijama, nevladinim organizacijama ili neformalnim posrednicima, jer se time odgovornost za pristup pravima prenosi sa institucije na privatno okruženje korisnika. Institucija koja digitalizuje postupak mora obezbijediti i pomoć onima koji taj postupak ne mogu koristiti bez podrške [2], [25], [7].

Treći uslov odnosi se na jednostavnost, razumljivost i pristupačnost digitalnih procedura. Nije dovoljno da platforma tehnički funkcioniše. Ona mora biti razumljiva korisnicima različitog obrazovanja, digitalnog iskustva i administrativne pismenosti. To podrazumijeva jasan jezik, jednostavne obrasce, kratka uputstva, objašnjenje svakog koraka, mogućnost provjere i ispravljanja unesenih podataka, kao i jasne informacije o daljem toku postupka. Korisnik mora znati da li je zahtjev uspješno podnesen, koji dokumenti nedostaju, koji su rokovi, kome se može obratiti i na koji način može osporiti odluku. Sistem koji korisnika ostavlja u neizvjesnosti ne povećava dostupnost, već proizvodi novu administrativnu nesigurnost [9]. Pristupačan dizajn posebno je važan za osobe sa invaliditetom, starije osobe i korisnike sa smanjenim funkcionalnim sposobnostima. Digitalne platforme treba da budu kompatibilne sa asistivnim tehnologijama i čitačima ekrana, da nude jednostavnu navigaciju, dovoljno vidljiv tekst, razumljive simbole, alternativne načine potvrde identiteta i mogućnost prekidanja i nastavka postupka bez gubitka podataka. Pristupačnost nije tehnički luksuz, već uslov jednakog ostvarivanja prava. Digitalni servis koji nije pristupačan nije univerzalno dostupan, čak i kada mu formalno mogu pristupiti svi građani [20].

Četvrti uslov jeste zaštita privatnosti i ličnih podataka. Digitalizovana socijalna zaštita mora jasno ograničiti koje podatke prikuplja, u koju svrhu ih koristi, koliko ih dugo čuva, sa kim ih dijeli i kako korisnik može ostvariti pravo na uvid, ispravku i zaštitu. Korisnici ne smiju biti dovedeni u situaciju da zbog potrebe za podrškom budu izloženi nesrazmjernom nadzoru. Prikupljanje i povezivanje podataka ne može se opravdavati samo opštim pozivanjem na efikasnost, bez procjene da li je obrada nužna, proporcionalna i usklađena sa svrhom ostvarivanja prava. U socijalnoj zaštiti zaštita podataka istovremeno predstavlja zaštitu privatnosti, autonomije i dostojanstva korisnika [18].

Peti uslov obuhvata transparentnost odlučivanja, stvarni ljudski nadzor i djelotvornu zaštitu prava. Korisnik mora znati na osnovu kojih činjenica, podataka i pravila je donesena odluka. Ako se koriste algoritamski sistemi, automatizovane provjere ili digitalne procjene rizika, mora biti

jasno da li je odluka donesena automatski ili uz ljudsko učešće, koji su kriterijumi primijenjeni i kako se mogu osporiti greška ili nepovoljan ishod. Transparentnost ne znači samo objavljivanje opštih pravila na internet stranici, već razumljivo objašnjenje konkretne odluke koja neposredno utiče na konkretnog korisnika. Bez toga pravo na žalbu ostaje formalno, ali ne i djelotvorno [16], [19]. Ljudski nadzor ne smije biti sveden na mehaničko potvrđivanje rezultata koje je sistem već proizveo. Službenik mora biti sposoban da razumije preporuku sistema, kritički je preispita, provjeri relevantne podatke, uvaži specifične okolnosti korisnika i donese odluku koja nije automatizovana posljedica tehničkog modela. Socijalna zaštita počiva na razumijevanju potreba, konteksta i životnih okolnosti. Ako se prostor stručnog rasuđivanja previše suzi, digitalni sistem može standardizovati korisnike i zanemariti ono što je u socijalnom radu i socijalnoj politici najvažnije — konkretnu ljudsku situaciju [17], [19].

Šesti uslov jeste prethodna procjena uticaja digitalnih rješenja i uključivanje korisnika i stručnjaka u njihovo oblikovanje. Prije uvođenja novih procedura potrebno je ispitati kako će one uticati na starije osobe, osobe sa invaliditetom, siromašne, ruralno stanovništvo, migrante, korisnike nižeg obrazovanja i druge grupe izložene tehnološkoj isključenosti. Procjena treba da utvrdi ko može biti isključen, na kojim mjestima nastaju prepreke, kakva podrška je potrebna i koje alternativne puteve pristupa treba obezbijediti. Digitalizacija koja nije prethodno provjerena iz perspektive ranjivih korisnika može proizvesti efikasnost za sistem, ali nove prepreke za građane [2], [3]. sistemi zato ne bi trebalo da budu razvijani samo iz perspektive informatičkih stručnjaka, administrativnih rukovodilaca i finansijske efikasnosti. U njihovo oblikovanje treba uključiti korisnike, organizacije koje zastupaju ranjive grupe, socijalne radnike, pravnike, stručnjake za ljudska prava i pristupačnost, kao i lokalne službe koje neposredno poznaju probleme u ostvarivanju prava. Takav pristup omogućava da se digitalno rješenje ne oblikuje samo prema unutrašnjoj logici sistema, već i prema iskustvima onih koji će ga koristiti.

Sedmi uslov odnosi se na jasnu institucionalnu odgovornost. Digitalizacija ne smije stvarati utisak da je odluka rezultat neutralnog tehničkog procesa iza kojeg ne postoji konkretan nosilac odgovornosti. Svaki digitalni sistem mora jasno definisati ko odgovara za tačnost podataka, zakonitost njihove obrade, objašnjenje odluke, ispravljanje grešaka, održavanje platforme i postupanje po žalbi. Korisnik ne smije biti upućen da sam traži odgovornost između institucije, dobavljača softvera, administratora baze i drugih tehničkih aktera. Odgovornost mora biti vidljiva, dostupna i institucionalno utvrđena [17], [19].

Osmi uslov jeste očuvanje profesionalne i etičke dimenzije socijalne zaštite. Digitalizacija ne smije potisnuti socijalnu zaštitu kao odnos podrške, procjene, savjetovanja i razumijevanja životne situacije korisnika. Ona može olakšati administrativni dio rada, ali ne može zamijeniti stručnu procjenu i neposredni kontakt tamo gdje su oni neophodni. U radu sa osobama u krizi, korisnicima sa složenim potrebama, porodicama u riziku, starijim osobama bez podrške ili osobama sa invaliditetom digitalni sistem može biti pomoćno sredstvo, ali ne i zamjena za odgovornu profesionalnu intervenciju. Socijalna zaštita ostaje javna funkcija koja zahtijeva povjerenje, odgovornost i osjetljivost prema ljudskoj ranjivosti.

Socijalno osjetljiva digitalizacija zahtijeva i promjenu kriterijuma kojima se procjenjuje uspješnost reforme. Digitalna transformacija ne bi trebalo da se vrednuje samo prema broju elektronskih zahtjeva, smanjenju troškova, brzini obrade ili stepenu automatizacije. Ta mjerila jesu važna, ali nisu dovoljna. Potrebno je pratiti koliko je korisnika lakše ostvarilo pravo, koliko je digitalno isključenih osoba dobilo odgovarajuću pomoć, koliko je grešaka ispravljeno, koliko su procedure razumljive i platforme pristupačne, kao i koliko su odluke jasno objašnjene i djelotvorno preispitane. Tek tada se digitalizacija može vrednovati iz perspektive korisnika i ostvarivanja prava, a ne samo iz perspektive administracije. Socijalno osjetljiva digitalizacija ne odbacuje tehnologiju, već joj postavlja socijalne granice i granice određene ljudskim pravima. Ona priznaje korisnost digitalnih alata, ali odbacuje pretpostavku da je digitalno samo po sebi bolje, pravednije ili dostupnije. U socijalnoj zaštiti digitalizacija je uspješna samo kada korisniku olakšava pristup pravima, smanjuje nepotrebne prepreke, čuva privatnost, omogućava razumijevanje postupka i jača

mogućnost zaštite. Ako povećava institucionalnu efikasnost, ali istovremeno udaljava ranjive korisnike od prava, onda nije socijalno uspješna.

Digitalna transformacija zato mora biti vođena principom da pravo prethodi proceduri. Svaka procedura, bilo papirna ili digitalna, postoji radi ostvarivanja prava, a ne da bi ga zamijenila. Kada digitalna procedura postane sama sebi cilj, korisnik se posmatra kao neko ko mora dokazati da može odgovoriti zahtjevima sistema, umjesto da sistem bude oblikovan prema njegovim legitimnim potrebama. Socijalno osjetljiva digitalizacija polazi od suprotnog stanovišta: tehnologija mora biti prilagođena pravu i korisniku, a ne pravo i korisnik tehnologiji.

Tehnološka uključenost u tom smislu postaje nova dimenzija socijalne uključenosti. Pristup digitalnim vještinama, internetu, uređajima, podršci i pristupačnim servisima sve neposrednije utiče na mogućnost ostvarivanja socijalnih prava. Država koja digitalizuje socijalnu zaštitu zato mora istovremeno razvijati politike digitalne uključenosti: digitalno opismenjavanje, javno dostupne pristupne tačke, asistirane digitalne usluge, lokalnu podršku, pristupačne platforme i kontinuirano praćenje posljedica digitalnih procedura po ranjive grupe. Bez takvih mjera digitalna socijalna zaštita može ostati stvarno dostupna samo građanima koji su već digitalno uključeni. Socijalno osjetljiva digitalizacija predstavlja pokušaj povezivanja administrativne modernizacije sa socijalnom pravdom. Ona ne polazi od odbacivanja tehnologije, već od svijesti da tehnologija uvijek djeluje unutar konkretnih društvenih odnosa. U društvu obilježenom siromaštvom, invaliditetom, starenjem, ruralnom izolovanošću, nižim nivoom pismenosti i nepovjerenjem u institucije, digitalni sistemi ne mogu biti neutralni ako te razlike zanemaruju. Digitalizovana socijalna zaštita zato mora biti oblikovana tako da najviše pomaže onima koji su najizloženiji isključenosti. Tek pod tim uslovom digitalizacija može postati instrument ostvarivanja ljudskih prava, a ne novi mehanizam njihove selektivne dostupnosti.

ZAKLJUČAK

Digitalizacija socijalne zaštite predstavlja jedan od važnih pravaca savremene transformacije javnih sistema. Ona može doprinijeti bržem postupanju, boljoj povezanosti institucija, smanjenju administrativnih prepreka i lakšem pristupu informacijama, pravima i uslugama. Njeni efekti, međutim, nisu unaprijed određeni. Digitalizacija sama po sebi ne garantuje veću dostupnost, jednakost i pravednost. Njena socijalna vrijednost zavisi od toga da li digitalni sistemi zaista olakšavaju ostvarivanje prava ili stvaraju nove tehničke, komunikacijske i institucionalne prepreke za korisnike koji se već nalaze u stanju socijalne ranjivosti. Analiza je pokazala da tehnološka isključenost nije samo posljedica nedostatka interneta, uređaja ili digitalnih vještina. Ona predstavlja širi socijalnopolitički problem koji nastaje kada digitalne procedure nisu prilagođene stvarnim mogućnostima korisnika. Starije osobe, osobe sa invaliditetom, siromašni, ruralno stanovništvo, migranti, osobe nižeg obrazovanja i drugi ranjivi korisnici mogu biti posebno pogođeni ako se digitalni kanal uspostavi kao jedini ili dominantni put do socijalnih prava. U takvim okolnostima pravo formalno postoji, ali njegova stvarna dostupnost postaje uslovljena tehnološkim resursima i sposobnostima korisnika. Iz perspektive ljudskih prava, ovaj problem ima posebnu težinu. Socijalna zaštita nije samo administrativna usluga, već dio sistema zaštite ljudskog dostojanstva, socijalne sigurnosti, jednakosti i zaštite od siromaštva i socijalne isključenosti. Zato digitalizacija mora biti usklađena sa principima nediskriminacije, pristupačnosti, transparentnosti, zaštite ličnih podataka, djelotvorne zaštite prava i institucionalne odgovornosti. Digitalni sistem koji korisnik ne razumije, ne može koristiti ili ne može djelotvorno osporiti nije stvarno dostupan, čak i kada je formalno otvoren svim građanima. Poseban izazov predstavlja upotreba podataka, automatizovanih procjena i algoritamskih sistema. Takvi alati mogu unaprijediti planiranje, koordinaciju i efikasnost, ali mogu proizvesti i netransparentnost, profilisanje, pojačan nadzor i diskriminatorne efekte. U oblasti socijalne zaštite, gdje odluke neposredno utiču na egzistencijalni položaj korisnika, algoritamski sistemi moraju biti objašnjivi, provjerljivi, ograničeni i pod stvarnim ljudskim nadzorom. Korisnik mora znati kako je odluka donesena, koji su podaci korišćeni, ko za odluku odgovara i na koji način može zaštititi svoja prava.

Osnovni zaključak rada jeste da je digitalizacija socijalne zaštite opravdana samo ako proširuje, a ne sužava prostor ostvarivanja socijalnih i ljudskih prava. To zahtijeva višekanalni pristup, očuvanje nedigitalnih alternativa, dostupnu ljudsku podršku, pristupačan dizajn, razumljive informacije, zaštitu privatnosti, mogućnost ispravljanja grešaka i djelotvorne mehanizme žalbe. Digitalni kanal treba da bude dodatna mogućnost za korisnika, a ne novi uslov koji mora savladati da bi pristupio pravu. Tehnološku isključenost zato treba prepoznati kao novu dimenziju socijalne isključenosti. U društvu u kojem se pristup pravima sve više posreduje digitalnim sistemima, tehnološka uključenost postaje sastavni dio stvarne socijalne uključenosti. Razvoj digitalizovane socijalne zaštite mora zbog toga biti praćen politikama digitalnog opismenjavanja, lokalne i institucionalne podrške, pristupačnih servisa i kontinuiranog praćenja posljedica digitalnih procedura po ranjive grupe. Digitalizovana socijalna zaštita ne smije biti oblikovana samo prema logici administrativne efikasnosti, već prema pravima, potrebama i dostojanstvu korisnika. Tek tada digitalizacija može postati instrument socijalne pravde, a ne novi mehanizam selektivne dostupnosti socijalnih prava.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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TECHNOLOGICAL EXCLUSION AND THE REALIZATION OF HUMANRIGHTS IN DIGITALIZED SOCIAL PROTECTION

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ABSTRACT

The digitalization of social protection is increasingly presented as an instrument for improvingthe efficiency, accessibility and transparency of public services. However, when access to social rightsbecomes predominantly mediated by digital platforms, electronic procedures, databases and automatedforms of decision-making, new forms of exclusion may emerge. This paper analyzes technologicalexclusion as a human rights issue within digitalized social protection systems. It focuses on theposition of users who lack digital skills, stable internet access, adequate devices, accessible digitalinterfaces or institutional support in navigating digital procedures. Special attention is given to therisks that digital transformation may create for older persons, persons with disabilities, people living inpoverty, rural populations and other socially vulnerable groups. The paper discusses the relationshipbetween administrative modernization and the effective realization of human rights, particularly theprinciples of equality, non-discrimination, accessibility, privacy, transparency and the right to aneffective remedy. The central argument is that digitalization should not replace the substantiveaccessibility of social protection, but should function as an additional and socially sensitive channelfor exercising rights. The paper concludes that digitalized social protection requires human rightssafeguards, non-digital alternatives and institutional mechanisms that prevent technological exclusionfrom becoming a new form of social inequality.

Keywords: social protection, human rights, technological exclusion, digitalization, social right

WOMEN'S RIGHTS AS HUMAN RIGHTS IN DEVELOPING COUNTRIES

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ABSTRACT

This paper analyzes women's rights as an integral part of human rights, with a particular focus on their realization in developing countries. Although the international legal framework formally guarantee equality and non-discrimination, the practical implementation of women's rights remains inconsistent across different socio-economic and cultural contexts. The aim of the study is to analyze key structural, legal and socio-cultural barriers that limit the effective enjoyment of women's rights, including unequal access to education, employment, healthcare and political participation. The research is based on a qualitative analysis of relevant international legal instruments, academic literature and selected reports from international organizations. Special attention is given to the gap between normative standards and their actual enforcement in practice. The results indicate that, despite certain progress in specific areas, significant systemic inequalities persist, largely due to deeply rooted social norms and weak institutional enforcement mechanisms. The paper concludes that stronger institutional framework, improved legal enforcement, and targeted policy measures are necessary to ensure the effective protection and full realization of women's rights as human rights.

Keywords: women's rights, human rights, developing countries, discrimination, international law

INTRODUCTION

Human rights can be understood from two diametrically opposed perspectives. On one hand, human rights are defined as natural rights, while on the other hand, they are based on a positive legal framework [1]. Human rights are inherent rights of every human being, rooted in moral principles [1]. The concept of women's rights as human rights was affirmed during the World Conference on Human Rights, where it was explicitly emphasized for the first time that women's

rights are an inalienable, integral, and indivisible part of universal human rights [2]. Women's rights refer to all rights that belong to women within the framework of universal human rights, including political, economic, social, and cultural rights [3], [2]. They are recognized as fundamental human rights in international documents, especially in the Convention on the Elimination of All Forms of Discrimination Against Women (CEDAW) [3].

Feminism is often misunderstood as seeking more rights for women than men, but the main goal is actually equality between women and men. The concept of women's rights implies gender equality, protection against discrimination, and the obligation of society and the state to ensure equal opportunities for women in all areas of life [3], [2]. In developing countries, the realization of these rights often faces significant obstacles. Social norms, economic barriers, insufficient implementation of laws, and weak institutional framework contribute to the fact that women are often unable to fully enjoy the rights formally guaranteed to them [4], [5], [6]. Therefore, it is important to analyze not only the legal framework, but also the practical implementation of laws and policies aimed at protecting women's rights [4], [5].

This paper primarily focuses on understanding the position of women in contemporary society and analyzing the ways in which their fundamental rights are respected, violated, or insufficiently realized in states facing political, economic, and social challenges characteristic of developing countries [4], [6], [7]. The paper is based on the premise that women's rights are an inseparable part of universal human rights, and that the achieved level of human rights protection cannot be assessed without insight into the status of women [1].

In many developing countries, women are still exposed to various forms of discrimination, violence, social marginalization, and deprivation of fundamental rights, including the right to education, healthcare, political participation, and economic security. These phenomena are most often connected to deeply rooted patriarchal patterns, lack of institutional protection, poverty, political instability, and traditions that restrict the position of women in society.

The paper analyzes various forms of violations of women's rights, including gender-based violence, forced and child marriages, female genital mutilation, restrictions on access to education, economic inequality, and political exclusion [4], [5], [7]. Special attention is also devoted to contemporary cases such as the situation in Afghanistan, where women are faced with severe restrictions on fundamental freedoms, including limitations on education, employment and participation in public life. Through this analysis, it is emphasized that women's rights represent the foundation of a stable, democratic, and just society, and that without full gender equality no country can achieve sustainable social and economic development [8].

MATERIALS AND METHODOLOGY

This paper is based on qualitative legal and socio-legal research focused on the analysis of women's rights as fundamental human rights and their realization in developing countries. The research combines normative, comparative, analytical, and interdisciplinary methods in order to examine both, the legal framework and the practical implementation of women's rights protection mechanisms.

The materials used in this research include academic books, monographs, scientific articles, international legal instruments, and reports published by international organizations dealing with human rights, gender equality, and social development. Particular attention was devoted to literature related to international human rights law, feminist legal theory, gender discrimination, and the social and economic position of women in developing countries.

The research relies on the analysis of academic works by authors such as Amartya Sen [9] , Catharine A. MacKinnon [10], and other scholars whose studies examine the relationship between women's rights, equality, and development. In addition, scientific articles concerning feminist approaches to international law, gender-based violence, and women's participation in social and political life were analyzed in order to provide broader theoretical framework for the research. Special emphasis was placed on the examination of international legal documents and mechanisms for the protection of women's rights, particularly the Convention on the Elimination of All Forms

of Discrimination Against Women (CEDAW) [3], the Beijing Declaration and Platform for Action [2], and United Nations Security Council Resolution 1325 [11]. These legal instruments were analyzed in order to identify international standards related to gender equality, protection against discrimination, and the promotion of women's rights.

The paper also uses reports and statistical data published by international organizations such as United Nations Development Programme (UNDP) [4], UN Women [5], World Bank [6], World Health Organization (WHO) [12], UNESCO [10], Food and Agriculture Organization (FAO) [11], and Organisation for Economic Co-operation and Development [8]. These reports provided relevant statistical indicators and practical insights into issues such as violence against women, access to education, economic inequality, healthcare, and political participation in developing countries.

The normative method was applied through the analysis of international and national legal provisions concerning the protection of women's rights. The comparative method enabled the comparison of the implementation of women's rights standards in different developing countries and regions. The analytical method was used to evaluate the effectiveness of institutional, legal, and social mechanisms for the protection of women's rights, while the interdisciplinary approach connected legal analysis with sociological, economic, and political perspectives.

The qualitative approach was considered the most appropriate for this research because the topic of women's rights in developing countries requires a broader understanding of social, cultural, political, and legal factors that cannot be explained exclusively through quantitative indicators [8]. Qualitative legal research allows a deeper interpretation of international legal standards, institutional practices, and the social realities that influence the realization of women's rights in different regions. This approach also enables the examination of the gap between formally guaranteed rights and their practical implementation in everyday life.

In addition to legal analysis, the research considered broader social and economic factors influencing the position of women, including poverty, political instability, patriarchal norms, limited access to education, and insufficient institutional protection [4] [5] [6]. Particular attention was devoted to the role of traditional and cultural practices that often affect the practical realization of women's rights despite the existence of formal legal guarantees [5] [8]. The interdisciplinary approach therefore enabled a more comprehensive understanding of the relationship between law, society, and gender equality.

The selection of developing countries as the primary focus of the research was based on the fact that women in these states are often exposed to multiple forms of discrimination and structural inequality [4] [6]. The research includes examples from regions such as the Middle East, Africa, and South Asia, where social and political conditions significantly affect the protection and realization of women's rights [4] [5]. Contemporary examples, including the situation in Afghanistan, were analyzed in order to demonstrate how political instability, restrictive legal systems, and patriarchal social structures directly influence women's freedoms and human rights [11] [5].

Although the research is primarily theoretical and based on secondary sources, the use of reports, case studies, and statistical indicators contributed to a more practical understanding of the issue [4] [5] [6]. The combination of legal analysis and socio-legal perspectives made it possible to evaluate not only the existence of legal protections, but also their effectiveness in practice and their impact on the everyday lives of women in developing countries.

Research also includes selected case studies and practical examples related to gender-based violence, discrimination, child and forced marriages, restrictions on education, and limitations of women's freedoms in certain developing countries, including Afghanistan [5] [4].

Research is primarily based on desk and secondary data analysis, using available academic literature, legal documents, institutional reports, and international standards related to women's rights and gender equality [8]. The interdisciplinary nature of the research enabled a broader understanding of the relationship between legal protection, social practices, economic inequality, and political conditions affecting the realization of women's rights in developing countries. The

selected materials and methods were used with the aim of providing a comprehensive overview of the challenges women face in exercising their fundamental human rights in different social and legal contexts.

RESULTS

Results of the research indicate that women in many developing countries continue to face serious obstacles in the realization of their fundamental human rights, despite the existence of international and national legal frameworks [9], [3], [2]. In most cases, the main issue is not the absence of laws, but their weak implementation and limited enforcement in practice.

The findings show that deeply rooted traditional norms, patriarchal structures and gender stereotypes continue to shape the position of women in both private and public life [10], [3], [5]. In many contexts, women are still primarily viewed through traditional family roles, which directly affects their access to education, employment, healthcare, political participation, and economic independence [4], [5], [6]. This suggests that legal reforms alone are not sufficient without broader social and cultural change. Another important finding relates to the economic position of women. Poverty and economic dependence remain key factors limiting gender equality in developing countries [6], [6], [7]. Women are often excluded from equal participation in the labor market, as well as from access to property, financial resources, and decision-making processes. In many cases, they also perform unpaid domestic and care work, which further limits their economic autonomy and social participation. The results also demonstrate that limited access to education and healthcare significantly affects the overall position of women [12], [7]. In rural and underdeveloped areas, women and girls often face restricted educational opportunities, inadequate healthcare services, and insufficient institutional support. Reports of international organizations show that women are disproportionately affected by weak healthcare systems, poverty, and social instability. Particular attention was devoted to the influence of cultural and patriarchal patterns on the status of women. The research confirms that practices such as child and forced marriages, restrictions on inheritance rights, normalization of domestic violence, and limitations on women's participation in public life remain present in many developing countries [3], [5], [7]. These practices are often socially tolerated despite being formally prohibited by law.

Table 1 presents a comparative overview of selected developing countries in relation to key indicators of women's rights protection.

Table 1. Comparative Overview of Selected Developing Countries

Criterion	Afghanistan	Tunisia	Bangladesh
Legal framework	Formal legal protections are practically non-existent	Relatively progressive; gender equality is formall recognized	Equality is formally recognized, but implementation resistance
Education	Education for women is prohibited beyond primary level	Accessible, but not fully utilized due to persistent stereotypes	Accessible, but gender-based barriers remain
Employment	Women are prohibited from working	Access to employment exists, but inequalities and gender pay gaps persist	Legal access to employment exists, but social remain
Discrimination and violence	Extreme forms of social and legal discrimination	Legal protection exists, but enforcement remains.	Legal framework exists alongside strong social resistance
Actual status of women	Among the worst globally	Social norms limit the implementation of legal protections	Despite legal safeguards, gender inequality remains significant

Source: Author's own elaboration based on general findings from UN Women, World Bank and UNESCO reports

Study additionally shows that international mechanisms such as Convention on the Elimination of All Forms of Discrimination Against Women [3], and various United Nations initiatives contribute to strengthening legal standards for the protection of women's rights [2], [11], [5]. However, the effectiveness of these mechanisms largely depends on the political will of states, institutional capacity, public awareness, and the willingness of societies to challenge discriminatory traditions and patriarchal norms [5], [4].

The research also indicates that insufficiently developed legal systems represent a serious obstacle to the effective protection of women's rights. Although many states have formally adopted laws prohibiting discrimination and violence against women, the implementation of these laws is often inconsistent due to corruption, lack of institutional capacity, weak judicial systems, and social tolerance of gender-based discrimination [4], [6], [8]. In many cases, women face difficulties in accessing legal protection because of financial barriers, fear of social stigma, or lack of trust in institutions [5], [6].

Collected data additionally reveal that political instability and armed conflicts significantly worsen the position of women in many developing countries [11], [4]. In conflict and post-conflict societies, women are often exposed to increased levels of violence, forced displacement, trafficking, and economic insecurity. Weak state institutions and the collapse of legal protection mechanisms further limit women's access to justice and institutional support. Contemporary examples, particularly the situation in Afghanistan, demonstrate how political and ideological systems can directly restrict women's access to education, employment, freedom of movement, and participation in public life [11], [5].

Another important finding of the research is that women in rural areas and marginalized communities are frequently exposed to multiple forms of discrimination [4], [6], [7]. Factors such as poverty, low educational attainment, ethnic background, and geographical isolation additionally increase women's vulnerability and reduce their opportunities for social and economic participation. The analysis confirms that women from disadvantaged social groups are often excluded from decision-making processes and face greater obstacles in accessing healthcare, education, employment, and legal protection [5], [6], [9].

The results further demonstrate that violence against women remains one of the most widespread forms of human rights violations in developing countries [3], [5]. Domestic violence, sexual violence, child marriages, and other forms of gender-based violence continue to affect the physical, psychological, and economic security of women. The research indicates that such violence is often normalized through traditional and patriarchal social norms, which discourages victims from reporting abuse and seeking institutional protection. In addition, the analysis confirms that improving women's access to education and economic resources has a direct positive impact on gender equality and social development [6], [7], [8].

Countries that invest in women's education, healthcare, and economic participation generally show lower levels of poverty, greater social stability, and stronger democratic development. The paper therefore suggest that the protection of women's rights should not be viewed solely as a legal obligation, but also as a fundamental condition for sustainable economic and social progress. The research ultimately confirms that the realization of women's rights is closely connected to the overall level of democratic, economic, and social development [4], [6], [8]. Without effective implementation of laws, equal access to education and economic resources, and changes in traditional social attitudes, the achievement of full gender equality in developing countries remains significantly limited.

DISCUSSION

Discussion of the research results confirms that the issue of women's rights in developing countries cannot be understood solely through the existence of formal legal guarantees and international protection mechanisms [3], [2], [11]. Although many states have formally adopted international conventions and national laws prohibiting discrimination and guaranteeing equality, the realization of these rights in practice remains significantly limited [6], [5], [6]. Findings suggest

that the gap between normative equality and actual social equality continues to represent one of the central challenges in the protection of women's human rights. It could be argued that the existence of legal norms alone is insufficient if institutional systems responsible for their implementation remain weak or ineffective.

In many developing countries, women formally possess rights guaranteed by constitutions, international conventions, and domestic legislation, yet practical obstacles continue to prevent the effective exercise of those rights [4], [6], [8]. Limited institutional capacity, corruption, political instability, economic inequality, and lack of access to justice often reduce the practical value of legal guarantees. In this sense, the law may sometimes function more as a symbolic declaration of equality than as an effective mechanism capable of ensuring protection in everyday life.

Findings collectively demonstrate that gender inequality in developing countries operates as a multidimensional structural issue in which legal, economic, cultural, and political factors reinforce one another [4], [5], [6]. Research further indicates that deeply rooted patriarchal norms continue to shape the social position of women in both private and public spheres. In many societies, traditional gender roles remain strongly connected to expectations that women should primarily fulfill domestic and caregiving responsibilities. Such expectations frequently influence women's access to education, employment, political participation, and economic independence. This may explain why legal reforms alone often fail to produce substantial social change. Even where legal equality formally exists, social attitudes and cultural expectations can continue to limit women's opportunities and autonomy.

At the same time, it is important to avoid overly simplified interpretations of cultural and religious influences. Findings do not suggest that religion itself is inherently incompatible with women's rights. Rather, the problem often lies in selective and patriarchal interpretations of religious teachings and cultural traditions that are used to justify unequal social relations [5]. In many contexts, discriminatory practices are presented as part of tradition or morality, despite the fact that such practices frequently contradict both international human rights standards and the broader principles of dignity and equality contained within religious traditions themselves. Economic inequality also appears to play a major role in maintaining structural gender discrimination [4], [6], [7]. Authors such as Amartya Sen and Naila Kabeer emphasize that poverty should not be understood only as lack of income, but also as limitation of human capabilities and opportunities. Research supports this perspective by demonstrating that women in developing countries are often excluded from equal participation in the labor market and decision-making processes. In addition, women disproportionately perform unpaid domestic and care work, which further limits their economic autonomy and reduces opportunities for social advancement.

Paper additionally suggests that economic dependence can increase women's vulnerability to violence and exploitation [5], [6]. In situations where women lack independent financial resources, access to property, or employment opportunities, leaving abusive relationships or seeking institutional protection becomes significantly more difficult. This raises the broader question of whether legal protection can ever be fully effective without simultaneous economic empowerment and social support mechanisms. Limited access to education represents another major issue identified through the research [12], [7]. Education does not only affect employment opportunities, but also influences awareness of rights, political participation, and long-term social mobility. In many developing regions, girls continue to face barriers related to poverty, early marriage, geographic isolation, and traditional social expectations.

UNESCO reports showing high numbers of girls excluded from formal education indicate that educational inequality remains a persistent global issue. The relationship between education and child marriage appears particularly significant. In communities where access to secondary education is limited, girls are more likely to enter marriage at an early age, which often results in interrupted education, economic dependency, and increased exposure to domestic violence. It may therefore be argued that improving access to education could produce broader social effects extending beyond the educational sphere itself.

Healthcare inequality likewise remains an important dimension of women's rights [12]. Women living in rural and underdeveloped areas frequently face inadequate healthcare systems, lack of reproductive healthcare services, and limited institutional support during pregnancy and childbirth. Reports from international organizations continue to demonstrate that women are disproportionately affected by weak healthcare infrastructure and poverty. Maternal mortality, insufficient prenatal care, and restricted access to healthcare institutions remain particularly serious concerns in certain regions of Sub-Saharan Africa and South Asia.

The discussion also highlights the persistence of gender-based violence as one of the most widespread forms of human rights violations affecting women globally [3], [5]. Domestic violence, sexual violence, trafficking, forced marriages, and harmful traditional practices continue to affect the physical and psychological security of millions of women and girls. Although many countries have adopted legislation criminalizing such acts, implementation often remains inconsistent. Fear of social stigma, economic dependency, distrust in institutions, and inadequate victim protection mechanisms frequently discourage women from reporting violence. Particular attention should also be given to the way violence becomes socially normalized within certain patriarchal environments. In some societies, violence against women may be minimized, justified, or treated as a private family matter rather than a serious violation of human rights. Such attitudes contribute to underreporting and weaken institutional responses. In this regard, the issue extends beyond criminal law and enters the broader sphere of social attitudes and cultural normalization.

Research additionally demonstrates that political instability and armed conflicts significantly worsen the position of women in many developing countries [11], [4]. In conflict and post-conflict societies, institutional protection mechanisms are often weakened or entirely absent. Women become more exposed to forced displacement, sexual violence, trafficking, and economic insecurity. Moreover, women are frequently excluded from peace negotiations and post-conflict reconstruction processes, despite the fact that these processes directly shape future political and legal systems. Situation in Afghanistan represents one of the most visible contemporary examples of systematic restrictions on women's rights [11], [5]. Restrictions on education, employment, movement, and participation in public life illustrate how political and ideological systems can directly influence the realization of fundamental human rights. However, it is also important to recognize that Afghanistan represents an extreme example and that the status of women differs significantly across developing countries depending on political systems, institutional development, and social conditions.

Another important issue concerns the representation of women within political institutions and decision-making processes. Although many states formally recognize women's political rights, their actual participation often remains limited [4], [6]. Women continue to face barriers related to political violence, lack of financial support, discriminatory institutional practices, and pressure from family or community structures. As a result, women are frequently underrepresented in positions where decisions regarding economic policy, governance, and development strategies are made. The findings also suggest that media representation and educational systems play an important role in either maintaining or challenging gender inequality [5], [7].

Media narratives that reinforce stereotypical gender roles may contribute to the normalization of discriminatory attitudes. On the other hand, education and public awareness campaigns can gradually influence social perceptions and encourage broader acceptance of gender equality principles. At the same time, some limitations of the research should also be acknowledged [8]. The study is primarily based on secondary sources, international reports, and qualitative analysis, which means that the findings depend significantly on available institutional data and previously published research. Conditions affecting women's rights also differ considerably between regions and states, making broad generalizations difficult. Therefore, some conclusions presented in this paper should be interpreted within the broader socio-political context of individual countries.

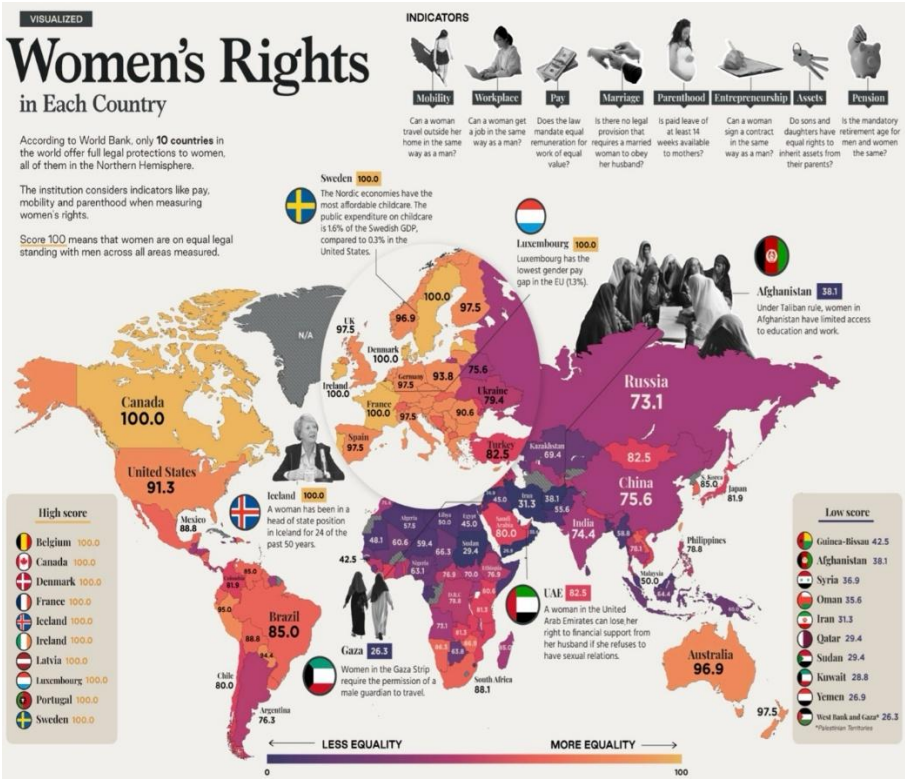

Figure 1. Global overview of women's legal rights and gender equality indicators by country. Source: World Bank, Women, Business and the Law Report.

During the research, one respondent emphasized that the only issue important to him was that his own daughters enjoy all fundamental rights and opportunities. While such a statement reflects personal concern for the wellbeing of one's family, it also reveals a limited understanding of women's rights as a broader social and human rights issue. The protection of women's rights cannot be viewed solely through individual or family circumstances, since many girls and women are born into environments where access to education, healthcare, legal protection, and basic freedoms remains restricted. For that reason, discussions on women's rights require a wider perspective that recognizes global inequalities and the structural barriers affecting women in different social, cultural, and economic contexts.

Findings of this research suggest that the gap between formal equality and lived reality remains one of the defining challenges in the protection of women's rights in developing countries [4], [5], [6]. While legal recognition of equality represents an essential foundation, it does not automatically dismantle the structural conditions that reproduce discrimination and exclusion [4], [6], [8]. As a result, the effectiveness of women's rights protection depends not only on the existence of legal norms, but also on the broader social, economic, and political environment in which those norms operate [4], [5], [6]. Discussion therefore highlights the need for a more comprehensive approach that views women's rights as inseparable from questions of development, education, institutional reform, and social transformation [7], [8].

Theoretical implications of the findings

Findings of this research may also be examined through broader theoretical approaches related to human rights, equality, and development [9], [10]. One of the central issues identified throughout the analysis is the distinction between formal legal recognition of rights and their realization in practice [3], [4]. Although international conventions and national legal systems

increasingly recognize gender equality as a fundamental principle, the everyday experiences of women in many developing countries continue to reflect substantial limitations and inequalities. This indicates that the existence of legal norms alone cannot automatically produce social equality or eliminate structural discrimination.

From a human rights perspective, the research supports the understanding that rights should not be viewed exclusively as abstract legal guarantees, but also as practical social conditions that individuals must be able to exercise in reality [3], [4]. In many developing countries, women formally possess rights related to education, employment, political participation, and protection from violence, yet economic dependency, social expectations, institutional weakness, and cultural barriers often prevent the effective realization of those rights [4], [5], [6]. In such circumstances, the gap between legal protection and lived reality becomes particularly visible. Findings are also consistent with theoretical approaches that connect development with human freedom and individual capabilities [9], [14], [15]. Amartya Sen argues that development should not be understood solely through economic growth, but through the expansion of people's real opportunities and freedoms [9].

Results of this study support such an approach by demonstrating that women's inequality is closely connected to limited access to education, healthcare, economic resources, and decision-making processes [4], [6], [12], [7]. In this sense, poverty and discrimination are not only economic issues, but also factors that directly limit personal autonomy and participation in society. At the same time, feminist legal theories provide an additional perspective for understanding why legal reforms often produce limited practical effects [10], [16]. Authors such as Catharine MacKinnon emphasize that legal systems do not operate separately from social power structures, but are influenced by historical inequalities and dominant social norms [10].

Findings of this research suggest that even when states formally adopt anti-discrimination laws and equality policies, institutional practices and social attitudes may continue to reproduce unequal gender relations [4], [5]. This may partly explain why reforms introduced through legislation are sometimes insufficient to change everyday social realities. Research further demonstrates that gender inequality cannot be analyzed only as an individual issue, but rather as a broader structural phenomenon shaped by economic, political, cultural, and institutional factors [4], [5], [6]. Discrimination against women often appears interconnected with poverty, political instability, weak institutional systems, and unequal access to resources [4], [6]. Because of this, the protection of women's rights should not be approached exclusively through criminal law or constitutional guarantees, but through wider social policies that address structural inequality more generally.

Another important theoretical implication concerns the relationship between universal human rights standards and local cultural contexts [3], [2]. Debates surrounding women's rights in developing countries frequently involve tensions between universal principles of equality and arguments related to cultural traditions or social values. However, the findings of this research suggest that many practices limiting women's rights are not simply cultural expressions, but mechanisms that maintain unequal power relations and social exclusion [5]. At the same time, it is important to recognize that cultural and religious traditions are not static and may be interpreted in different ways depending on political and social circumstances.

Findings additionally indicate that women's rights should be understood as closely connected to democratic development and institutional legitimacy [4], [8]. Societies in which women face systematic exclusion from education, political participation, employment, or access to justice often experience broader weaknesses in democratic governance and institutional accountability [4], [6]. In this regard, the status of women may serve as an important indicator of the overall level of social equality, rule of law, and democratic development within a state. Overall, the research confirms that the realization of women's rights requires a multidimensional approach that goes beyond formal legal reform [4], [5], [6]. Legal protection remains an essential foundation, but sustainable progress depends equally on institutional effectiveness, access to education and

economic opportunities, social awareness, and gradual transformation of discriminatory norms and practices [12], [7], [8].

Feminist theoretical perspectives

Feminist theoretical approaches help explain why formal legal equality does not necessarily translate into real, substantive equality [10], [16]. Feminist legal theory challenges the idea that law is neutral. Instead, it argues that legal systems develop within existing power relations that have historically tended to favour men [10]. Because of that, even laws that clearly prohibit discrimination can still operate in ways that reproduce inequality in practice [10], [16].

Liberal feminist perspectives tend to focus on legal reform, education, and increasing women's participation in institutions, with the assumption that removing formal barriers will gradually lead to equality. More critical approaches, including radical feminist theory, are less optimistic about this [10]. They argue that inequality is embedded much more deeply in social structures and cultural norms, so legal change alone cannot really address the problem. Findings of this research sit somewhere in between these positions: legal reforms are clearly necessary, but they are not enough on their own if broader social patterns remain unchanged [10], [16].

Structural economic and social barriers

Economic inequality remains one of the most persistent barriers to the realization of women's rights [4], [6], [14]. In many developing countries, women are still more likely to be in low-paid, insecure, or informal forms of work, and more likely to experience poverty [4], [6]. This kind of economic dependence limits their autonomy and affects almost every aspect of life, from education and employment to health and personal safety [9], [14], [15]. Large part of women's work also remains unpaid, particularly domestic work and caregiving. Although this work is essential for households and for society more broadly, it is rarely recognised in formal economic systems [14]. As a result, it does not provide financial independence or social protection, which reinforces existing inequalities. This economic vulnerability also has direct consequences when it comes to violence and exploitation. When women do not have their own financial resources, leaving abusive situations or seeking protection becomes significantly more difficult [5], [6]. For this reason, economic empowerment should be seen not only as a development objective, but also as a core part of human rights protection [9], [14].

Cultural, social, and normative frameworks

Social and cultural norms play a central role in shaping gender relations and often act as deeply rooted barriers to equality [5], [10]. In many contexts, women are still primarily expected to take on domestic and caregiving roles, while their participation in public and economic life is limited [5], [16]. These expectations are not formed overnight. They are passed on through families, education systems, and community practices, which makes them resistant to quick change. In some cases, discriminatory practices are even seen as socially acceptable or "normal", despite clearly conflicting with international human rights standards [1], [3]. At the same time, culture is not fixed; it changes over time and can be influenced through education, policy, and wider social awareness. This helps explain why legal reforms alone rarely produce immediate or visible social change. Even when equality is guaranteed on paper, social expectations can continue to shape behaviour and limit women's opportunities in practice [10], [16].

Role of international law and implementation gap

International legal instruments form an important framework for the protection of women's rights [2], [3], [11]. Instruments such as CEDAW, the Beijing Declaration and Platform for Action, and UN Security Council Resolution 1325 set out global standards for gender equality and non-discrimination [2], [3], [11]. However, there is still a clear gap between international commitments and their actual implementation at the national level [4], [5]. Many states have ratified these instruments, but the extent to which they are incorporated into domestic law and effectively

enforced varies significantly. This gap is especially visible in countries with limited institutional capacity and weak governance structures [4], [8].

Ultimately, the effectiveness of international law depends not only on formal ratification, but also on political will, administrative capacity, and social acceptance of gender equality principles [1], [3]. Where these elements are missing, international norms risk remaining largely symbolic. Even so, they still play an important role in shaping policy debates and supporting advocacy efforts by civil society actors [5].

Intersection of law, development, and governance

Women's rights are closely linked to broader issues of development and governance [4], [8], [9]. Countries with stronger institutions, better access to education, and more stable political systems generally show higher levels of gender equality [4], [7], [8]. In contrast, in contexts marked by poverty, conflict, and weak institutions, women are more likely to face exclusion and insecurity [4], [11]. This suggests that gender equality cannot be treated as a separate policy issue, but rather as something that is closely tied to wider processes of economic and political development [9], [15].

Policy implications

In practice, there is often a noticeable gap between what laws say and what women actually experience in everyday life [3], [4]. Although most legal systems formally prohibit discrimination and violence against women, the way these rules are applied is often uneven and inconsistent. In many contexts, institutions struggle with issues such as corruption, political pressure, limited funding, and weak accountability, which all reduce how effective legal protections are in reality [4], [8]. Access to justice is still a serious problem, especially for women living in rural areas or in lower-income communities [5], [6]. Even when legal options technically exist, they are not always realistic to use. Costs, lack of information, fear of social judgement, family pressure, and distrust in institutions often discourage women from reporting violence or discrimination [5].

In some situations, the social consequences of speaking up can feel more difficult to deal with than the original problem itself. Available reports and case studies indicate that in some instances, women who report domestic violence may still face severe consequences, including lethal outcomes, even when protective measures such as restraining orders are in place. Such cases have been documented across different contexts, including both developing and European countries, suggesting that the enforcement of protective measures may not always be effective in practice.

Education plays a key role over the long term, not only in terms of employment and income, but also in shaping awareness of rights and the ability to make independent decisions [7], [9]. In many developing countries, girls still leave school earlier than boys, often because of poverty, household responsibilities, or early marriage [7]. These early limitations tend to follow them later in life and restrict their opportunities. Economic dependence is another factor that increases vulnerability [6], [14]. When women do not have financial stability, it becomes significantly harder to leave abusive relationships or to take an equal role in society. Because of this, economic empowerment should be seen not only as a development issue, but also as part of broader protection of basic rights [9], [14].

Support systems for survivors of gender-based violence are still often underdeveloped [5], [12]. Even where laws exist, they have limited impact if there are no shelters, legal aid services, healthcare support, or psychological assistance available in practice. This is particularly visible outside of major urban centres, where services are often scarce. At the same time, legal reforms alone rarely lead to real, long-term change [10], [16]. Deeply rooted social attitudes and traditional views about gender still strongly influence behaviour in many societies. For this reason, broader social change is just as important as legal and institutional reform, with education and public awareness playing a central role [5], [7].

Overall, improving the position of women requires more than formal legal equality [1], [9]. Law, institutions, education, economic conditions, and social norms are closely connected, and progress in one area often depends on progress in the others [4], [8], [15].

CONCLUSION

Women's rights, as an integral and inseparable part of universal human rights, represent a fundamental precondition for equality, dignity, and sustainable development [3], [4], [5]. Despite the existence of extensive international legal frameworks, including the Convention on the Elimination of All Forms of Discrimination Against Women and other UN human rights instruments, the analysis shows that the practical realization of women's rights in many developing countries remains limited and uneven [3], [6], [7].

Research confirms that the central problem is not the lack of legal guarantees, but the persistent gap between formal equality and real-life conditions [6], [8]. Although most states formally prohibit discrimination and violence against women, implementation is often weak due to insufficient institutional capacity, lack of accountability, and limited access to justice [6], [8], [12]. This results in a situation where legal norms exist, but their effect in practice remains significantly reduced.

Key finding of this study is that structural and deeply rooted social factors continue to represent the main barrier to full realization of women's rights [6], [7], [8]. Patriarchal norms, traditional cultural patterns, and socially accepted gender roles still shape the position of women in many developing societies. These norms are reinforced through family structures, education systems, religious interpretations, and broader social expectations, which makes them difficult to change solely through legal reforms [7].

This paper also highlights the strong connection between economic inequality and the vulnerability of women [6], [8], [10]. Limited access to education, employment opportunities, property ownership, and financial resources significantly reduces women's autonomy and reinforces dependency. In such conditions, women are more exposed to discrimination, exclusion from decision-making processes, and various forms of violence and exploitation. In addition, weak institutional frameworks and underdeveloped legal systems further limit the effectiveness of existing protections [6], [8], [12].

Even when laws against discrimination and violence exist, their enforcement is often inconsistent, while access to legal remedies remains difficult, especially for women in rural and marginalized communities. Political instability and conflict situations further intensify these challenges, as they weaken state institutions and increase women's exposure to violence, displacement, and social insecurity [5], [6]. At the same time, cultural and traditional practices, when combined with patriarchal interpretations, continue to justify unequal treatment and restrict women's rights in both private and public spheres [7]. Despite these challenges, the research emphasizes that education and economic empowerment remain key long-term tools for improving the position of women [9], [10]. Strengthening access to education, increasing participation in the labor market, and ensuring equal opportunities contribute directly to greater independence and social inclusion of women. Equally important is the role of international cooperation and civil society, which provide support, monitoring, and advocacy for the implementation of gender equality standards [7].

In conclusion, the realization of women's rights in developing countries requires a comprehensive and multidimensional approach that goes beyond legal reforms. It demands institutional strengthening, economic empowerment, social awareness, and cultural transformation [6], [8], [12]. Only through the combined efforts of states, international organizations, and civil society can formal legal equality be transformed into substantive equality in practice. Ultimately, the level of protection and realization of women's rights represents a key indicator of the overall development, justice, and democratic maturity of a society [6], [8], [12]. Ensuring these rights is therefore not only a legal obligation, but also a necessary condition for sustainable development and long-term social progress.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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IT SECTION
IT SEKCIJA

AUTOMATA AS COALGEBRAS IN CATEGORY OF MATRICES

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ABSTRACT

This paper considers automata as models of systems used for information processing and computational execution. Special attention is devoted to the coalgebraic approach and the category of matrices as modern methods for the formal description of dynamic and state-based systems. By viewing automata as coalgebras, it becomes possible to model system behavior through sets of states and transitions while emphasizing behavioral equivalence. On the other hand, the category of matrices provides a natural algebraic framework for representing transitions, relations, and weights between states. The combination of these approaches establishes a unified theoretical model suitable for the analysis of finite, probabilistic, and weighted automata, as well as for applications in formal verification, communication protocols, and programming language theory. The results indicate that the coalgebraic interpretation within the category of matrices enables a deeper understanding of the structure and behavior of computational systems, thereby connecting automata theory with modern developments in computer science.

Keywords: Automata, coalgebra, category, matrix.

INTRODUCTION

Standard algebraic techniques have proven useful for describing various essential aspects of data structures used in computer science. But it is it turns out to be difficult to algebraically describe some of the dynamic structures that are widely used, especially because a notion of state which often appears can be understood in many ways. Automata or transition systems are most often used to formally describe such systems. During the last decades, there is a growing belief that it is better, instead of algebras, to represent such structures with coalgebras.

Coalgebra theory can be viewed as a framework for studying the behavior of large classes of dynamical systems, including many types of automata (deterministic, non-deterministic, probabilistic, etc.) and infinite data types (streams, trees, etc.).

Finite automata and their variants are among the fundamental structures in computer science, and their applications are wide-ranging. Deterministic finite automata are perhaps the simplest machines with finite memory (although they can represent infinite sets) and, together with finite non-deterministic automata, they represent basic examples of coalgebras.

Weighted automata [6], [10] generalize deterministic automata [1], [2] in the sense that transitions carry, in addition to an input symbol, a weight from an underlying structure and each state of these automata is assigned an output weight in that structure.

If we analyzing weighted finite automata through the lens of vector spaces and matrix operations, the behavior of a weighted finite automaton can be expressed as the product of the row vector representing the initial weights, matrices representing the weights of the transitions induced by input letters, and the column vector representing the terminal weights. Such a representation of a weighted finite automaton is called a linear representation [11].

In that sense, the set of states of a deterministic weighted automaton is equipped with a vector space structure. This formulation arises from the determinization of non-deterministic weighted automata over generic field using subset construction, a process that typically yields an infinite state set. Despite this, the algebraic properties of the linear state space enable a finite representation of these automata and efficient algorithms for their manipulation.

To formalize behavioral equivalence and construct minimization algorithms if we are using linear representation of weighted automata, it is convenient to frame them as coalgebras.

Reflecting this paradigm shift, coalgebraic theory is being adapted to quantitative contexts [3], [4], grounded by Larsen and Skou's work [5] and extended to linear weighted automata [6]. However, this framework introduces significant complexity, as it requires states to be interpreted as vectors and coalgebras as linear maps.

PRELIMINARIES

A finite weighted automaton is a quintuple $W = (A, Q, \lambda, \mu, \gamma)$, where A is the input alphabet, Q is a finite set of states, and $\lambda, \gamma: Q \to S$ are the initial and final weight functions, respectively. The function $\mu: A \to S^{(Q\times Q)}$ is defined such that $\mu(a)(p,q)$ represents the transition weight of $p \xrightarrow{a} q$. If $\mu(a)(p,q) = 0$, which means that there is no transition from state p to state q under the input symbol a. For each $a \in A, \mu(a) \in S^{(Q\times Q)}$ can be viewed as a Q-indexed matrix expressing the weights of the transitions involving the input symbol a. In a similar vein, the functions λ and γ can be regarded as Q-indexed vectors.

Underlying algebraic structure for this type of automata can be semiring $(S, +, \times, 0, 1)$ or some richer structure (for example, the field of real numbers will serve as a framework for our example).

In computer science, matrices are conventionally viewed as rectangular data structures implemented as two-dimensional arrays. On the other hand, in mathematics matrices are often treated as linear transformations. Thus, a matrix M with n rows and m columns can be defined as a function that assigns a value to each cell (r, c) of the matrix, for $1 \leq r \leq n$ and $1 \leq c \leq m$. Since the type of entries in the cells can vary, the minimal algebraic structure required for matrix operations is a semiring. Standard linear algebra typically utilizes a richer structure, primarily a field (field of real numbers serving as the canonical example).

The type of an $m \times n$ matrix M will be denoted by an arrow $m \to n$. The notation $m \xrightarrow{M} n$ (or equivalently, $n \xleftarrow{M} m$) declares the matrix M and its type. We outline some of the key operations on matrices:

– Matrix composition (multiplication) $M \cdot N$ is given by

–

$$r(M \cdot N)c = \sum_x \big((rMx) \times (xNc)\big),$$

where we denote the (r,c)-entry of the matrix $M \cdot N$ by $r(M \cdot N)c$, $\times$ is the multiplicative operation of the underlying semiring from which the matrix entries take their values, and $\sum$ denotes the finite iteration of its additive operation. The type of resulting matrix $M \cdot N$ is given by

$$n \xleftarrow{M} m \xleftarrow{N} k, \quad n \xleftarrow{M \cdot N} k$$

Identity matrix of dimension n, denoted by $n \xleftarrow{id_n} n$ or $n \xleftarrow{1} n$ $(n \in \mathbb{N})$, in which all elements on the main diagonal are 1 and all off-diagonal elements are 0. Consequently, it holds that

$$id_n \cdot M = M = M \cdot id_m.$$

Transposition operation: replacing the rows of a given matrix with their corresponding columns (and vice versa). Given a matrix $n \xleftarrow{M} m$, the notation $m \xleftarrow{M^\circ} n$ refers to its transposed matrix, i.e., its converse, satisfying:

$$(M^\circ)^\circ = M,$$
$$(M \cdot N)^\circ = N^\circ \cdot M^\circ.$$

Addition: for given matrices $n \xleftarrow{M,N} m$ of the same type, the matrix $M + N$ is defined as

$$r(M+N)c = rMc + rNc, \qquad (1 \le r \le n, 1 \le c \le m),$$

where the symbol $+$ refers to the additive operator of the underlying semiring. Furthermore, the zero matrix is defined as a matrix where each entry contains the additive identity 0 of the semiring; hence, it holds that:

$$M + 0 = M = 0 + M,$$
$$M \cdot 0 = 0 = 0 \cdot M,$$

and composition is a bilinear operation with respect to $+$, i.e.

$$M \cdot (N+P) = M \cdot N + M \cdot P,$$
$$(N+P) \cdot M = N \cdot M + P \cdot M.$$

Hadamard product: the multiplication of two matrices of the same type, denoted by $M \times N$ (or MN) is commutative, associative, and distributive with respect to addition and yields a matrix of the same type, where

$$r(MN)c = rM \cdot rNc, \quad (1 \le r \le n, 1 \le c \le m).$$

The identity element for this product is the matrix whose entries all equal 1 (the multiplicative identity of the underlying semiring).

Together with the composition operation and the identity element, matrices form a category whose objects are the matrix dimensions and whose morphisms $(m \xleftarrow{M} n)$ are the matrices themselves [8], [9]. We will denote this category by Mat_S, parameterized by a semiring S or some other (richer) algebraic structure. Also, vectors can be viewed as a special case of matrices where one of the dimensions is 1.

AUTOMATA AND CATEGORY OF MATRICES

Due to the commutative property of the additive operation in the semiring S, the objects in the matrix category Mat_S, namely the matrix types, can be generalized from numerical values $n, m \in \mathbb{N}_0$ to arbitrary non-numerical sets (types) (A, B). This is achieved by replacing $m + n$

with the disjoint union $A + B$, mn with the Cartesian product $A \times B$, 1 (the multiplicative identity of the semiring S) with a singleton set, 0 (the additive identity of the semiring S) with the empty set $\emptyset$, and so forth. Conversely, a dimension n corresponds to the type $\{0, 1, 2, \ldots, n-1\}$.

So, we can define the weighted automaton in [6] as a quadruple $W = (Q, A, \mu, \gamma)$, where the initial weight function λ is omitted. In this case, the final weight function γ is assigned the type $Q \to 1$, which is now considered a row vector in the category Mat_S. The transition function μ can be seen in two ways: either as a matrix of type $Q \times A \to Q$ or as a matrix of type $Q \to Q \times A$. In the category Mat_S, these two types are isomorphic, and since the representation $Q \to Q \times A$ of the function μ is coalgebraic, the weighted automaton in the category Mat_S can be defined by the following diagram

$$Q \times A \overset{\mu}{\leftarrow} Q \overset{\gamma}{\to} 1.$$

Since every matrix can be partitioned into corresponding matrix blocks (submatrices), there are two ways to construct a new matrix from two given matrices, say M and N:

1. The matrix $[M \mid N]$ is formed by appending the columns of N to the columns of M;
2. The matrix $\left[\frac{M}{N}\right]$ is formed by stacking the matrix M on top of the matrix N.

A detailed description of both constructions can be found in [7].

Now, the functions μ and γ of the weighted automaton $W = (Q, A, \mu, \gamma)$ can be viewed as a single matrix of type

$$(Q \times A) + 1 \overset{W}{\leftarrow} Q,$$

where

$$W = \left[\frac{\mu}{\gamma}\right].$$

In other words, a weighted automaton represents a coalgebra of the functor

$$FX = (X \otimes id) \oplus id,$$

in the category Mat_S, where $\otimes$ denotes the Kronecker product of matrices.

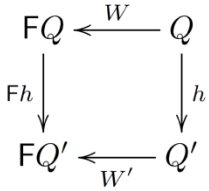
To define the basic coalgebraic concepts in the category Mat_S, every function $A \overset{f}{\to} B$ must be represented by a matrix $[[f]]$ of the same type, defined by

$$b[[f]]a \ (b =_S f(a)),$$

where $b =_S x$ equals the multiplicative identity 1 of the semiring S if $y = x$, and 0 otherwise.

Based on this, the matrix $[[f]]$ is a representation of the graph of the function f: an entry of the matrix $[[f]]$ is equal to 1 for $(f(a), a)$ and 0 otherwise.

For the functor $FX = (X \otimes id) \oplus id$, an F-coalgebra homomorphism (or F-cohomomorphism) between two weighted automata W and W' is a function h for which the following diagram commutes:



In other words, the following holds

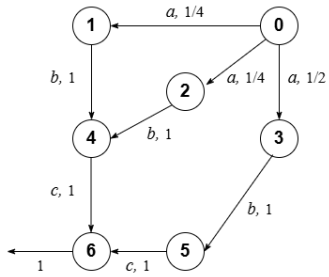
$$(Fh)\cdot W = W'\cdot h \Leftrightarrow \begin{cases}(h \otimes id)\cdot \mu = \mu'\cdot h,\\ \gamma = \gamma'\cdot h.\end{cases}$$

The identity $(h \otimes id)\cdot \mu = \mu'\cdot h$, for matrices of type $Q' \times A \leftarrow Q$, means that the weight corresponding to the transition $q' \overset{a}{\leftarrow} h(q)$ in the target weighted automaton is the accumulation of the weights of all transitions $p \overset{a}{\leftarrow} q$ in the source automaton, for every p such that $h(p) = q'$.

The second identity, $\gamma = \gamma'\cdot h$, implies that $\gamma(q) = \gamma'(h(q))$ when γ and γ' are viewed as functions again.

EXAMPLE

Let us consider the weighted automaton $W = (Q, A, \mu, \gamma)$ from the figure, where $Q = \{0, 1, 2, 3, 4, 5, 6\}$ and $A = \{a, b\}$.



The matrix μ is given by the following table, where the columns are indexed by the elements of Q and the rows by the Cartesian product $Q \times A$. Transitions that do not lead to any state and are labeled with 1 correspond to the row vector $\gamma = (0\ 0\ 0\ 0\ 0\ 0\ 1)$ of type $1 \leftarrow Q$.

Q	A	0	1	2	3	4	5	6
0	a	0	0	0	0	0	0	0
0	b	0	0	0	0	0	0	0
0	c	0	0	0	0	0	0	0
1	a	$\frac{1}{4}$	0	0	0	0	0	0
1	b	0	0	0	0	0	0	0
1	c	0	0	0	0	0	0	0
2	a	$\frac{1}{4}$	0	0	0	0	0	0
2	b	0	0	0	0	0	0	0
2	c	0	0	0	0	0	0	0
3	a	$\frac{1}{2}$	0	0	0	0	0	0
3	b	0	0	0	0	0	0	0
3	c	0	0	0	0	0	0	0

Q	A	0	1	2	3	4	5	6
4	a	0	0	0	0	0	0	0
4	b	0	1	1	0	0	0	0
4	c	0	0	0	0	0	0	0
5	a	0	0	0	0	0	0	0
5	b	0	0	0	1	0	0	0
5	c	0	0	0	0	0	0	0
6	a	0	0	0	0	0	0	0
6	b	0	0	0	0	0	0	0
6	c	0	0	0	0	1	1	0

Figure 1. Transition matrix μ of automaton

Is the equivalence relation K shown in the following figure a bisimulation relation?

K	0	1	2	3	4	5	6
0	1	0	0	0	0	0	0
1	0	1	1	0	0	0	0
2	0	1	1	0	0	0	0
3	0	0	0	1	0	0	0
4	0	0	0	0	1	1	0
5	0	0	0	0	1	1	0
6	0	0	0	0	0	0	1

Figure 2. Equivalence relation K

The relation K has five equivalence classes, which can be represented by a quotient automaton with a new state set $Q' = \{0, I, II, III, IV\}$, using the corresponding surjective homomorphism $Q' \overset{h}{\leftarrow} Q$.

h	0	I	II	III	IV
0	1	0	0	0	0
1	0	1	0	0	0
2	0	1	0	0	0
3	0	0	1	0	0
4	0	0	0	1	0
5	0	0	0	1	0
6	0	0	0	0	1

Figure 3. Homomorphism $h: Q' \leftarrow Q$

From [6], the equivalence relation $Q \overset{K}{\leftarrow} Q$ is a bisimulation for a given weighted automaton, if $K = h^{\circ} \cdot h$ and

$$FK \cdot W = FK \cdot W \cdot K^{*},$$

where $K^{*} = h^{\bullet} \cdot h$, and $h^{\bullet}$ is inverse of homomorphism h.

It is easy to check that for given relation K and $h^{\bullet} = h^{\circ} \cdot (h \cdot h^{\circ})^{-1}$, obtained by inversion of diagonal $h \cdot h^{\circ}$, holds

$$(K \otimes id) \cdot \mu = (K \otimes id) \cdot \mu \cdot K^{*},$$
$$\gamma = \gamma \cdot K^{*}.$$

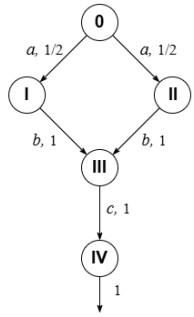
Quotient automaton $W' = W_{/K} = (Fh) \cdot W \cdot h^{\bullet}$, is defined by

$$\mu' = \mu_{/K} = (h \otimes id) \cdot \mu \cdot h^{\bullet},$$
$$\gamma' = \gamma_{/K} = \gamma' \cdot h^{\bullet}.$$

Q'	A	0	I	II	III	IV
0	a	0	0	0	0	0
0	b	0	0	0	0	0
0	c	0	0	0	0	0
I	a	$\frac{1}{2}$	0	0	0	0
I	b	0	0	0	0	0
I	c	0	0	0	0	0
II	a	$\frac{1}{2}$	0	0	0	0
II	b	0	0	0	0	0
II	c	0	0	0	0	0
III	a	0	0	0	0	0
III	b	0	1	1	0	0
III	c	0	0	0	0	0
IV	a	0	0	0	0	0
IV	b	0	0	0	0	0
IV	c	0	0	0	1	0

Figure 4. Transition table μ' of quotient automaton

We also give transition graph of a quotient automaton Q' :



CONCLUSION

Category of matrices can be viewed as a natural evolution of the category of sets, because enables a coalgebraic approach to weighted automata. The paper highlights the importance of the representation of weighted automata in a coalgebraic setting, and through our example, we illustrate the procedure of computing an equivalence relation which represents a bisimulation for the given weighted automaton. The obtained quotient automaton simulates the original automaton and obviously features a smaller state space.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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RFID-BASED IoT SYSTEM FOR WIRELESS IDENTIFICATION

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ABSTRACT

This paper examines the development and application of integrated circuits for wireless communication in IoT networks, with a particular focus on their role in the design and implementation of practical low-power systems. The theoretical part of the paper addresses the fundamental concepts of IoT architecture, the principles of wireless communication, and the role of integrated communication circuits in device connectivity, data acquisition, and remote system control. Special attention is devoted to the analysis of the characteristics of low-power microcontrollers and communication modules, as well as their application in smart infrastructure solutions.

The practical part of the paper includes the design and implementation of a toll-gate system prototype based on the Arduino UNO R3 platform, representing an example of an IoT device with wireless user identification. The system uses an RFID integrated circuit for contactless communication and authentication, a servo motor for mechanical barrier control, and an LCD display for user interaction. Before the physical prototype was implemented, a system simulation was developed in the Tinkercad environment, enabling verification of the operating logic, sequence of actions, and system behaviour under controlled conditions.

Based on the simulation, a physical prototype was developed, confirming the correctness of communication between the integrated circuits, as well as the functionality of the system under real operating conditions. The obtained results show that it is possible to implement a embedded identification system using simple and widely available integrated circuits. The paper emphasizes the importance of integrating hardware and software components in the development of IoT solutions and indicates the potential application of such systems in smart traffic and automated infrastructure.

Keywords: Internet of Things, low-power integrated circuits, System-on-Chip, duty cycling, energy efficiency.

INTRODUCTION

The rapid evolution of integrated circuits and wireless communication technologies has significantly transformed the development of modern Internet of Things (IoT) systems [1], [3]. IoT represents a paradigm in which physical devices are interconnected through communication networks, enabling data exchange, remote monitoring, and automated control without direct human intervention [1], [2]. This technological concept has become a fundamental foundation for smart environments, including intelligent transportation systems, industrial automation, and security infrastructures [3].

A key aspect of IoT systems is the integration of efficient wireless communication modules and embedded processing units within a single system architecture [2], [3]. These integrated communication circuits, often implemented as system-on-chip (SoC) solutions, enable reliable data transmission while maintaining low power consumption and high scalability [3]. Their role is crucial in sensor networks, where large numbers of devices must operate under energy constraints and limited computational resources [5].

Among various IoT applications, radio frequency identification (RFID) technology has emerged as a widely used solution for automated identification and access control systems [3], [6]. RFID enables contactless communication between a reader and a tag, providing fast and reliable identification of users or objects [6]. Due to its simplicity, low cost, and high efficiency, RFID technology is commonly applied in access control systems such as parking management, toll gates, and secure facility entry systems [6].

This paper presents the design and implementation of an RFID-based IoT system for wireless identification and automated vehicle access control. The developed system integrates a microcontroller-based processing unit, an RFID reader module, a servo motor for mechanical barrier control, and an LCD display for real-time user feedback. The system is designed as a low-cost embedded solution that demonstrates the practical application of integrated communication circuits in IoT environments [3].

A toll gate scenario is implemented as a case study to validate the proposed system architecture. The system was first developed and tested in a simulation environment, followed by the construction of a physical prototype. The results confirm the reliability of the system in performing real-time identification and automated control tasks, demonstrating its potential application in smart transportation and infrastructure systems.

The main contribution of this work is the practical demonstration of how integrated communication circuits can be combined with embedded processing units to develop a functional and cost-effective IoT-based access control solution.

FUNDAMENTALS OF WIRELESS COMMUNICATIONS IN IOT NETWORKS

Wireless communication represents the fundamental enabling technology for modern Internet of Things (IoT) systems. It allows interconnected devices to exchange data without physical wiring, thereby enabling flexible, scalable, and distributed system architectures [1], [3]. In IoT environments, wireless communication is used to connect embedded devices, sensors, and processing units into a unified network capable of real-time monitoring, control, and automation [2].

The IoT concept is based on the integration of physical devices with network connectivity and data processing capabilities. This integration enables systems to operate autonomously with minimal human intervention [1], [2]. As a result, IoT technologies are widely applied in smart environments such as intelligent transportation systems, industrial automation, healthcare monitoring, and security systems [3].

As illustrated in Figure 1, a typical IoT system is organized into four functional layers, each responsible for a specific task in data acquisition, communication, processing, and user interaction [2], [3]. The lowest layer is the sensing layer, which is responsible for data acquisition from the physical environment. This layer includes sensors and identification technologies such as Radio Frequency Identification (RFID). RFID systems enable contactless identification of objects or users through radio frequency signals and are widely used in access control and tracking applications [6]. The communication between the RFID reader and tag is based on electromagnetic

coupling, where the reader generates a radio frequency field that enables energy transfer and data exchange with the RFID tag.

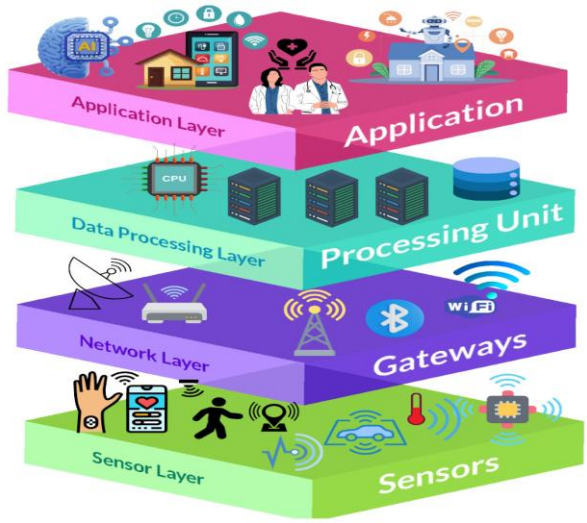

Figure 1. Four-layer architecture of an Internet of Things (IoT) system

In this work, RFID technology is used as the primary method for user identification in automated toll-gate system. Above the sensing layer is the communication layer, which ensures reliable data transmission between devices. Depending on system requirements, different wireless technologies can be applied, such as Wi-Fi, Bluetooth, Zigbee, and other low-power communication protocols [4], [5]. The choice of communication technology depends on factors such as transmission range, data rate, power consumption, and overall system reliability.

The processing layer is responsible for analyzing incoming data and executing appropriate control actions. This layer is typically implemented using microcontrollers or embedded processing units capable of running real-time control algorithms [3]. In the proposed system, a microcontroller processes RFID input data, verifies user authorization, and controls actuators such as servo motors for barrier operation.

The application layer represents the interface between the system and the end user. It provides real-time feedback and system status information through displays or user interfaces. In access control systems, this layer is responsible for displaying messages such as access granted or access denied, thereby improving usability and system transparency [2].

Wireless communication in IoT systems is characterized by several key parameters that directly affect system performance. One of the most important factors is transmission range, which defines the distance over which devices can communicate reliably. Short-range communication technologies are typically used in localized systems such as access control, while long-range technologies are used in wide-area IoT deployments [4], [5].

Another important characteristic is data rate, which determines how much information can be transmitted within a given time interval. IoT systems generally do not require extremely high data rates but rather prioritize stable and efficient communication. Closely related to this is power consumption, which is a critical constraint in embedded and battery-powered IoT devices. Low-power operation is essential for ensuring long-term system functionality and reducing maintenance requirements [5].

Reliability is also a key factor in wireless communication systems, as it ensures consistent data transmission and minimizes errors caused by interference or signal degradation. In practical IoT implementations, reliability is achieved through robust hardware design and communication protocols capable of handling unstable network conditions [3].

In addition to these characteristics, IoT systems must satisfy several fundamental requirements. Massive connectivity is necessary to support many interconnected devices within a

single network. Scalability ensures that the system can be expanded without significant degradation in performance. Security is another essential requirement, as IoT systems often handle sensitive identification and control data. Therefore, proper authentication mechanisms and secure communication strategies are critical for system integrity [3], [6].

INTEGRATED CIRCUITS FOR WIRELESS COMMUNICATION

Integrated circuits (ICs) represent the core hardware components that enable modern wireless communication systems. In the context of Internet of Things (IoT), these circuits integrate processing units, memory, and communication interfaces into compact and energy-efficient modules [3]. Their development has significantly contributed to the miniaturization, reliability, and scalability of embedded systems used in smart applications [1], [3].

In IoT environments, integrated communication circuits are responsible for acquiring, processing, and transmitting data between devices. These circuits are commonly implemented as microcontrollers, communication modules, or system-on-chip (SoC) solutions that combine multiple functional units within a single silicon platform [3]. The integration of such components allows the design of low-cost and energy-efficient systems suitable for large-scale deployment [2], [5].

A widely used example of an embedded processing IC is a microcontroller-based platform, such as the Arduino family. These platforms provide a simple development environment for interfacing sensors, actuators, and communication modules. In this work, an Arduino Uno R3 microcontroller is used as the central processing unit responsible for managing system operations, including RFID data processing and actuator control. A practical example of an integrated processing platform used in IoT applications is shown in Figure 2. The Arduino Uno R3 combines a microcontroller unit with digital and analog interfaces, enabling simple integration with sensors, actuators, and communication modules.



Figure 2. Arduino Uno R3 microcontroller platform used for embedded IoT applications

The Arduino Uno R3 is based on the ATmega328P microcontroller, operating at a clock frequency of 16 MHz and powered by a 5 V supply. It provides 14 digital input/output pins, including six Pulse Width Modulation (PWM) outputs, and six analog input channels with a 10-bit analog-to-digital converter (ADC). The board also incorporates UART, SPI, and I²C communication interfaces, enabling efficient integration with various sensors, actuators, and peripheral communication modules [11]. These features make the Arduino Uno R3 a suitable platform for rapid prototyping and the development of low-cost IoT applications [3]. Due to its open-source architecture, extensive software support, and compatibility with numerous sensors and communication modules, the Arduino Uno R3 is widely used for educational, research, and prototype development purposes.

In the proposed system, the Arduino Uno R3 communicates with the MFRC522 RFID reader through the Serial Peripheral Interface (SPI), a synchronous communication protocol designed for fast and reliable data exchange between embedded devices [11]. The SPI interface supports clock frequencies of up to 8 MHz on the Arduino Uno platform, enabling rapid transmission of RFID identification data with minimal communication latency. This high-speed interface allows the

microcontroller to process authentication requests in real time and control peripheral devices immediately after user identification.

Another important integrated component used in IoT systems is the Radio Frequency Identification (RFID) module. RFID systems consist of a reader and a passive or active tag, where communication is established through electromagnetic induction or radio waves [6]. In the proposed system, the MFRC522 RFID reader operates at a carrier frequency of 13.56 MHz and complies with the ISO/IEC 14443 Type A standard [12]. Under typical operating conditions, the communication range extends up to approximately 5 cm, allowing fast contactless identification within a few milliseconds [12]. Due to its simplicity, reliability, and low implementation cost, RFID technology is widely adopted in access control systems, parking management, and automated identification applications [6]. An example of the RFID reader module used in the proposed system is shown in Figure 3.

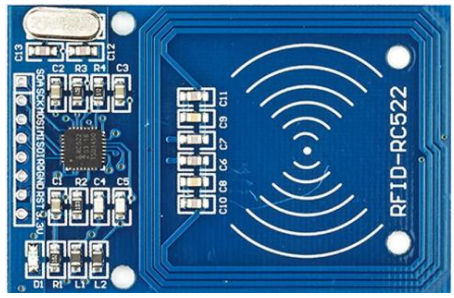

Figure 3. MFRC522 RFID reader module used for wireless identification

After detecting an RFID tag, the MFRC522 reader transfers the unique identification number (UID) to the Arduino Uno through the SPI interface. The microcontroller compares the received UID with the list of authorized identifiers stored in its memory and executes the corresponding control algorithm. If authentication is successful, a control signal is generated to activate the servo motor, while the LCD display simultaneously provides visual feedback to the user regarding the access status. This integration of identification, processing, and actuation represents a typical architecture of embedded IoT-based access control systems [3], [6].

In addition to microcontrollers and RFID modules, modern IoT systems increasingly rely on wireless communication chips such as Wi-Fi and Bluetooth modules [3], [4]. These modules can be integrated directly into microcontroller boards or implemented as standalone communication ICs. They enable connectivity with external networks and cloud-based services, extending the functionality of embedded systems beyond local operation [3].

System-on-chip (SoC) architectures represent a further advancement in integrated circuit design. SoC solutions combine processing units, memory, and communication interfaces into a single chip, significantly improving performance while reducing power consumption and physical size [3]. Such architectures are particularly suitable for large-scale IoT deployments where efficiency and scalability are critical [2], [3]. An example of a System-on-Chip architecture is illustrated in Figure 4, where processing units, memory, communication interfaces, and peripheral modules are integrated into a single semiconductor device.

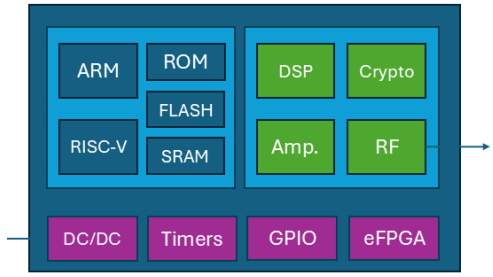

Figure 4. Internal architecture of a System-on-Chip (SoC) device

The selection of appropriate integrated circuits in IoT system design directly affects system performance, including power consumption, processing capability, communication range, and overall reliability. Therefore, careful consideration of hardware components is essential when designing embedded IoT solutions.

DEVELOPMENT AND IMPLEMENTATION OF COMMUNICATION ICs IN IoT DEVICES

The development of IoT systems relies heavily on the practical implementation of integrated communication circuits within embedded platforms. This stage of system design focuses on combining hardware components and software algorithms into a functional architecture capable of performing real-time data acquisition, processing, and control [3].

In modern IoT applications, communication integrated circuits are embedded into sensor nodes and embedded controllers to enable efficient interaction between physical devices and digital systems. These circuits must ensure low power consumption, reliable communication, and fast response times to support real-time applications such as access control, monitoring, and automation [2], [3].

A typical IoT device consists of a processing unit, communication module, input sensors, and output actuators. The processing unit is responsible for executing control logic, while communication modules handle data exchange between devices or external systems. Sensors provide input data from the environment, and actuators perform physical actions based on system decisions [2].

In the implemented system, an Arduino Uno R3 microcontroller serves as the central processing unit responsible for coordinating all system operations. The system uses an RFID reader module for wireless identification, where each RFID tag contains a unique identifier used for user authentication. Once the identifier is read, it is processed by the microcontroller, which determines whether access should be granted or denied based on predefined logic.

If the authentication process is successful, the system activates a servo motor that simulates a barrier mechanism. At the same time, an LCD display provides real-time feedback to the user by displaying system status messages such as “Access Granted” or “Access Denied”. This ensures clear communication between the system and the user.

Before physical implementation, the system logic was verified using a simulation environment. This allowed validation of communication flow, control algorithms, and component interaction without the risk of hardware damage. After successful simulation testing, a physical prototype was constructed and tested under real operating conditions.

The implementation demonstrates how integrated circuits can be effectively combined within IoT architectures to create low-cost, reliable, and scalable embedded systems. The proposed solution highlights the importance of proper hardware-software integration in achieving efficient system performance [3].

EXPERIMENTAL PART – CASE STUDY: TOLL GATE SYSTEM

This section presents the experimental implementation of the proposed IoT-based system for wireless identification and automated access control. The case study is designed to demonstrate the practical application of integrated communication circuits in a real embedded environment [3].

The developed system simulates a toll gate scenario where users are identified using RFID technology, and access is granted or denied based on authorization. RFID-based identification is widely used in automated access control applications due to its contactless operation, reliability, and fast data exchange capabilities [6]. The system is built using an Arduino Uno R3 microcontroller as the central processing unit, which coordinates all input and output operations. The RFID reader module is responsible for detecting and reading unique identifiers from RFID cards, while a servo motor is used to simulate a physical barrier mechanism. An LCD display provides real-time feedback to the user regarding system status.

System Operation Principle

The operation of the system is based on a sequential process. When an RFID card is brought close to the reader, the RFID module captures the unique identifier and sends it to the microcontroller. The Arduino then compares the received identifier with a predefined list of authorized users stored in memory.

If the identifier matches an authorized entry, the system triggers the servo motor to open the barrier, allowing vehicle passage. Simultaneously, the LCD display shows a message indicating successful authentication. After a predefined time interval, the system automatically returns the servo motor to its initial position, simulating barrier closure.

In cases where the RFID tag is not recognized, the system denies access and displays an appropriate message on the LCD screen. This ensures secure and controlled access to the system.

Simulation Environment

Before building the physical prototype, the system was designed and tested using a simulation environment. The simulation allowed verification of system logic, component interaction, and control flow under controlled conditions. This step was essential for identifying potential errors in the system design before hardware implementation.

The simulation confirmed correct operation of RFID-based identification, microcontroller processing, and actuator control. It also demonstrated that the system logic behaves as expected in both authorized and unauthorized access scenarios.

The simulation model was developed in the Tinkercad simulation environment, where the main system components and their interactions were virtually implemented and tested. The developed Tinkercad simulation is presented in the following figure.

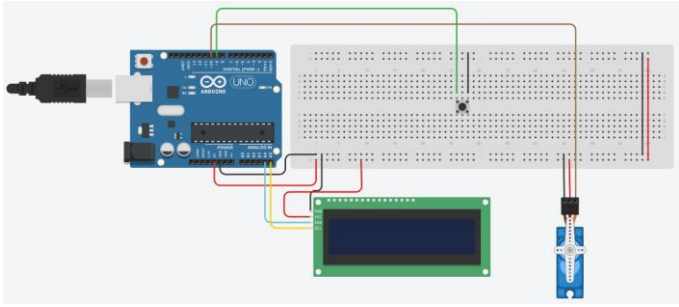

Figure 5. Tinkercad simulation

Physical Prototype and Toll-Gate Implementation

The physical prototype represents the final implementation of the proposed system. It is built using the same architecture validated in the simulation phase. The hardware components are interconnected to form a functional embedded system capable of real-time operation.

The system demonstrates stable performance in detecting RFID tags, processing data, and controlling the servo motor. The LCD display provides clear and immediate feedback to the user, improving system usability and transparency.

The experimental results confirm that the proposed design is suitable for low-cost automated access control applications, such as parking systems, secure facilities, and toll gate infrastructure.

The wiring diagram of the implemented physical prototype, including the connections between the Arduino Uno microcontroller, RFID reader, LCD display, and servo motor, is shown in the following figure.

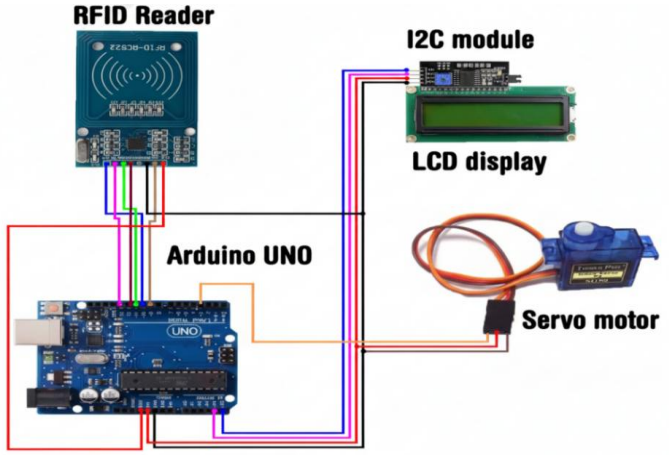

Figure 6. Wiring diagram of the physical prototype

The final physical realization of the proposed RFID-based toll-gate system is presented in Figure 7. The implemented prototype integrates all previously described hardware components, including the Arduino Uno R3 microcontroller, MFRC522 RFID reader, LCD display, and servo motor mechanism. The assembled system demonstrates the practical operation of the proposed IoT architecture, where RFID-based identification is processed by the microcontroller and converted into an automated access control action. The prototype successfully represents the transition from simulation to real hardware implementation and confirms the feasibility of the developed low-cost embedded solution.

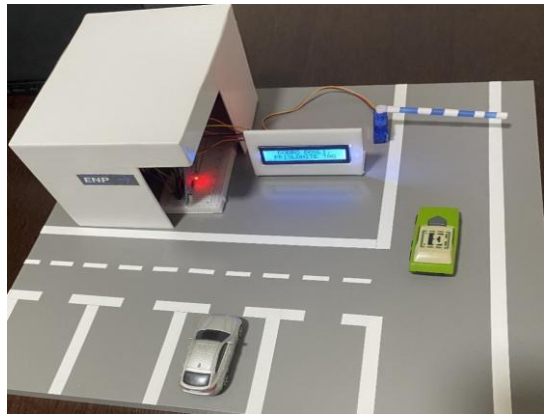

Figure 7. Implemented physical prototype of the RFID-based toll-gate system

DISCUSSION

The implemented RFID-based IoT system demonstrates a functional and efficient approach to automated access control using low-cost embedded components. The combination of an Arduino Uno R3 microcontroller, RFID reader module, servo motor, and LCD display enables a complete closed-loop system capable of real-time identification and response.

One of the key advantages of the proposed system is its simplicity and reliability. The RFID-based identification process is fast and stable, allowing near-instant user recognition. This makes the system suitable for real-time applications such as toll gates, parking systems, and secured entry points [6]. The use of microcontroller-based architecture ensures deterministic behavior and low latency in decision-making processes.

From a performance perspective, the system operates with minimal delay between RFID detection and actuator response. The servo motor provides a clear mechanical representation of

access control, while the LCD display improves user interaction by providing immediate system feedback. This combination of visual and physical response enhances system transparency and usability.

However, the system also has certain limitations. The RFID technology used in this implementation has a limited reading range, typically only a few centimeters, which restricts its use to close-proximity applications. Additionally, basic RFID systems without advanced security mechanisms may be vulnerable to cloning or unauthorized duplication, which represents an important consideration in high-security environments [6].

Another limitation is the absence of a full IoT backend or cloud integration in the implemented prototype. Although the system is conceptually aligned with IoT principles, its current implementation operates locally without remote monitoring or data storage capabilities. This reduces its scalability in large distributed systems.

Despite these limitations, the system provides a strong foundation for future enhancements. Possible improvements include integration with Wi-Fi or cellular communication modules, cloud-based user authentication, and database logging of access events. These upgrades would significantly increase system functionality and enable real-world deployment in smart infrastructure environments [3].

In comparison with traditional manual access control systems, the proposed solution offers improved automation, reduced human involvement, and increased operational efficiency. The use of embedded integrated circuits ensures low-cost implementation while maintaining acceptable levels of performance and reliability.

Overall, the results confirm that RFID-based IoT systems represent a practical and scalable solution for modern access control applications, especially in environments where cost efficiency and simplicity are primary requirements [3], [6].

CONCLUSION

This paper presented the design and implementation of an RFID-based IoT system for wireless identification and automated access control. The proposed system integrates an Arduino Uno R3 microcontroller, an MFRC522 RFID reader module, a servo motor, and an LCD display to achieve a simple and functional model of an automated toll gate system.

The main objective of the work was to demonstrate how integrated communication circuits and embedded systems can be combined to create a low-cost and efficient solution for real-time identification and access control. The implemented system successfully performs user identification through RFID technology, processes authentication data using a microcontroller, and executes physical access control through a servo motor mechanism.

The results obtained from both simulation and physical prototype testing confirm that the system operates reliably under real-time conditions. The system responds quickly to RFID input, provides clear user feedback through the LCD display, and accurately controls the barrier mechanism. This confirms the practicality of using simple embedded IoT architectures for access control applications.

The validation of the proposed system was performed through simulation and physical prototype implementation. During experimental operation, the system successfully detected authorized and unauthorized RFID tags, executed the corresponding access control logic, and provided appropriate feedback through the LCD display. These observations confirm the correct interaction between the RFID communication module, microcontroller-based processing unit, and actuator components, demonstrating the functionality of the proposed embedded IoT solution.

Although the current implementation operates as a standalone system without cloud connectivity, it provides a solid foundation for future improvements. Potential enhancements include integration with wireless communication modules, cloud-based data storage, and real-time monitoring systems. These improvements would enable scalability and deployment in larger smart infrastructure environments.

In conclusion, the developed system demonstrates that RFID-based IoT solutions can provide effective, reliable, and cost-efficient alternatives to traditional access control mechanisms. The

integration of hardware and software components highlights the importance of embedded systems in the development of modern intelligent infrastructure.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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THE APPLICATION OF ARTIFICIAL INTELLIGENCE IN THE NEW PUBLIC MANAGEMENT: STATUS, CHALLENGES AND PERSPECTIVES IN THE REPUBLIC OF NORTH MACEDONIA

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ABSTRACT

This paper analyzes the role of artificial intelligence (AI) in the transformation of the public sector through the concept of new public management (NPM). In the Republic of North Macedonia, NPM has not been implemented as a single, coherent model, but as a set of reforms and instruments that are gradually introduced in various institutions, most often under the influence of European integration processes. In conditions of increased demands for efficiency, transparency and accountability, AI is emerging as a key instrument for the modernization of public administration. The concept of new public management emerges as a response to these challenges, promoting principles such as results orientation, competition and rationalization of resources. In parallel, technological development, especially in the field of artificial intelligence, opens up new opportunities for the transformation of public administration. AI enables automation, analysis of large amounts of data and improvement of processes in the The paper focuses on global trends and their application in the Republic of North Macedonia, identifying the main benefits, limitations and institutional challenges. This paper aims to analyze the institutional application of NPM in the country, as well as the key challenges associated with its implementation. The research methodology is based on a qualitative approach, which includes: analysis of relevant scientific literature, analysis of international reports, comparative approach that allows for a systematic understanding of trends and challenges. The results indicate that AI has significant potential for improving the public sector through: increased efficiency, reduced administrative costs, improved transparency, better decision-making. However, there are also serious risks: algorithmic bias,

privacy threats. dependence on technology In the context of North Macedonia, these risks are further emphasized due to institutional unpreparedness. The research shows that while there is potential for significant progress, the implementation of AI is limited due to insufficient digital maturity, legal framework, and human resources.

Keywords: artificial intelligence, new public management, public administration, digitalization, public policies

INTRODUCTION

New Public Management (NPM) is a paradigm in public administration that developed in the late 20th century, with the aim of improving the efficiency, effectiveness and accountability of the public sector by applying management practices from the private sector. This concept is based on principles such as management by results, decentralization, competition and orientation towards users of public services. The main elements of NPM include: performance management; strengthening competition, decentralization of competencies; introduction of market mechanisms; professionalization of public administration; orientation towards citizens as users. Instead of focusing on procedures and rules, NPM emphasizes the importance of results, efficiency and quality of services [1]. (Hood, C. (1991). In recent decades, the public sector has faced increasing pressure to improve its efficiency and the quality of services. The concept of new public management has emerged as a response to these challenges, promoting principles such as results orientation, competition and rationalization of resources. In parallel, technological developments, especially in the field of artificial intelligence, are opening up new opportunities for the transformation of public administration. AI enables automation, analysis of large amounts of data and improvement of decision-making processes [2]. In the Republic of North Macedonia, NPM has not been implemented as a single, coherent model, but as a set of reforms and instruments that are gradually being introduced in various institutions, most often under the influence of European integration processes. New Public Management is characterized by a transition from traditional Weberian bureaucracy to a management-oriented public sector.

Artificial intelligence (AI) is a field of computer science that focuses on creating machines and systems capable of performing tasks that traditionally require human intelligence. These tasks include learning, reasoning, problem solving, perception, language understanding, and decision-making. Unlike traditional computer programs that follow pre-programmed instructions, AI systems have the ability to adapt, learn from experience, and improve their performance over time. This characteristic makes them particularly powerful and useful for solving complex problems that cannot be easily solved with traditional programming techniques. The term “artificial intelligence” was first used in 1956 at the Dartmouth Conference, where a group of scientists gathered to discuss the possibility of computers “thinking” like humans. Since then, AI has evolved from a theoretical concept to a practical technology that we use every day today, often without realizing it [3]. Modern AI does not attempt to completely copy human intelligence, but rather develops its own unique ways of solving problems that can be even more efficient than human approaches in certain areas. For example, AI systems can process vast amounts of data much faster than humans, but at the same time they can have difficulty with tasks that are intuitive to humans, such as recognizing emotions or understanding context.

RESEARCH METHODOLOGY

New Public Management is a paradigm that integrates management techniques from the private sector into public administration. According to Hood (1991), NPM is characterized by: a focus on results rather than procedures; decentralization of management; introduction of market mechanisms and performance measurement [1]. This approach emphasizes the need for efficiency and accountability, which is directly related to the potential of AI. Artificial intelligence is a set of technologies that enable machines to perform tasks that require human intelligence. Key components include: machine learning; natural language processing; computer vision In the context of the public sector, AI enables a shift from reactive to proactive, data-driven management.

Hence, the subject of the research is focused on analyzing the concept of the new public management that is oriented towards results, competition and rationalization of resources. In parallel, technological development, especially in the field of artificial intelligence, opens up new opportunities for the transformation of public administration. AI enables automation, analysis of large amounts of data and improvement of labor processes.

The subject of the research focuses on global trends and their application in the Republic of North Macedonia, the main benefits, limitations and institutional challenges in the application of artificial intelligence in the new public management. This paper aims to analyze the institutional application of NPM in the country, as well as the key challenges associated with its implementation. Also, the aim of the paper is to understand the application of artificial intelligence in the practice of the new public management in the Republic of North Macedonia.The paper will analyze the legal framework related to the new public management and artificial intelligence in the Republic of North Macedonia. It will also analyze the processes and actions taken to implement the new public management in the state administration bodies in the Republic of North Macedonia. Special emphasis will be placed on the advantages and disadvantages of applying artificial intelligence in the new public management.

The research methodology is based on a qualitative approach, which includes: analysis of relevant scientific literature; analysis of international reports and a comparative approach. This method allows for a systematic understanding of trends and challenges. Special emphasis is placed on the analysis of public documents, legal and by-laws, and previous research relevant to the subject of the research. The state administration and local government bodies will be analyzed in the context of the application of the new public management and artificial intelligence from a structural, organizational, professional and technical perspective.

IMPLEMENTATION OF NEW PUBLIC MANAGEMENT IN THE REPUBLIC OF NORTH MACEDONIA

In the Republic of North Macedonia, NPM has not been implemented as a single, coherent model, but as a set of reforms and instruments that are gradually being introduced in various institutions, most often under the influence of European integration processes. Let us first understand the application of NPM in the Macedonia, by highlighting the main characteristics of NPM. Thus, the main characteristics of NPM are: -performance management; -decentralization of competencies; -introduction of market mechanisms; -professionalization of public administration; -orientation towards citizens as users. Instead of focusing on procedures and rules, NPM emphasizes the importance of results, efficiency and quality of services [4]. The NPM in the RSM has been partially implemented, and this creates difficulties in the application of artificial intelligence. We will highlight the departments where the application of the new public management has begun, divided into departments. In recent years, significant steps have been made in digitalization, such as: electronic services, digital registers and transparency platforms.

Thus, the application of NPM in the fiscal sector will be seen in the Ministry of Finance, which plays a central role in the implementation of NPM and the principles in the field of public finances. Practices such as: - medium-term budgeting; - program budgeting and cost-benefit analysis have been introduced; These mechanisms enable better allocation of resources and increased accountability in the spending of public funds. In addition, the State Audit Office conducts performance audits, which is a significant step from formal to functional control.

The Ministry of Public Administration and the Agency for Administration are the carriers of the reforms in the administrative system. These institutions apply: - human resources management systems; - performance evaluation of civil servants; and a merit-based employment system. These practices aim to increase the professionalism and efficiency of the administration.

The application of NPM can be seen in local self-government. The decentralization process has enabled a significant transfer of competencies to municipalities. They manage: education, urbanism and local services. Municipalities in the RSM apply strategic planning and budgetary It is particularly important to highlight the application of NPM in the public sector, by public service

providers. Progress in the application of NPM has been made in the health and employment sectors, with the application of result-oriented models. The Health Insurance Fund uses services such as: contracts with service providers, cost control and service-based financing.

The Employment Agency applies: active employment policies and measurement of program effects. These practices are an example of results-based management.

In addition, progress in the application of NPM has been made in the Public Procurement and Regulation sector. Thus, the Public Procurement Bureau introduces: electronic tender systems, competition between economic operators and transparency. This represents the application of market mechanisms in the public sector, which is a key feature of NPM. autonomy, which is in accordance with the NPM principles of management closer to the citizens.

The new public management emphasizes digitalization and e-government. The ministry responsible for digital transformation is the ministry of the same name, established in 2024 as the main carrier of digitalization. The ministry is responsible for establishing e-government, providing digital services, and interoperability between institutions. The Central Population Register has established an electronic database for citizens, which enables them to: automate services and improve coordination. In the following text, we will list the state institutions in the Republic of Macedonia that provide electronic services. The Ministry of Internal Affairs provides the following E-services: citizenship certificate, certificates of record, personal documents (applications). The Public Revenue Office as E-services: issues tax certificates, issues certificates of paid taxes and enables electronic declarations. In doing so, the Public Revenue Office, through the introduction of electronic services, has achieved goals such as reducing administrative costs, increasing efficiency and improving services for citizens. Health Insurance Fund as E-services: issues health insurance certificates and certificates of insured status Employment Agency as E-services: issues unemployment certificates and records of work status. Central Registry as E-services: issues company certificates and registration documents.Real Estate Cadastre as E-services: issues property certificates and real estate data. Ministry of Education and Science as E-services: electronic certificates of education and student documents (in some systems). Local self-government units as E-services: issuing urban permits, property tax certificates and utility service certificates. The NPM approach is also used by the Secretariat for European Affairs through a project approach, such as: management of EU funds, monitoring and evaluation, and use of indicators.

Digitalization is an important tool for the modernization of public administration. The digitalization of the administration in the Republic of Macedonia has not yet been fully implemented. Citizens are still waiting in line at counters, paper is wasted, and institutions are not yet digitally connected in a single system and offer a small number of electronic services. For a birth or marriage certificate, a marriage certificate or a newborn baby certificate, you can apply online, but one option is to pick up the document at a counter or have it delivered to you in a few days by mail. For passports and ID cards, you can only schedule an appointment for a photo, and everything else is done on paper and with a physical presence in the institutions. The main problems surrounding the digitalization of North Macedonia are that the institutions are not interconnected electronically, dozens of laws have not yet been adopted to accelerate digitalization, but also the digital literacy of the population, which is at a low level, and the state needs to raise it. North Macedonia has adopted a Public Administration Reform Strategy 2023-2030, which provides guidelines for digitalization according to European practices and regulations, but despite this, the NGO Metamorphosis says that the system of digital solutions in the public sector at the national and local levels is fragmented and does not ensure efficient communication between state institutions [5].

In 2019, a package of laws on digitalization was adopted: the Law on the Central Population Registry;2 the Law on Electronic Documents, Electronic Identification and Trust Services3 as well as the Law on Electronic Governance and Electronic Services.4 They represent general laws according to which all current laws should be adjusted and are related to the digitalization of processes and procedures in authorities as well as the digitalization of the provision of services to

citizens. There are over 100 laws that need to be amended and supplemented.2 The Law on the Central Population Registry is one of the laws in the package of laws on digitalization. It unifies the population data available to the Ministry of Interior (data from citizens' personal documents) and the Ministry of Justice, i.e. the Civil Registry Administration (data on citizens from the civil registry books of births, marriages and deaths). These two ministries are the "sources" of this data, that is, they are obliged to integrate all the data they have into the Central Population Registry [5].

LEGAL FRAMEWORK FOR ARTIFICIAL INTELLIGENCE IN EUROPE AND THE EU

The Artificial Intelligence Act is the first proposal for a legal framework in the world to regulate specific uses of AI, while the AI Coordination Plan offers strategic alignment, policy action and acceleration of investment. Together, they outline a European approach to AI that puts people first. The new rules will ensure that advances in AI promote trust, security and fundamental rights, while fostering excellence in innovation. The European Council in October 2020, following a debate on artificial intelligence, where EU leaders discussed the digital transition, in its conclusions asked the European Commission to:

- propose ways to increase European and national public and private investment in research, innovation and the use of AI;
- ensure better coordination and more networks and synergies between European research centres based on excellence;
- provide a clear, objective definition of high-risk AI systems.

The development and application of artificial intelligence (AI) in the public sector are closely linked to the establishment of an appropriate legal framework that ensures a balance between innovation, the protection of human rights and the public interest. In this regard, AI regulation is developing at multiple levels: international, European and national.

European regulation on artificial intelligence

The European Union is a global leader in regulating AI, with the adoption of the AI Act. This act, adopted on 13 June 2024 and published in the Official Journal of the EU on 12 July 2024, is the first comprehensive legal instrument to regulate AI at a global level. The AI Act establishes a risk-based approach, according to which AI systems are classified into four categories: systems with unacceptable risk (which are prohibited), high-risk systems (subject to strict regulation), systems with limited risk and systems with minimal risk. This approach aims to ensure proportionate regulation, with greater attention paid to systems that may have a significant impact on human rights and security.

In addition to the AI Act, the General Data Protection Regulation, adopted on 27 April 2016, also plays a significant role. This regulation does not apply exclusively to AI, but is essential for its implementation, especially in the area of personal data protection and automated decision-making.

In addition, the European Commission has adopted ethical guidelines such as the Ethics Guidelines for Trustworthy AI (8 April 2019), which emphasize the need for legality, transparency and accountability in the use of AI. Although these guidelines are not legally binding, they have a significant impact on policymaking.

International regulation

At the global level, a significant document is the OECD AI Principles, adopted on 22 May 2019 [6]. These principles represent the first international standard for AI and focus on transparency, accountability and inclusive development.

The Council of Europe is also working on establishing a legally binding framework through the Framework Convention on Artificial Intelligence, adopted in May 2024. This document aims to ensure the protection of human rights, democracy and the rule of law in the context of AI.

Legal Framework in the Republic of North Macedonia

In the Republic of North Macedonia, there is still no specific law that directly regulates artificial intelligence. However, there are several laws and strategies that indirectly cover this area.

A key act is the Law on Personal Data Protection, adopted on 16 February 2020, which is GDPR compliant and constitutes the basis for regulating data processing in AI systems.

In addition, the Law on Electronic Governance and Electronic Services (adopted on 21 May 2019) provides a legal framework for the digitalization of public services, which is a prerequisite for the application of AI in public administration.

In a strategic context, documents such as the Public Administration Reform Strategy and the National ICT Strategy are also important, which emphasize digital transformation as a priority, although they do not contain specific measures for AI.

THE APPLICATION OF ARTIFICIAL INTELLIGENCE IN EUROPEAN COUNTRIES AND THE REPUBLIC OF NORTH MACEDONIA

Generative Artificial Intelligence (AI) has quickly transformed from a new technology into an everyday tool. From personal use to work and education, millions of people across Europe now rely on tools like ChatGPT, Gemini and Grok, but adoption rates of the technology vary dramatically between countries, Euronews Next reports [7].

Generative AI tools allow users to create new content such as text, images, code or video based on simple requests. According to Eurostat data for 2025, about a third of the European Union population aged 16 to 74 had used one of these tools at least once. Over 1/3 of the population in OECD countries uses generative AI (2025), About 20.2% of companies globally use AI (2025), Usage doubled from 8.7% (2023) → 20% (2025).

However, data for 33 European countries reveals a huge gap in the use of AI – from just 17 percent in Turkey to 56 percent in Norway. Within the European Union itself, the range ranges from 18 percent in Romania to 48 percent in Denmark. In 13 European countries, more than 40 percent of the population has used generative AI tools. This group, along with Norway and Denmark, includes Switzerland (47 percent), Estonia (47 percent), Malta (46 percent), Finland (46 percent), Ireland (45 percent), the Netherlands (45 percent), Cyprus (44 percent), Greece (44 percent), Luxembourg (43 percent), Belgium (42 percent) and Sweden (42 percent).

On the other hand, in eight countries, less than a quarter of the population uses these tools. Along with Turkey and Romania, these are Serbia (19 percent), Italy (20 percent), Bosnia and Herzegovina (20 percent), Macedonia (22 percent), Bulgaria (23 percent) and Poland (23 percent). Among the EU's largest economies, Italy (20 percent) and Germany (32 percent) are below the EU average, while Spain (38 percent) and France (37 percent) are slightly above it, showing a clear divide between the digitally more advanced north and west and the lagging south and east of Europe.

Experts explain that these differences are not accidental. "First, AI adoption rates tend to follow the overall digital base of the country. Countries that show the highest adoption, such as Denmark and Switzerland, are already very advanced in digitalization," Colin van Nordt, a researcher at KU Leuven University in Belgium, told Euronews Next.

He points out that people in these countries already have digital skills, use the internet more often and are generally more technologically savvy. "This is reflected in the data: in countries with lower adoption, people are not using it because they did not know that generative AI exists or do not know how to use it," he added.

Van Nordt emphasizes that it is one thing to have access to the technology, but quite another to understand how to use it. "Many people across Europe say they are not using generative AI simply because they don't know what to use it for. This shows that 'AI literacy' is a huge factor," he said.

In developed countries, the application of AI is already integrated into the public sector. Thus, Estonia is a leader in digital governance, the United Kingdom is using AI for public policy analysis, and Singapore is developing smart cities.

These examples show that successful implementation depends on: strategic planning, institutional coordination, and investment in technology.

POSITIVE SIDES AND POSSIBLE RISKS IN THE APPLICATION OF ARTIFICIAL INTELLIGENCE

Artificial intelligence when used in the new public management has positive and negative sides. As we have previously stated, the application of artificial intelligence should have a legal basis. Thus, legal and by-laws should precisely state the benefits and risks that may arise in the application of artificial intelligence. The application of AI raises important issues, such as preserving privacy and data protection, as well as ensuring the security of personal data. Decisions made by AI must be understandable and verifiable. It is especially important in by-laws to clearly define responsibility for decisions made with AI.

First, we will look at the benefits of AI in the new public management. AI in the new public management is used for: automatic document processing, predictive analysis for policies, budget optimization, improving services for citizens, potentially reducing bureaucracy, increasing productivity in public services and enabling the transition to data-driven management. Other benefits of AI in the domain of management: automated decision-making, big data processing, predictive analysis, intelligent automation.

With these capabilities, AI is becoming a key instrument in modern management. In addition, the role of AI in the transformation of the public sector in improving administrative processes is significant. In addition, AI enables the automation of routine tasks, which results in: reducing human errors, faster processing of requests and better organization of data. In addition, AI in the public sector is data analysis for public policies, digital assistants for citizens and resource management (health, transport, security). Another important role that AI has is helping in fast and efficient data-based decision-making. Thus, AI, through the analysis of extensive data and information, enables institutions to: predict trends, identify risks and create more effective policies. AI is particularly important in increasing the efficiency of administration, reducing administrative costs, better transparency and faster decision-making [3]. In the domain of public service delivery, AI helps improve public services. In doing so, AI enables personalized services, such as: digital assistants, automated support systems and 24/7 availability of services.

The application of artificial intelligence in public management brings significant benefits, but at the same time creates complex risks. The biggest challenges are related to ethics, transparency, security, privacy and institutional readiness. The regulatory framework defines four levels of risk in AI. 1. Unacceptable risk 2. High risk 3. Limited risk 4. Minimal risk.

The application of artificial intelligence (AI) in the public sector and new public management, although it brings significant benefits in terms of efficiency, transparency and digitalization of services, at the same time opens up serious risks and challenges that must be systematically analyzed and managed. These risks are of a technological, organizational, legal and ethical nature.

Ethical risks and algorithmic bias

One of the most significant challenges is the emergence of algorithmic bias. AI systems learn from historical data, which often contain existing social, economic or institutional inequalities. As a result, the systems can produce discriminatory results in decision-making in areas such as social assistance, employment or public services. This problem calls into question the principle of equal treatment of citizens and can reduce trust in public institutions.

Lack of transparency and explainability

Modern AI systems, especially those based on deep learning, often operate as “black box” systems, where the decision-making process is not clearly explained. This is a serious problem in public administration, where every decision must be justified and legally explained. The lack of

transparency makes oversight difficult, reduces accountability and creates the risk of improperly made decisions without the possibility of effective appeal.

Privacy and data protection

The application of AI in the public sector requires the processing of large amounts of personal data. This creates risks related to privacy violations, unauthorized access and potential data misuse. In addition, there is a risk of mass surveillance and profiling of citizens, which can lead to violations of fundamental human rights if strict regulatory mechanisms are not in place.

Cybersecurity risks

AI systems are exposed to various types of cyberattacks, including data poisoning, hacker intrusions and abuse of automated systems.

With the increasing digitalization of public services, the risk of attacks on critical infrastructure increases, which can have serious consequences for the functioning of state institutions.

Organizational and institutional challenges

The effective application of AI requires significant organizational changes in public administration. Among the most common challenges are: lack of qualified personnel and digital skills, resistance to technological changes in institutions, insufficient coordination between different authorities, limited financial and technical resources. These factors significantly slow down the process of digital transformation.

Reliability and system errors issues

While AI systems are highly accurate in certain tasks, they are not without errors. There are cases of inaccurate results, known as “AI errors” or hallucinations, which can lead to wrong decisions.

In addition, there is a risk of over-reliance on automated systems, which can reduce the role of the human factor in critical decisions.

Legal and regulatory challenges

One of the key challenges is the insufficient or fragmented legal framework for regulating AI. In many countries, including developing countries, there are still no clear rules on liability for errors in AI systems.

In addition, the question of legal liability arises: is the developer, the institution or the system responsible?

Social and economic implications

The application of AI can lead to the transformation of jobs in the public sector, with certain administrative functions being automated. This creates the risk of reducing the need for certain worker profiles, but at the same time requires the creation of new digital skills. Additionally, there is a risk of digital inequality among different groups of citizens who do not have equal access to technology.

ANALYSIS OF RESEARCH RESULTS

The analysis shows that the legal framework for AI in North Macedonia is fragmented and underdeveloped. Unlike the European Union, where there is a systematic approach through the AI Act, the national regulation is based on indirect norms. The results indicate that AI has significant potential to improve the public sector through: increased efficiency, reduced administrative costs, improved transparency and better decision-making. However, there are also serious risks: algorithmic bias, privacy threats and technology dependence. In the context of North Macedonia, these risks are further highlighted due to institutional unpreparedness.

AI has a wide potential for application in: public finance, health, education and urban planning. There are numerous limitations to the implementation of AI in the Republic of North Macedonia, such as: lack of staff, poor coordination, limited resources and insufficient legal regulation. In addition, we can specify that in the Republic of North Macedonia there is no specific regulation, exclusively for the application of AI, which needs to be harmonized with European regulations, there is insufficient institutional readiness, and capacities for implementation and supervision are limited. In this regard, the future development of the legal framework should be directed towards the adoption of a national strategy and law on AI, in accordance with European standards.

Although AI offers significant benefits, its implementation is not a simple process. It requires: institutional transformation, change in organizational culture and long-term investments. In North Macedonia, these factors are still under development, which slows down the process of digital transformation. In addition, as other challenges and limitations in the implementation of AI in the Republic of Macedonia is the management process in public administration. The Macedonian administration has established a hybrid management system that combines traditional bureaucratic elements with modern management practices. Attempts at reform so far indicate a slow and formal implementation without substantial changes in operations. Political influence limits the functioning of the merit system and ultimately, although measurement mechanisms exist, they are not always used in decision-making.

CONCLUSION AND RECOMMENDATIONS

From the above, we can conclude that AI is already a structural part of the new public management. The risks and challenges associated with the application of artificial intelligence in public management are complex and interconnected. They arise not only from the technology, but also from the manner of its implementation, management and regulation. Therefore, the successful application of AI requires an integrated approach that includes technical, legal, ethical and organizational measures, in order to minimize risks and maximize benefits for the public interest.

Europe has high institutional integration (up to 87% in public projects), globally, adoption is fast (20% companies, >1/3 users,) however there is a large digital divide between countries and regions. The main trend of AI is the transition from traditional administration to data-driven and AI-supported governance.

The application of AI in the Republic of North Macedonia has the potential to improve the efficiency, transparency and quality of public services. However, to realize this potential, a systemic and strategic approach to the implementation of AI is needed, with a focus on institutional readiness and ethical responsibility. In the Republic of North Macedonia, although there are initiatives for digitalization, the application of AI is still limited. North Macedonia is in the phase of harmonization with EU regulations, missing: a separate law on AI and a national strategy for AI. The main challenges faced by the RSM in the application of AI include: lack of specialized regulation on AI, insufficient institutional readiness, need for harmonisation with European legislation, limited capacities for implementation and supervision. In this regard, the future development of the legal framework should be directed towards the adoption of a national strategy and law on AI, in accordance with European standards.

To promote the application of AI, the RSM recommends: Adoption of a national strategy for AI, Development of digital skills, Strengthening of the legal framework, Strengthening of institutional capacity, Investments in infrastructure in education and digital skills, investments, Development of public-private partnerships and enhanced international cooperation related to the application of AI

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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DEEP NEURAL NETWORKS FOR SCOLIOSIS DETECTION AND ANALYSIS: A LITERATURE REVIEW

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ABSTRACT

Scoliosis affects 2–3% of the population, and manual measurement using the Cobb angle — the gold standard since 1948 — is subject to inter-observer variability and too slow for use in mass screening programs.

This paper presents a systematic review of the application of deep neural networks (DNNs) in the detection and analysis of scoliosis through an analysis of the relevant literature published between 2015 and 2024, using the PubMed, IEEE Xplore, Scopus, and Web of Science databases. A range of architectures is considered — from classical convolutional neural networks and encoder–decoder models to Transformer and hybrid CNN–Transformer approaches — together with the key datasets, evaluation metrics, and open problems in the field.

Technical progress is clearly visible and measurable: recent literature shows that hybrid CNN–Transformer models achieve a Cobb angle estimation error that approaches the level of disagreement between two experienced radiologists. Nevertheless, most published models have been tested exclusively on data from the institution in which they originated, which raises serious concerns regarding external validity — it remains unclear whether these models would achieve the same performance in other hospitals, with different imaging equipment and different patient populations. This is one of the key open questions in the field and an important direction for future research.

Keywords: deep learning, convolutional neural networks, scoliosis, Cobb angle, medical image analysis, literature review

INTRODUCTION

Scoliosis is a three-dimensional deformity of the spinal column in which the spine bends laterally by more than 10 degrees, as measured by the Cobb angle on a radiograph. In addition to the curvature itself, vertebral rotation is present, as well as changes in the natural curves of the

spine when viewed from the side. This condition occurs in approximately 2–3% of the population, and its most common form is adolescent idiopathic scoliosis (AIS), which accounts for about 80% of all scoliosis cases [1]. If not recognized and treated in time, progressive scoliosis can lead to functional and health complications, including chronic pain, reduced respiratory function, and a significant deterioration in quality of life.

The gold standard in scoliosis diagnosis, manual measurement of the Cobb angle, has been used since 1948. Although widely accepted in clinical practice, this method has certain limitations: inter-observer variability can reach up to 7 degrees [2], and the procedure itself is time-consuming and impractical for use in mass screening programs. For this reason, automating Cobb angle measurement is a clinically and methodologically justified goal.

Over the past decade, deep learning methods have undergone significant development and found wide application in medical image analysis [3]. In certain well-defined tasks and under controlled research conditions, studies have shown that deep learning–based systems can achieve performance comparable to clinicians, including the diagnosis of diabetic retinopathy [4], the classification of skin cancer [5], and the detection of pulmonary nodules on CT scans [6]. The application of DNNs in spinal analysis has grown significantly since 2017. The aim of this paper is to review, classify, and critically analyze the key approaches and results published in this area, to identify existing gaps in the literature, and to propose directions for future research. The review is based on an analysis of relevant papers published between 2015 and 2024, retrieved from the PubMed, IEEE Xplore, Scopus, and Web of Science databases.

LITERATURE REVIEW METHODOLOGY

The review was conducted by searching the PubMed, IEEE Xplore, Scopus, and Web of Science databases for papers published between 2015 and 2024. Combinations of keywords were used that cover scoliosis-related terms (scoliosis, Cobb angle, adolescent idiopathic scoliosis, spinal deformity) and deep learning methods (deep learning, convolutional neural network, transformer, segmentation, landmark detection). The review included peer-reviewed papers in English that apply deep neural networks to the tasks of detection, segmentation, classification, or Cobb angle estimation in scoliosis. Papers that do not use deep learning methods, that do not concern the spinal column, and short conference abstracts without sufficient methodological detail were excluded. After removing duplicates and checking eligibility based on title, abstract, and full text, 15 papers were included in the qualitative synthesis. Given the pronounced heterogeneity of datasets, evaluation metrics, and annotation protocols, a narrative (qualitative) synthesis was applied instead of a formal meta-analysis.

CLINICAL CONTEXT

To understand the role and potential of deep neural networks in scoliosis analysis, it is first necessary to consider the clinical context of the diagnosis itself — which decisions the physician makes, on the basis of which data, and at which stages of the process errors arise that automated analysis can help mitigate.

Classification and diagnosis of scoliosis

Scoliosis is classified according to etiology, anatomical region, and degree of curvature. The Cobb angle remains the universally accepted measure for assessing deformity severity and making treatment decisions. Conservative treatment, including the use of an orthopedic brace, is most commonly used for mild and moderate deformities, while surgical correction is considered for more severe and progressive cases [7].

Early detection of scoliosis is considered important for the timely initiation of conservative treatment and the prevention of deformity progression. The effectiveness of orthopedic brace treatment was confirmed by the randomized controlled BRAIST study, which showed that 72% of adolescents treated with a brace reached skeletal maturity without curve progression to the surgical threshold (≥50°), compared with 48% in the control group [8]. These results highlight the

importance of early diagnosis and regular monitoring, which is an important motivation for developing automated systems that enable more precise and more frequent monitoring with a reduced need for radiographic examinations and therefore lower exposure to ionizing radiation.

In clinical practice, the initial assessment of scoliosis is based on physical examination and clinical evaluation, after which, in suspected or confirmed cases, radiographic analysis is used to precisely determine the degree of deformity. The cumulative radiation exposure from repeated radiographic examinations in children and adolescents is an important clinical aspect that is taken into account during monitoring and treatment decision-making. Epidemiological data show that AIS is significantly more frequent and more severe in girls than in boys — the female-to-male ratio ranges from 1.5:1 to 3:1 and increases with age [9]. The curve magnitude at the time of diagnosis and the degree of skeletal maturity are the most significant predictors of progression, with younger patients who have larger initial curves at a considerably higher risk of deformity progression if left untreated [10].

Limitations of manual diagnosis

Inter-observer variability in Cobb angle measurement is particularly pronounced in borderline cases. A difference of only a few degrees can be clinically significant and influence the treatment decision — for example, crossing the 25-degree threshold, which is often used as an indication for bracing, or the 45–50-degree threshold, which is considered an indication for surgical treatment. Automated systems that enable consistent and rapid angle measurement, free from the influence of observer fatigue and with reduced inter-observer variability, represent a clinically justified approach, provided that they are validated on representative populations and reliably identify borderline cases.

Beyond manual measurements, increasing attention is being paid to the development of AI applications that automate Cobb angle measurement directly from radiographic images. Li et al. [11] developed a deep learning–based mobile application (CobbAngle Pro) and evaluated it on 802 radiographs from 601 patients. The mean absolute error was 2.00° when analyzing photographed images and 2.08° when analyzing uploaded images, with both methods remaining within the clinically acceptable threshold of 5°. Similarly, Russo et al. [12] analyzed 197 radiographic images and compared manual and automated Cobb angle measurements, indicating that the use of image processing techniques, such as contrast correction, can significantly reduce the discrepancy between automated and manual estimates.

OVERVIEW OF DEEP NEURAL NETWORK ARCHITECTURES

The application of deep learning in medical image analysis has grown rapidly over the past decade, and an overview of the methods is given in Litjens et al. [3]. Spinal analysis follows this trend — the number of papers applying deep neural networks to the detection and analysis of scoliosis has grown significantly since 2017, when CNN approaches first achieved performance comparable to manual methods.

Based on the reviewed literature, we identify eight classes of architectures applied in scoliosis analysis. The classification is based on the dominant architectural principle, since the same architectures are used across different tasks — e.g., encoder–decoder models for segmentation and detection, and CNN classifiers for severity assessment and screening.

The boundaries between classes are not strict, particularly in more recent work where hybrid CNN–Transformer approaches blur the clear distinctions between architectures. Models such as ConvNeXt and CvT combine CNN and Transformer principles, while some Transformer models integrate convolutional layers for better local representation, which makes the classification partly arbitrary.

Each class is presented through typical representatives, primary tasks, and indicative performance, with the caveat that direct comparisons should be interpreted with caution due to differences in datasets and evaluation protocols. The reviewed studies suggest a general trend of decreasing Cobb angle estimation error from classical CNN models toward Transformer and

hybrid CNN–Transformer approaches [20], [21], reflecting the general evolution of the field. The values given in Table 1 are approximate, rounded values summarizing the results reported in the reviewed studies; they are not the outcome of a pooled statistical analysis, and the way they were compiled is explained in the section on evaluation metrics (Table 1).

Table 1 presents a classification of the deep learning architectures most commonly used in scoliosis analysis, together with representative models, primary application areas, and typical results reported in the literature, thereby illustrating the dominant development directions and the performance levels achieved in this field.

Table 1. Architecture classes and typical results in scoliosis analysis

Architecture class	Typical examples	Primary task	Typical results
CNN (classical)	ResNet, DenseNet, EfficientNet	Classification, regression	MAE ~3–4° / AUC ~0.92–0.97
Encoder–decoder	U-Net, SegNet, Attention U-Net	Segmentation	Dice 0.88–0.93
Recurrent models	CNN–LSTM hybrid	Sequential vertebra analysis	Limited data availability
Generative models (GAN)	GAN, DCGAN, GAN inversion	Augmentation, data representation	Improved generalization (indirect effect)
Transformer models	ViT-B, Swin, DeiT	Modeling global dependencies	MAE ~2.5–3.5° / AUC ~0.95–0.98
Hybrid CNN–Transformer	ConvNeXt, CvT, ViT–ResNet	Classification, regression	MAE ~2–3° / AUC ~0.96–0.99
3D convolutional models	3D U-Net, nnU-Net, VerSe	CT/MRI segmentation	Dice 0.91–0.94
Graph networks (GNN)	SpineGCN	Inter-vertebral relations	Research stage

Classical CNN architectures

Classical CNN architectures (ResNet, DenseNet, EfficientNet) dominated the literature until 2021 and are still frequently used as backbone or hybrid components in many studies. ResNet-50 and ResNet-101 are the most common choices due to their good balance between accuracy and computational efficiency. The use of transfer learning has significantly improved performance in scoliosis analysis, particularly in automated Cobb angle measurement, where some studies report errors below 2° and a high ICC relative to clinical measurements [13], although the results were mostly obtained on smaller, single-institution datasets. DenseNet [14] has proven particularly useful in tasks where fine vertebral features are key for discrimination, thanks to its dense connections that enable the preservation and reuse of low-level features across all network layers.

Beyond diagnostic tasks, CNN architectures are also applied in specific clinical applications. Vergari et al. [15] proposed a CNN model combined with discriminant analysis for the automatic identification of the type of scoliosis treatment (brace, spinal implant, or no treatment) on posteroanterior radiographs, achieving an accuracy of 98.3% and high brace detection (99.7%). Wang et al. [16] developed a cascaded CNN architecture with a PCA shape constraint for vertebral landmark localization, decomposing the task into a two-stage process (localization of centers and vertebral angles) and achieving a significant reduction in error on the AASCE dataset. Zhang et al. [17] developed ScolioNets, which uses smartphone back photographs to assess AIS without exposure to ionizing radiation, achieving an AUC of 0.902 for surgical treatment recommendation and a sensitivity comparable to that of specialists.

Encoder–decoder architectures

U-Net and its variants dominate vertebra segmentation tasks. Skip connections between the encoder and decoder preserve the key spatial information needed for accurate reconstruction of vertebral anatomy. The most common variants include Attention U-Net, U-Net++, and 3D U-Net for volumetric segmentation of CT scans. VerSeNet [18], a specialized 3D variant, enables simultaneous vertebra localization and labeling and serves as a reference model for 3D spinal segmentation, with a Dice coefficient of 0.932 on an international benchmark. These architectures are also applied in non-invasive approaches. Duan et al. [19] developed a Dual Attention U-Net that segments back photographs instead of radiographs, for scoliosis detection in 350 patients and 108 controls. Channel and spatial attention mechanisms improved segmentation accuracy, indicating the potential of AI screening without ionizing radiation.

Transformer architectures

Transformer architectures, including the Vision Transformer (ViT) and Swin Transformer models, began to be applied in scoliosis analysis around 2021–2022 and represent one of the most significant development directions of modern medical image analysis methods. Unlike classical CNN architectures, Transformer models enable more efficient modeling of long-range spatial dependencies between anatomically distant vertebrae through attention mechanisms, which can be significant in spinal deformity assessment tasks. A review of the current literature indicates that hybrid CNN–Transformer approaches achieve competitive or improved performance compared with classical CNN models, particularly in AIS classification and automated Cobb angle measurement tasks [20], [21].

Zhao et al. [20] developed SpineHRformer, an architecture that combines HRNet for multi-scale feature extraction with a Transformer encoder for modeling global dependencies between vertebrae. The model was evaluated on 1,934 radiographs with prospective validation and achieved a localization error of 2.47 pixels and a correlation with manual measurements of $r = 0.86$. In addition, recent review papers on automated Cobb angle measurement point to the growing use of Transformer and attention-based architectures in spinal analysis, particularly because of their ability to integrate local and global anatomical information [21].

Hybrid CNN–Transformer approaches

Hybrid CNN–Transformer approaches are among the most active research directions in medical image analysis. These models combine local CNN features and global Transformer representations, enabling more efficient modeling of anatomical relationships between vertebrae. Architectures such as the Convolutional Vision Transformer (CvT) integrate convolutional layers into Transformer models for better local representation and more stable learning on smaller datasets [22]. Such approaches show significant potential for improving automated AIS classification and Cobb angle estimation. In addition, the ability to simultaneously model local and global features allows these architectures to generalize better across different datasets and more complex spinal deformities.

Generative networks and augmentation

Generative adversarial networks (GANs) are applied in scoliosis analysis primarily for data augmentation and learning representations in latent space. Lee et al. [23] proposed a GAN inversion that maps radiographs into latent space and enables their reconstruction, thereby yielding a compact representation of the features relevant for scoliosis detection. This approach shows good performance in AIS screening tasks and stability even on external datasets. Nevertheless, the use of GANs in direct augmentation remains limited, although they have the potential to improve model generalization. Their importance is particularly pronounced in medical domains with a limited number of annotated images, where synthetically generated data can help reduce the problems of class imbalance and insufficient training samples.

Three-dimensional and graph-based approaches

3D convolutional models, particularly nnU-Net [24], as well as methods based on the VerSe benchmark [18], are used for volumetric segmentation of CT scans and achieve Dice coefficients in the range of 0.91–0.94.

Graph neural networks (GNNs) model the spinal column as a graph structure, where the vertebrae are nodes and the spatial relationships are edges. This approach is intuitive from an anatomical standpoint, but it is still in an early research stage compared with CNN and Transformer methods.

DATASETS

One of the key findings of the available literature review is the pronounced fragmentation of available datasets. The dominant problem is the fact that most published studies use private datasets that are not available to the wider research community, which in practice makes direct comparison of methods and reproduction of results difficult. As a consequence, research groups often develop their own databases and evaluation protocols, which further contributes to the heterogeneity of results and complicates the verification of the progress achieved.

Table 2 provides an overview of the most significant datasets identified in the reviewed literature, with notes on availability, modality, and annotation type.

Table 2. Overview of key datasets for scoliosis analysis using DNNs

Dataset	N (approx.)	Modality	Availability	Annotations	Origin	Note
AASCE 2019 (MICCAI Challenge)	481	PA X-ray	Public	Vertebral landmarks, Cobb angles	International	Frequently used benchmark for Cobb regression [25]
VerSe Challenge	~374	CT (3D)	Public	Vertebral labels and segmentation	International	Standard benchmark for 3D vertebral analysis [18]
UK Biobank	22,000+	PA X-ray	Restricted	General musculoskeletal and clinical data	UK	Large population-based biomedical dataset
NHANES (X-ray subset)	~7,000+	PA X-ray	Public	Epidemiological and clinical variables	USA	Diverse demographics; epidemiological context
Private clinical datasets	Variable	PA X-ray/CT	Not available	Various (Cobb, segmentation, classification)	Multiple centers	Dominant in the existing literature; limited reproducibility

The AASCE 2019 Challenge dataset, with 481 annotated radiographs from the MICCAI competition — used, among others, by Wu et al. [25] — is one of the few widely used benchmark datasets for Cobb angle regression on posteroanterior radiographs. Although it is often used as a reference dataset for evaluating algorithms, its size is limited for training modern deep models without the use of transfer learning. A similar role in the area of 3D vertebra segmentation and labeling on CT scans is played by the VerSe Challenge dataset [18], which has become one of the standard reference frameworks for evaluating spinal segmentation methods.

Despite the importance of these datasets, the field of spinal analysis still lags behind other domains of medical image analysis in the availability of large public datasets. Unlike the analysis of fundus photographs or mammography, where publicly available datasets with tens of thousands of annotated samples exist, spinal analysis still lacks an equivalent large, multicenter public

resource. The limited availability of standardized datasets represents one of the key obstacles to the development of robust and generalizable deep learning models in this field.

An additional problem is the insufficient standardization of evaluation protocols and annotation procedures across different studies. Annotation protocols are documented in detail in a relatively small number of the reviewed papers, while the inter-observer reliability of annotations is quantified even more rarely. This is particularly significant given that the Cobb angle inherently exhibits inter-observer variability of approximately 3–7 degrees [2]. This variability represents a realistic limit on the expected accuracy of automated systems compared with manual measurements, while the insufficient documentation of annotation procedures further complicates a reliable comparison of performance between different methods and studies.

Key studies by category

Table 3 presents representative studies covering the main classes of deep neural networks and the most common tasks in scoliosis analysis. The selected papers illustrate different approaches based on CNN and hybrid CNN–Transformer architectures, with differences in imaging modalities, dataset sizes, and evaluation metrics.

The studies presented cover typical clinical tasks such as anatomical landmark localization, screening, deformity classification, and automated Cobb angle estimation. The aim of the presentation is not an exhaustive review of the literature, but rather an illustration of representative approaches and typical model performance under different experimental conditions.

Particular emphasis is placed on studies with clearly defined evaluation protocols and quantitative metrics, so that the results are more transparent and more suitable for mutual comparison. Due to differences in datasets, annotation protocols, and clinical criteria, the reported performance should be interpreted as indicative rather than directly comparable across all studies.

Table 3. Overview of key studies on the application of DNNs in scoliosis analysis (2017–2024)

Authors (ref.)	Year	Architecture	Task	Modality	N	Metric	Key result
Wu et al. [25]	2017	BoostNet	Anatomical landmark localization	PA X-ray	481	MSE	0.0046 (test)
Yang et al. [26]	2019	DenseNet-121	AIS screening	Back photographs	1,780	Sensitivity	89.5%
Zhao et al. [20]	2023	SpineHRformer (HRNet + Transformer)	Landmark localization + Cobb regression	PA X-ray	1,934	MED / Pearson	2.47 px / 0.86
Vergari et al. [15]	2020	CNN	Scoliosis treatment detection	X-ray	1,013	Accuracy	98.3%
Wang et al. [16]	2024	Multi-stage cascaded CNN	Vertebral landmark localization	X-ray	—	Localization error	High precision
Zhang et al. [17]	2023	Deep CNN	AIS classification and monitoring	Smartphone photographs	1,726	AUC	0.902
Tao et al.[27]	2021	Spine-Transformers (3D Transformer)	Vertebra segmentation and labeling	CT (3D)	1005 CT volumes	Dice	High segmentation precision

EVALUATION METRICS AND QUANTITATIVE ANALYSIS

The heterogeneity of evaluation metrics in the reviewed literature is a significant obstacle to the direct comparison of studies. Differences in datasets, validation protocols, and annotation criteria make it difficult to draw fully comparable conclusions across different models and architectures.

For Cobb angle regression, most recent studies achieve an error within the clinically acceptable threshold of approximately 5° [2]. Modern hybrid CNN–Transformer approaches report lower MAE values compared with earlier CNN models, while classification tasks often record high AUC-ROC values. For segmentation tasks, Dice coefficients in most papers range approximately between 0.90 and 0.94. Examples of individual values reported in the reviewed studies include a mean absolute error of 2.00–2.08° for a deep learning–based mobile application [11], Cobb angle errors below 2° for a CNN-based measurement algorithm evaluated on a single-institution dataset [13], a Dice coefficient of 0.932 for 3D vertebra segmentation on the VerSe benchmark [18], and an AUC of 0.902 for smartphone-based AIS assessment [17].

Table 4 presents the typical performance ranges by architecture class in the analyzed studies.

Table 4. Typical performance ranges by architecture class in the analyzed studies

Architecture class	Cobb angle MAE	AUC-ROC (classification)	Dice (segmentation)
CNN classical	~3–4°	~0.92–0.97	~0.89
Encoder–decoder	~3–5°	~0.90–0.96	~0.91
Transformer	~2.5–3.5°	~0.95–0.98	~0.92
Hybrid CNN–Transformer	~2–3°	~0.96–0.99	~0.93
3D CNN / volumetric models	N/A	N/A	~0.92–0.94
Recurrent models	~2.7–4°	~0.93–0.97	N/A

It is important to emphasize that the values presented represent indicative performance ranges and cannot be directly compared across all studies. Differences in deformity complexity, radiograph quality, dataset size and heterogeneity, as well as in evaluation protocols, significantly affect the reported results. The ranges in Table 4 were compiled by grouping the reviewed studies according to their dominant architecture class and taking the approximate (rounded) interval of the values reported for each metric; N/A indicates that the metric is not typically reported for that class. Since the number of studies per class is small and the studies differ in datasets, annotation protocols, and validation schemes, no pooled mean or meta-analytic estimate was computed. Individual studies on smaller, single-institution datasets may report values outside these ranges (e.g., errors below 2° in [13]), which further illustrates the limited comparability of the reported results.

Studies on automated Cobb angle measurement, such as the work of Russo et al. [12], have shown that the quality of the input radiographs can significantly affect model accuracy. The authors demonstrated that simple contrast-enhancement techniques can reduce deviations relative to manual measurements, indicating the importance of standardizing input data in the evaluation of automated systems.

For segmentation tasks, specialized architectures such as nnU-Net consistently achieve better results than generic U-Net variants, particularly with 3D volumetric data. Nevertheless, most studies remain limited to relatively small, single-center datasets, often collected under controlled research conditions. The lack of external validation and heterogeneous clinical datasets remains one of the main obstacles to the wider clinical application of these models.

DISCUSSION

The results of the reviewed literature indicate significant development of the field over the past decade — from early attempts at automated Cobb angle measurement based on classical CNN models to modern hybrid architectures that, under controlled research conditions, achieve accuracy comparable to that of experienced radiologists. However, technical progress does not necessarily imply clinical applicability, and it is precisely this discrepancy that is one of the central issues in contemporary research on the application of artificial intelligence in medicine.

It is important to emphasize that most reported results are based on retrospective studies conducted under experimental conditions, often with relatively small, single-center datasets, without adequate external validation on independent clinical populations. Such limitations significantly reduce the generalizability of the reported performance and represent one of the main obstacles to the wider clinical application of these systems [28], [29].

An additional problem is the heterogeneity of imaging protocols, radiograph quality, and annotation criteria across different institutions, which can lead to reduced model performance when deployed under real clinical conditions.

In this context, artificial intelligence–based systems should be viewed primarily as tools for supporting clinical decision-making, rather than as a replacement for the expert judgment of radiologists or orthopedists [30].

Key trends and progress

The literature review points to several clear development trends in the application of deep learning to scoliosis analysis. First, there is a shift from classical CNN classifiers toward more complex hybrid architectures that combine local feature extraction via convolutional networks with global modeling of spatial dependencies using attention mechanisms and Transformer components. This development has been accompanied by improved performance, particularly in Cobb angle regression and anatomical structure localization tasks.

A second important trend is the increasingly wide use of multi-task learning, in which models simultaneously perform several interrelated tasks, such as segmentation, anatomical landmark localization, and Cobb angle estimation. The reviewed studies indicate that joint training often leads to better performance and more stable generalization compared with separately trained models, which is consistent with the regularization effect of this paradigm.

A third trend concerns the increasing transparency and reproducibility of research. Whereas studies published before 2020 rarely provided access to source code and experimental protocols, more recent work increasingly uses platforms such as GitHub to share implementations, models, and datasets. Although reproducibility in deep learning for medical imaging remains a significant challenge, this trend contributes to easier comparison of methods and more reliable evaluation of reported results.

Methodological weaknesses

Despite significant technical progress, the literature review points to several systemic methodological limitations that complicate the interpretation and clinical application of the reported results. The dominance of single-institution and private datasets indicates that the true generalizability of most published models remains insufficiently examined [32], [33]. Models trained and evaluated within the same institution, using identical radiographic systems and standardized imaging protocols, may not achieve the same performance in different clinical environments. Small single-center datasets also increase the risk of model overfitting, while external validation on independent datasets is rarely performed [33].

An additional problem is small test sets, often with fewer than 100 images, which can lead to unstable and highly variable evaluation metrics. Statistical comparisons between models are rarely reported, while effect sizes, confidence intervals, and statistical significance analyses are largely absent from the reviewed literature. In addition, annotation protocols and inter-observer reliability

are often not adequately documented, even though they directly affect the assessment of automated system performance.

The regulatory and organizational aspects of clinical application also remain insufficiently addressed. Algorithms intended for medical use must undergo rigorous validation and regulatory approval processes, including FDA and CE procedures, which require multicenter studies and proof of measurable clinical benefit. In addition, questions of liability for potential diagnostic errors, model interpretability, and integration into existing clinical workflows have not yet been fully resolved.

Because of these limitations, despite impressive research results, the widespread application of artificial intelligence–based systems in routine orthopedic and radiological practice remains limited for now. Future research should therefore focus on multicenter datasets, the standardization of evaluation protocols, and prospective clinical validation of models (see also Table 5).

Open problems and recommendations

Prediction of disease progression is one of the clinically most important, yet at the same time least explored, areas of artificial intelligence application in scoliosis analysis. Reliable progression prediction could enable timely intervention before the surgical indication is reached, but the development of such models is hindered by the lack of longitudinal datasets with long-term patient follow-up.

One of the few papers that directly addresses this problem is the pilot study by Yahara et al. [31], in which a DCNN model was developed to predict the progression of adolescent idiopathic scoliosis in patients with an initial Cobb angle of 10–25 degrees. The model was trained on 58 patients and achieved an accuracy of 69% and an AUC of 0.70, with performance comparable to or slightly better than the average assessment of spine surgeons within the same study. Although the results indicate that automated progression prediction is technically feasible, the small sample size and the retrospective design represent significant limitations.

Table 5 provides an overview of the key open problems identified in the reviewed literature, together with recommendations for future research.

Table 5. Open problems and recommendations for future research

Open problem	Comment and recommendation
Lack of public datasets	Existing public datasets are small for modern deep models. Large multicenter datasets with standardized annotations are needed.
Neglected 3D nature of scoliosis	Most studies use 2D PA X-ray images, while 3D analysis and EOS systems are far less explored.
Rare external validation	Few studies validate models on independent datasets, so generalizability often remains unknown.
Prediction of disease progression	A clinically very important area that is still poorly explored and mostly based on retrospective studies.
Interpretability and uncertainty	Clinical models should enable interpretation of decisions and estimation of prediction uncertainty.
Regulatory framework	FDA, CE, and EU AI Act requirements are rarely considered despite their importance for clinical application.

CONCLUSION

This paper has presented an overview of the key approaches to applying deep neural networks in the detection and analysis of scoliosis, based on the relevant literature published between 2015 and 2024. The literature analysis covered several dominant architecture classes, with hybrid CNN–Transformer models representing the most advanced approaches for Cobb angle regression, with indicative Cobb angle MAE values of approximately 2–3 degrees (Table 4), which approaches the limit of inter-observer variability among experienced clinicians.

Despite significant technical progress, the field is still characterized by pronounced methodological limitations, including the dominance of single-institution private datasets, rare external validation, and a lack of prospective clinical studies. Further development requires the standardization of evaluation protocols, the development of larger publicly available datasets, multicenter validation of models, and closer collaboration between researchers, clinicians, and regulatory bodies.

Although the results to date indicate significant potential for deep learning in the automated analysis of scoliosis, the transition from experimental systems to routine clinical practice requires additional validation of the robustness, generalizability, and clinical reliability of the proposed approaches.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the research presented in this paper.

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ULOGA VJEŠTAČKE INTELIGENCIJE U TRANSFORMACIJI IT POSLOVA: SMANJENJE POTREBE ZA VJEŠTINAMA I RUTINSKIM ZADACIMA U FINANSIJSKOM SEKTORU

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SAŽETAK

Ovaj rad razmatra uticaj vještačke inteligencije (AI) na transformaciju IT poslova u finansijskom sektoru, s posebnim osvrtom na automatizaciju rutinskih zadataka i fenomen deskillinga. Pojam deskilling označava promjene u organizaciji rada koje mogu smanjiti nivo vještina potrebnih za obavljanje pojedinih zadataka ili ograničiti mogućnosti zaposlenih da razvijaju i održavaju praktična znanja i stručnu samostalnost.

Empirijski dio rada zasniva se na anketnom istraživanju provedenom među 138 zaposlenih u finansijskom i IT okruženju, s ciljem ispitivanja njihovih stavova o primjeni AI alata, automatizaciji radnih zadataka, sigurnosti zaposlenja i razvoju kompetencija. Rezultati ukazuju na to da ispitanici prepoznaju mogućnosti povećanja produktivnosti i smanjenja vremena potrebnog za rutinske zadatke, ali istovremeno izražavaju zabrinutost zbog mogućeg smanjenja potrebe za pojedinim početnim IT pozicijama i rizika od slabljenja praktičnih znanja uslijed pretjeranog oslanjanja na automatizovane sisteme.

Rad ukazuje na značaj kontinuiranog stručnog usavršavanja, mentorstva i očuvanja prilika za samostalno rješavanje problema. Budući da se istraživanje zasniva na samoprocjeni, nalazi se

tumače kao percepcija zaposlenih o mogućim posljedicama primjene AI, a ne kao neposredno mjerenje promjena njihovih kompetencija.

Ključne riječi: vještačka inteligencija, deskilling, IT poslovi, finansijski sektor, automatizacija.

UVOD

Razvoj vještačke inteligencije (AI) mijenja način organizacije rada, raspodjelu radnih zadataka i kompetencije koje se očekuju od zaposlenih. U finansijskom sektoru, u kojem su obrada podataka, upravljanje rizicima, korisnička podrška i usklađivanje poslovanja s regulatornim zahtjevima važni dijelovi svakodnevnog rada, AI alati mogu ubrzati pojedine procese i smanjiti obim rutinskih aktivnosti. Istovremeno, automatizacija otvara pitanja o promjenama u strukturi zaposlenosti, budućim potrebama za stručnim profilima i mogućnostima zaposlenih da kroz praktičan rad stiču i održavaju profesionalne vještine.

Jedan od teorijskih pristupa kojim se razmatraju ove promjene jeste koncept tehnologijom omogućenog deskillinga. Za razliku od pristupa koji naglašavaju rast potražnje za visokokvalifikovanim radnicima ili polarizaciju zaposlenosti, ovaj koncept razmatra mogućnost da tehnologija preuzme složenije dijelove posla, dok zaposlenima ostaju standardizovaniji zadaci koji zahtijevaju uži skup vještina. U savremenom okruženju AI može preuzeti dio analize, pripreme sadržaja, obrade podataka ili početne dijagnostike problema. Takve mogućnosti mogu povećati efikasnost, ali istovremeno uticati na način na koji zaposleni razvijaju praktično iskustvo i samostalnost.

Važno je razlikovati smanjenje nivoa vještina potrebnih za obavljanje određenog zadatka od stvarnog gubitka znanja kod pojedinca. Prvo se odnosi na promjenu zahtjeva posla, dok drugo podrazumijeva slabljenje ili nedovoljno razvijanje kompetencija zaposlenog. U ovom radu pojam deskilling koristi se kao teorijski termin za razmatranje tih povezanih, ali ne i istovjetnih pojava. Empirijski dio istraživanja ne mjeri neposrednu promjenu kompetencija, nego ispituje percepciju zaposlenih o mogućem riziku takvih promjena.

Cilj rada je analizirati percepciju zaposlenih u finansijskom sektoru o uticaju AI na transformaciju IT poslova, s posebnim fokusom na automatizaciju rutinskih zadataka, promjene u potrebnim kompetencijama i rizik deskillinga. Istraživanje nastoji sagledati kako zaposleni procjenjuju koristi AI alata, moguće promjene u početnim IT pozicijama i značaj kontinuiranog stručnog usavršavanja.

METODOLOGIJA ISTRAŽIVANJA

Radi ispitivanja percepcije zaposlenih o uticaju AI na IT poslove u finansijskom sektoru provedeno je anketno istraživanje među zaposlenima u bankama i drugim finansijskim institucijama. Istraživanje je realizovano od novembra 2025. do maja 2026. godine putem onlajn upitnika.

U istraživanju je učestvovalo 138 ispitanika koji obavljaju različite poslove u IT i finansijskom okruženju, uključujući sistemsku administraciju, programiranje, IT podršku, upravljanje IT funkcijom i bankarske poslove. Upitnik je sadržavao 15 pitanja organizovanih u tri tematske cjeline:

- primjena AI alata u svakodnevnom radu;
- uticaj AI na radna mjesta i automatizaciju zadataka;
- uticaj AI na razvoj i očuvanje kompetencija zaposlenih.

Struktura ispitanika prema radnoj poziciji prikazana je u Tabeli 1. Uzorak obuhvata više profesionalnih grupa, što omogućava sagledavanje stavova zaposlenih koji obavljaju različite vrste poslova. Ipak, struktura uzorka sama po sebi ne potvrđuje reprezentativnost za cjelokupan finansijski sektor, te nalaze treba tumačiti u okviru obuhvaćene grupe ispitanika.

Tabela 1. Struktura ispitanika prema radnoj poziciji

Radna pozicija	Broj ispitanika	Udio %
Sistemski administratori	32	23,2
Programeri	28	20,3
IT podrška	24	17,4
IT menadžeri	16	11,6
Bankarski službenici	38	27,5
Ukupno	138	100

Najveću grupu u uzorku čine bankarski službenici (38 ispitanika; 27,5%), zatim sistemski administratori (32; 23,2%), programeri (28; 20,3%), zaposleni u IT podršci (24; 17,4%) i IT menadžeri (16; 11,6%). Brojevi i procenti prikazuju se odvojeno kako bi se izbjeglo poistovjećivanje apsolutnog broja ispitanika s njihovim udjelom u uzorku.

Za tvrdnje koje su se odnosile na stavove ispitanika korištena je Likertova skala od pet stepeni, pri čemu je vrijednost 1 označavala potpuno neslaganje, a vrijednost 5 potpuno slaganje s ponuđenom tvrdnjom. Procenti prikazani u rezultatima predstavljaju udio ispitanika koji su, prema obradi odgovora, iskazali slaganje s odgovarajućim tvrdnjama.

Istraživanje je usmjereno na procjenu toga da li zaposleni prepoznaju uticaj AI na smanjenje obima rutinskih zadataka, promjene u potrebnim kompetencijama i mogući rizik deskillinga. Budući da se podaci zasnivaju na odgovorima ispitanika, istraživanje pruža uvid u njihove stavove i procjene, ali ne omogućava zaključivanje o uzročno-posljedičnom uticaju AI niti neposredno mjerenje stvarnog gubitka vještina.

TEORIJSKI OKVIR O VJEŠTAČKOJ INTELIGENCIJI I TRANSFORMACIJI PROFESIJA

Istorijski razvoj i savremeni trendovi

Rani teorijski pristupi tehnološkim promjenama na tržištu rada uključuju koncept skill-biased technological change, prema kojem tehnološki napredak relativno više koristi visokokvalifikovanim radnicima i može povećati potražnju za njihovim znanjima. Drugi pristup, poznat kao polarizacija poslova, ukazuje na mogućnost istovremenog rasta zaposlenosti u zanimanjima na oba kraja raspodjele kvalifikacija i smanjenja udjela pojedinih srednjekvalifikovanih poslova, posebno onih koji sadrže rutinske zadatke. Okvir zasnovan na zadacima dodatno razlikuje rutinske i nerutinske, kognitivne i manuelne aktivnosti te naglašava da se uticaj tehnologije ne može objasniti samo nivoom formalnih kvalifikacija zaposlenih.

U radu Xue i saradnika (2022), zasnovanom na panel-podacima za više od 1.300 javno kotiranih preduzeća u Kini u periodu 2007–2018, analiziran je odnos primjene AI i obrazovne strukture radne snage [1]. Autori izvještavaju da je upotreba AI povezana s većim rastom potražnje za radnicima na poslovima koji zahtijevaju niži nivo formalnog obrazovanja nego za radnicima na poslovima koji zahtijevaju viši nivo obrazovanja, pri čemu je obrazac bio izraženiji u uslužnom nego u proizvodnom sektoru. Na osnovu tih nalaza autori predlažu koncept tehnologijom omogućenog deskillinga kao jedno od objašnjenja promjena u strukturi zaposlenosti [1].

Ove teorijske perspektive ne treba posmatrati kao međusobno isključive u svim okolnostima. Posljedice tehnoloških promjena mogu zavisiti od vrste djelatnosti, načina uvođenja tehnologije, organizacije rada i zadataka koji se automatizuju. Za finansijski sektor to znači da AI može istovremeno povećavati produktivnost, mijenjati strukturu radnih mjesta i stvarati nove potrebe za analitičkim, nadzornim i upravljačkim kompetencijama.

Fenomen deskiliranja i promjene radnih zadataka

Pojam deskilling u literaturi o ekonomiji rada, organizaciji rada i tehnološkim promjenama označava proces u kojem se smanjuje nivo vještina potrebnih za obavljanje određenog posla ili se rad organizuje tako da zaposleni imaju manje prilika da koriste i razvijaju složenije kompetencije.

Pojam može obuhvatiti promjenu sadržaja posla, sužavanje raspona zadataka, smanjenje stručne samostalnosti ili rizik od slabljenja praktičnih znanja. Ove pojave su povezane, ali nisu istovjetne: smanjenje potrebnih vještina za zadatak ne znači automatski da je pojedinac izgubio prethodno stečeno znanje.

U kontekstu AI, deskilling se može javiti kada automatizovani sistemi preuzmu aktivnosti koje su ranije zahtijevale samostalnu analizu, dijagnostiku, procjenu ili rješavanje problema, dok zaposlenima ostaju zadaci nadzora, provjere ili obrade standardizovanih izlaza. Ako se takva promjena odvija bez odgovarajuće obuke i praktičnog rada, zaposleni mogu imati manje prilika da razvijaju ili održavaju vještine koje su ranije sticali kroz neposredno izvršavanje zadataka. Ovaj rizik može biti naročito relevantan za zaposlene na početku karijere, kojima rutinski zadaci često služe kao osnova za sticanje iskustva prije preuzimanja složenijih odgovornosti.

U ovom radu izvorni termin deskilling zadržava se zbog njegovog specifičnog teorijskog značenja i zastupljenosti u međunarodnoj literaturi. Izrazi „smanjenje potrebnih vještina" i „gubitak praktičnih znanja i vještina" koriste se kao objašnjenja pojedinih aspekata fenomena, ali nisu uvijek potpune zamjene za njega. Empirijski dio rada ispituje percepciju zaposlenih o riziku deskillinga, a ne neposredno mjeri promjene njihovih kompetencija.

Upravo je ta razlika važna pri tumačenju rezultata ankete: slaganje s tvrdnjom da AI može dovesti do gubitka praktičnih znanja predstavlja procjenu ispitanika o mogućem riziku, a ne dokaz da je do gubitka znanja već došlo. Za pouzdanije utvrđivanje stvarnog deskillinga bilo bi potrebno longitudinalno praćenje zaposlenih ili neposredno mjerenje promjena u njihovim vještinama i radnim zadacima.

AI U FINANSIJSKOM SEKTORU

Primjene u poslovnim procesima

Primjena AI u finansijskim institucijama obuhvata automatizaciju obrade podataka i dokumenata, podršku korisnicima, prepoznavanje obrazaca u transakcijama, analizu rizika i podršku poslovnom odlučivanju. U bankarstvu se robotska procesna automatizacija (RPA) koristi za ubrzavanje standardizovanih postupaka, kao što su unos podataka, obrada zahtjeva i pojedini administrativni poslovi. AI i RPA mogu smanjiti obim ponavljajućih aktivnosti, naročito u pozadinskim poslovnim operacijama i osnovnoj korisničkoj podršci, ali njihova primjena zavisi od kvaliteta podataka, nadzora, regulatornih zahtjeva i načina integracije u postojeće procese [2].

Zianko i Nechyporenko (2023) razmatraju primjenu AI u finansijskom sektoru Ukrajine [3]. Njihov pregled obuhvata rješenja za prepoznavanje govora, razgovorne agente, mašinski prevod, podršku odlučivanju, kompjuterski vid, analizu tekstualne dokumentacije, prognoziranje i otkrivanje anomalija. Autori ukazuju na potencijal AI za povećanje efikasnosti finansijskih procesa, ali i na pitanja etike, transparentnosti, zaštite podataka i pouzdanosti automatizovanih odluka. Ovaj primjer odnosi se na Ukrajinu, a ne na neimenovanu evropsku državu.

U kreditnim i finansijskim procesima mogu se koristiti modeli za procjenu kreditnog rizika, sistemi za otkrivanje prevara i rješenja za personalizaciju finansijskih usluga. Takve primjene mogu ubrzati obradu zahtjeva i podržati analizu velikih skupova podataka, ali zahtijevaju provjeru kvaliteta modela, praćenje mogućih pristrasnosti i jasno definisanu odgovornost za odluke. Automatizacija zato ne uklanja potrebu za ljudskom stručnošću, nego može promijeniti mjesto na kojem se stručnost primjenjuje: od ručne obrade pojedinačnih slučajeva ka nadzoru, validaciji i tumačenju rezultata sistema.

Pored tehnoloških koristi, uvođenje AI donosi rizike povezane sa sajber sigurnošću, privatnošću, regulatornom neusklađenošću, kvalitetom podataka i nedostatkom odgovarajućih kompetencija. Organizacije stoga trebaju povezati automatizaciju s upravljanjem rizicima, stručnim usavršavanjem i jasnim pravilima za provjeru rezultata AI sistema. Ovakav pristup posebno je važan kada se automatizuju zadaci koji su ranije zaposlenima omogućavali sticanje iskustva.

Percepcija zaposlenih o AI – sigurnost radnih mjesta i nove mogućnosti

Uticaj AI na sigurnost radnih mjesta ne može se svesti samo na pitanje da li će pojedina zanimanja nestati. Automatizacija može smanjiti potrebu za određenim zadacima, promijeniti raspodjelu odgovornosti unutar postojećih radnih mjesta ili stvoriti potrebu za novim kompetencijama. Zbog toga je važno razlikovati ukidanje radnog mjesta od transformacije njegovog sadržaja. Istraživanja o razvoju radne snage naglašavaju značaj prekvalifikacije, kontinuiranog usavršavanja i saradnje između poslodavaca i obrazovnih institucija kako bi zaposleni mogli prelaziti na zadatke koji zahtijevaju složenije analitičke i stručne sposobnosti [4], [5].

U kontekstu deskillinga, posebnu pažnju treba posvetiti mogućnostima učenja kroz rad. Ako AI preuzme jednostavne zadatke koje su početnici ranije obavljali pod nadzorom iskusnijih kolega, može se smanjiti broj prilika za razvoj osnovnih dijagnostičkih, analitičkih i tehničkih vještina. Taj ishod nije neizbježan: organizacije mogu nadomjestiti izgubljene prilike strukturisanim praktičnim zadacima, mentorstvom, rotacijom poslova i obavezom da zaposleni provjeravaju i obrazlažu rezultate AI sistema.

Istovremeno, dostupnost AI alata može otvoriti prostor za nove zadatke povezane s provjerom kvaliteta rezultata, upravljanjem podacima, procjenom rizika, sigurnošću i odgovornom primjenom automatizovanih sistema. Očuvanje zapošljivosti zato zavisi i od spremnosti zaposlenih da razvijaju nove kompetencije i od sposobnosti organizacija da osiguraju pravedne mogućnosti za obuku i profesionalni razvoj. Ove tvrdnje predstavljaju teorijski okvir za tumačenje stavova ispitanika, a ne dokaz da su navedeni ishodi već nastupili u organizacijama iz kojih dolaze ispitanici.

REZULTATI ISTRAŽIVANJA

Rezultati ankete pokazuju da je upotreba AI alata prisutna u svakodnevnom radu ispitanika: 81% navelo je da ih koristi najmanje jednom sedmično, dok ih 46% koristi svakodnevno.

U pogledu uticaja AI na poslovne procese, 86% ispitanika smatra da AI povećava produktivnost zaposlenih, dok 79% navodi da smanjuje vrijeme potrebno za izvršavanje rutinskih zadataka. Ovi rezultati ukazuju na to da ispitanici prepoznaju neposredne koristi alata u organizaciji svakodnevnog rada.

Stavovi o budućnosti radnih mjesta pokazuju određenu zabrinutost: 67% ispitanika smatra da će primjena AI u narednih pet godina smanjiti potrebu za pojedinim početnim IT pozicijama, dok 59% očekuje da će neki rutinski poslovi biti u potpunosti automatizovani.

Posebno je značajno da 72% ispitanika smatra da pretjerano oslanjanje na AI može dovesti do postepenog gubitka praktičnih znanja i vještina. Nadalje, 76% prepoznaje rizik da mlađi stručnjaci neće steći dovoljno iskustva u samostalnom rješavanju problema ako se previše oslanjaju na automatski generisana rješenja. Ovi nalazi odražavaju percepciju mogućeg rizika deskillinga i ne predstavljaju neposredno mjerenje stvarne promjene kompetencija.

Tabela 2 sažima ključne rezultate istraživanja. Procenti se prenose prema obradi odgovora iz ankete; njihovo tumačenje treba vezati za konkretne tvrdnje iz upitnika i način na koji su odgovori na Likertovoj skali grupisani.

Tabela 2. Stavovi zaposlenih prema AI

Tvrdnja	Udio ispitanika koji se slažu
AI povećava produktivnost zaposlenih	86%
AI smanjuje vrijeme potrebno za rutinske zadatke	79%
AI će smanjiti potrebu za pojedinim početnim IT pozicijama	67%
Pretjerano oslanjanje na AI može dovesti do deskillinga	72%
Kontinuirana edukacija zaposlenih je potrebna	91%

Diskusija rezultata

Rezultati ukazuju na dvostruku percepciju primjene AI u finansijskom i IT okruženju. S jedne strane, ispitanici prepoznaju povećanje produktivnosti i smanjenje vremena potrebnog za rutinske zadatke. S druge strane, izražavaju zabrinutost zbog smanjenja potrebe za pojedinim početnim IT pozicijama i mogućnosti da pretjerano oslanjanje na automatizovane alate oslabi razvoj praktičnih kompetencija. Takva kombinacija očekivanih koristi i rizika odgovara širem teorijskom pristupu prema kojem tehnološke promjene ne utiču samo na broj radnih mjesta nego i na sadržaj poslova i raspodjelu zadataka.

Nalazi se mogu razmatrati u odnosu na koncept tehnologijom omogućenog deskillinga koji opisuju Xue i saradnici [1]. Njihova analiza preduzeća u Kini za period 2007–2018 ukazuje na povezanost primjene AI s većim rastom potražnje za radnicima na poslovima koji zahtijevaju niži nivo formalnog obrazovanja u odnosu na poslove koji zahtijevaju viši nivo obrazovanja. Taj nalaz ne znači da se svaki AI sistem nužno povezuje sa smanjenjem vještina, nego ukazuje da automatizacija može promijeniti obrazovnu i kvalifikacionu strukturu rada. Rezultati ankete dopunjuju ovu raspravu informacijom da ispitanici prepoznaju rizik gubitka praktičnih znanja i smanjenja prilika za sticanje iskustva.

Za tumačenje rezultata važno je razlikovati tri nivoa promjene. Prvi je automatizacija pojedinačnih zadataka, odnosno preuzimanje aktivnosti koje su ranije obavljali zaposleni. Drugi je promjena zahtjeva radnog mjesta, kada se od zaposlenih očekuju drugačije kompetencije, na primjer provjera rezultata, nadzor sistema ili tumačenje analitičkih izlaza. Treći je mogući deskilling, koji može nastati ako smanjenje neposrednog učešća u zadacima ograniči prilike za razvijanje i održavanje praktičnih vještina. Anketa pruža uvid u stavove ispitanika o trećem nivou, ali ne dokazuje da se takav proces već dogodio.

Posebno su relevantni odgovori o zaposlenima na početku karijere. Rutinski zadaci mogu djelovati jednostavno, ali često omogućavaju učenje osnovnih postupaka, sistematsku dijagnostiku grešaka i razumijevanje šireg konteksta rada. Ako ih AI u velikoj mjeri preuzme, organizacije trebaju namjerno obezbijediti druge načine učenja: mentorstvo, simulacije, praktične zadatke, pregled i obrazlaganje AI izlaza te postepeno povećavanje složenosti radnih obaveza. U suprotnom postoji rizik da se očekivanja od početnika povećaju, dok se smanjuju prilike kroz koje oni tradicionalno stiču iskustvo.

Rezultat da 91% ispitanika smatra kontinuiranu edukaciju važnom dodatno naglašava značaj organizacijske podrške. Obuka ne bi trebala biti ograničena na tehničko korištenje AI alata, nego bi trebala obuhvatiti kritičku procjenu rezultata, zaštitu podataka, razumijevanje ograničenja modela, prepoznavanje grešaka i očuvanje samostalnih sposobnosti rješavanja problema. Takav pristup može pomoći da AI bude sredstvo proširivanja stručnih mogućnosti, a ne zamjena za učenje i profesionalnu procjenu.

Pri generalizaciji nalaza potrebno je uzeti u obzir ograničenja istraživanja. Uzorak od 138 ispitanika pruža uvid u stavove obuhvaćenih zaposlenih, ali bez dodatnih informacija o načinu odabira uzorka i njegovoj reprezentativnosti ne može se zaključiti da rezultati predstavljaju sve zaposlene u finansijskom sektoru. Uz to, podaci se zasnivaju na samoprocjeni i presječnom prikupljanju odgovora, pa ne omogućavaju utvrđivanje uzročnosti niti praćenje stvarne promjene kompetencija tokom vremena. Buduća istraživanja mogla bi kombinovati ankete s intervjuima, analizom promjena radnih zadataka i longitudinalnim mjerenjem kompetencija.

ZAKLJUČAK

Vještačka inteligencija postaje važan činilac transformacije poslovnih procesa i radnih uloga u finansijskom sektoru. Njena primjena može unaprijediti efikasnost, ubrzati obradu podataka i smanjiti vrijeme potrebno za rutinske aktivnosti. Istovremeno, automatizacija mijenja raspodjelu radnih zadataka i može uticati na kompetencije koje se očekuju od zaposlenih.

Rezultati ankete pokazuju da ispitanici prepoznaju koristi AI za produktivnost, ali i rizike povezane sa smanjenjem potrebe za pojedinim početnim IT pozicijama i mogućim slabljenjem praktičnih znanja. Posebno je važno da se rezultati o deskillingu tumače kao percepcija zaposlenih

o mogućim posljedicama pretjeranog oslanjanja na automatizovane sisteme, a ne kao neposredan dokaz da su njihove kompetencije već smanjene.

Nalazi upućuju na potrebu da organizacije prilikom uvođenja AI razmotre ne samo efikasnost i smanjenje troškova nego i posljedice po profesionalno učenje. Mentorstvo, praktičan rad, kontinuirana obuka i provjera rezultata AI sistema mogu pomoći zaposlenima da razvijaju nove kompetencije, uz očuvanje samostalnog razmišljanja i rješavanja problema.

Može se zaključiti da uspješna integracija AI u finansijski sektor zahtijeva ravnotežu između automatizacije i razvoja ljudskih potencijala. Tehnologija može preoblikovati radna mjesta bez njihovog nužnog potpunog ukidanja, ali način na koji se zadaci raspoređuju i kako se organizuje učenje ima važnu ulogu u očuvanju stručnosti. Buduća istraživanja trebala bi provjeriti da li se percipirani rizici deskillinga odražavaju u mjerljivim promjenama radnih zadataka i kompetencija zaposlenih.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the research presented in this paper.

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THE ROLE OF ARTIFICIAL INTELLIGENCE IN RESTRUCTURING IT JOBS: DESKILLING AND REDUCING THE NEED FOR ROUTINE TASKS IN THE FINANCIAL SECTOR

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ABSTRACT

This paper examines the impact of artificial intelligence (AI) on the transformation of IT jobs in the financial sector, focusing on the automation of routine tasks and the phenomenon of deskilling. Deskilling refers to changes in work organization that may reduce the skills required to perform particular tasks or limit employees' opportunities to develop and maintain practical knowledge and professional autonomy.

The empirical part is based on a survey of 138 respondents working in IT and financial settings. The questionnaire examined perceptions of AI use, task automation, job security, and changing competency requirements. The findings indicate that respondents recognize the potential of AI to increase productivity and reduce the time required for routine tasks. At the same time, they express concerns about reduced demand for some entry-level IT positions and the risk that excessive reliance on automated systems may weaken opportunities to develop practical skills.

The results highlight the importance of continuous professional development, mentoring, and preserving opportunities for independent problem-solving. Since the study relies on self-reported responses, the findings are interpreted as employees' perceptions of potential consequences rather than direct measurements of changes in their competencies.

Keywords: artificial intelligence, deskilling, IT jobs, financial sector, automation

SYNTHETIC MEDIA AS A THREAT TO CRISIS COMMUNICATION: AI-GENERATED VIDEOS, DISINFORMATION, AND ALGORITHMIC AMPLIFICATION IN EMERGENCY SITUATIONS

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ABSTRACT

The development of generative artificial intelligence and its multimodal capabilities—particularly in the domain of producing realistic video content and synthesized speech—constitutes one of the most significant contemporary threats to effective crisis communication. This paper examines the ways in which AI-generated video and audio content function as vectors of disinformation in the context of natural disasters and crisis situations, and analyzes the mechanisms of their algorithmic dissemination across platforms such as TikTok, YouTube, Instagram, and X (Twitter). Adopting a theoretical-analytical approach, and combining a review of relevant academic literature, reports by international organizations, and case studies—including Hurricane Melisa and the associated AI-generated viral content—the paper maps the key risks this phenomenon poses to crisis management. Particular attention is devoted to the psychological mechanisms that render AI-generated visual and auditory content especially persuasive under conditions of heightened anxiety, as well as to institutional and technological responses to these threats. These include synthetic media detection tools, regulatory frameworks such as the EU AI

Act and the Digital Services Act, and the C2PA initiative for digital media authenticity verification. The paper concludes that there is no single technical solution capable of effectively suppressing the spread of AI-generated disinformation in real time, and that a comprehensive approach is required—one that integrates technological tools, regulatory measures, proactive institutional communication, and investment in public digital literacy. **Keywords:** generative artificial intelligence, deepfake, crisis communication, disinformation, crisis management

INTRODUCTION

The development of generative artificial intelligence—particularly tools for creating realistic video content such as OpenAI's Sora system and Google's Gemini—has enabled the creation of convincing synthetic content within seconds, without the need for specialized knowledge. This accessibility poses a serious challenge to crisis communication, whose effectiveness depends on the timely and accurate flow of information. A seminal study published in the journal *Science* demonstrated that false information on social media spreads farther, faster, and more broadly than truthful information, particularly when it elicits strong emotional reactions [1] — a pattern that AI-generated content further amplifies, contributing to the phenomenon that the RAND Corporation refers to as "truth decay" [2].

Natural disasters have proven to be particularly fertile ground for this type of disinformation due to the information vacuum preceding official announcements and the algorithmic prioritization of high-engagement content [3]. An analysis conducted by Logically Intelligence, which examined eight major disasters in the United States during the 2024–2025 period, confirms that AI-generated content systematically accelerates the spread of disinformation [4]. This is illustrated by Hurricane Melissa (2025), during which AI-generated videos of sharks in flooded swimming pools accumulated millions of views within a matter of hours [5], as well as the Los Angeles wildfires, where fabricated footage of the Hollywood Sign engulfed in flames received more than 12.6 million views before fact-checking organizations confirmed its AI-generated nature [6]. The aim of this paper is, through a theoretical-analytical approach and a combination of literature review and case studies, to map the mechanisms through which AI-generated content functions as a vector of disinformation during crisis situations and to analyze the existing technological, regulatory, and institutional responses to this threat.

KEY FIGURES: AI-GENERATED DISINFORMATION

The scale of the problem of AI-generated disinformation during natural disasters is best illustrated by quantitative indicators collected during recent crisis events in 2024 and 2025 (Table 1) [4], [5], [6], [7].

Table 1. Key indicators of the scale of AI-generated disinformation during selected natural disasters

Key data	Scope of the problem
Prereviews of AI -generated video content - Hurricane Melissa	3.6M+
Prereviws of AI -generated video content – Los Angeles fires	12.6M
Sharing AI shark videos – Instagram	200K+
Number of hours to reach viral spread	<24h
Disaster monitoring 2024 – 2025 (Logically AI)	8

The data indicate that AI-generated content during natural disasters does not represent an isolated or marginal phenomenon but rather a systematic pattern that recurs from one crisis to another. During Hurricane Melissa, videos depicting non-existent damage in Jamaica —including the well-known footage of sharks in a flooded hotel swimming pool—accumulated more than 3.6 million views within a matter of hours, while the shark footage itself was further disseminated

through thousands of individual shares on Instagram [8]. Similarly, during the Los Angeles wildfires in January 2025, fabricated footage of the Hollywood Sign engulfed in flames and other AI-generated content related to the wildfires reached a total of more than 12.6 million views across Facebook, TikTok, X, and Instagram before independent fact-checking organizations confirmed their artificial nature [7]; [6].

Of particular significance is the finding that AI-generated content typically reaches viral dissemination within less than 24 hours of the onset of a disaster—a timeframe shorter than the standard verification and publication cycle of official information by the competent authorities. This temporal asymmetry, confirmed by an analysis conducted by Logically Intelligence covering a total of eight major natural disasters during the 2024–2025 period, represents one of the central structural challenges addressed in this paper [9].

CASE STUDY 1: FAKE HURRICANE VIDEOS FEATURING AI-GENERATED SHARKS

Hurricane Melissa, which struck the Caribbean in late October 2025—with particularly severe consequences for Jamaica—represents a turning point in the phenomenon of AI-driven disinformation during natural disasters. It was the first major natural disaster to occur following the public release of the latest version of OpenAI's Sora video generation system, enabling researchers to observe, for the first time under real-world conditions, the scale and speed at which high-quality AI-generated content spreads during a crisis situation [5].

As the storm moved through the region, two particularly viral videos rapidly spread across social media platforms, primarily TikTok ((Figure 1), X, and Instagram [22].



Figure 1. AI generated video content on TikTok during Hurricane Melissain in 2025

The first depicted four sharks swimming through the swimming pool of a hotel in Jamaica, allegedly flooded as a result of the storm. The second falsely portrayed the complete destruction of Kingston Airport. Analyses demonstrated that neither of these depicted events had actually occurred—both videos had been created entirely using the Sora system. The shark video was particularly notable for the speed of its dissemination, initially appearing with the watermark of a TikTok account identifying itself as a creator of AI-generated visual effects from the Dominican Republic, while the Instagram version circulated without any indication of its context or origin [5].

Within only a few hours, the videos had accumulated millions of views, appearing alongside authentic footage of actual damage, thereby causing significant confusion among users regarding the true extent of the disaster [10]. The situation became so pronounced that Jamaica's Minister of

Education, Dana Morris Dixon, publicly urged citizens to obtain information exclusively through official channels, stating that even she herself regularly received false content through numerous WhatsApp groups [5]. A similar pattern was observed in the United States, where emergency management officials in Louisiana warned that AI-generated content was making it increasingly difficult for the public to distinguish the actual consequences of the disaster from fabricated scenarios, such as alleged sharks swimming through the streets of flooded cities [11].

Experts in disinformation emphasize that the motivation behind the creation of such content rarely has an explicit political dimension; rather, it primarily reflects a conventional engagement-driven monetization model, in which content that provokes strong emotional reactions generates a greater number of clicks and views, regardless of its authenticity [5]. According to analysts, the case of Hurricane Melissa marked the point at which tools such as the Sora system became sufficiently accessible and convincing to enable the mass production of crisis-related disinformation without requiring technical expertise, thereby inaugurating a new and more dangerous phase in the relationship between synthetic media and crisis reporting [12].

CASE STUDY 2: THE LOS ANGELES WILDFIRES (JANUARY 2025)

The devastating wildfires that affected Los Angeles in January 2025—including the well-known Palisades Fire and the Sunset Fire in the Hollywood Hills—constitute the second key case study examined in this paper, as they illustrate how AI-generated content spreads in parallel with an actual disaster, further complicating the public's ability to distinguish authentic reporting from fabricated material. While the fires engulfed an area approximately twice the size of Manhattan Island, forcing nearly 180,000 people to evacuate, social media platforms were inundated with AI-generated images and videos within 24 hours of the onset of the disaster [6].

Among the most widely disseminated pieces of false content were videos depicting the iconic "Hollywood" sign allegedly completely surrounded by flames (Figure 2). In one such video, the word "Hollywood" was misspelled, providing a clear visual indication of its artificial nature [6]. Despite this, the video accumulated 1.3 million views on Facebook alone within 24 hours, while the official Hollywood Sign page was compelled to publicly refute the claims, confirming that the sign "is still standing" [13]. Analyses conducted by VERA Files, in cooperation with the Indian Deepfakes Analysis Unit, employed detection tools such as Hive AI, "Is it AI?", and "AI or Not" to confirm that all analyzed videos were "highly likely" or "extremely likely" to have been generated by artificial intelligence [7].



Figure 2. AI Generated Video Content During the Los Angeles Fires in 2025

In addition to the videos of the Hollywood Sign, other fabricated content also circulated—including footage allegedly showing firefighters rescuing animals from the flames—in which unnatural physical characteristics (distorted movements, inconsistent lighting, and background artifacts) clearly indicated AI generation. McAfee researchers traced the origin of many of these

videos to the Gemini tool, while some Instagram posts contained visible watermarks from tools such as Grok, which most users, despite their presence, failed to recognize as indicators of AI-generated content [6]. According to VERA Files, a single compilation of fabricated videos on Facebook alone accumulated more than 139,700 reactions, 18,900 comments, 58,400 shares, and 12.6 million views [7].

According to the fact-checking community, the Los Angeles wildfires are now regarded as a turning point at which AI-driven disinformation entered a qualitatively new and more dangerous phase—not only because of the scale of its dissemination, but also because the content was sufficiently convincing to deceive users who, due to their own exposure to danger and emotional distress, were less likely to rely on critical evaluation of the authenticity of the information they encountered [6].

AFP FACT CHECK: VERIFICATION OF AI-GENERATED CONTENT DURING NATURAL DISASTERS

What Is AFP Fact Check

AFP Fact Check (also known as **AFP Factuel** in its French-language editions) is the specialized fact-checking division of the French news agency *Agence France-Presse* (AFP), established in 2017 exclusively for the purpose of fact verification and combating disinformation [14]. Unlike individual independent fact-checking initiatives, AFP Fact Check operates within one of the world's oldest and largest news agencies, with teams distributed across the globe verifying content in 18 working languages, including French, English, Spanish, and Portuguese [14]. This linguistic and geographical diversity enables AFP to monitor and verify viral content in real time on a global scale, including in regions that are rarely covered by smaller, local fact-checking organizations.

Operating Principles

The methodology employed by AFP Fact Check is based on a combination of several standardized digital forensic techniques, which are consistently applied regardless of the platform or type of content being verified:

- Visual verification through reverse image search—using tools such as Google Reverse Image Search and the InVID-WeVerify extension, the team determines whether the disputed image or video has previously appeared online, in what context, and from which year it originates, thereby identifying cases in which older content has been recycled and presented under a false description [15].
- Geolocation — the disputed content is compared with satellite imagery and street-level images from Google Maps and Google Earth from the corresponding time period in order to determine whether the depicted location physically corresponds to the claimed place and time of recording.
- Consultation with independent sources and institutions — as a standard practice, AFP editors first attempt to contact the individual or institution that made the disputed claim, review AFP's own archives, and, where necessary, consult external experts in relevant specialized fields [16].
- Transparent publication — each fact-check report includes comparative visual evidence (the original and disputed images or videos displayed side by side), identifies the specific analytical tools used during the verification process, and, whenever possible, identifies the original creator of the content, thereby enabling readers to independently verify the presented conclusions [16].

This methodology was applied, among other cases, during Hurricane Melissa in October 2025, as well as in exposing the false claim regarding an alleged tsunami in Italy, where the combination of reverse image searching and geolocation enabled investigators to rapidly determine

that the depicted content did not correspond to the claimed time and location of the event. An example of an AFP report is shown in Figure 3.

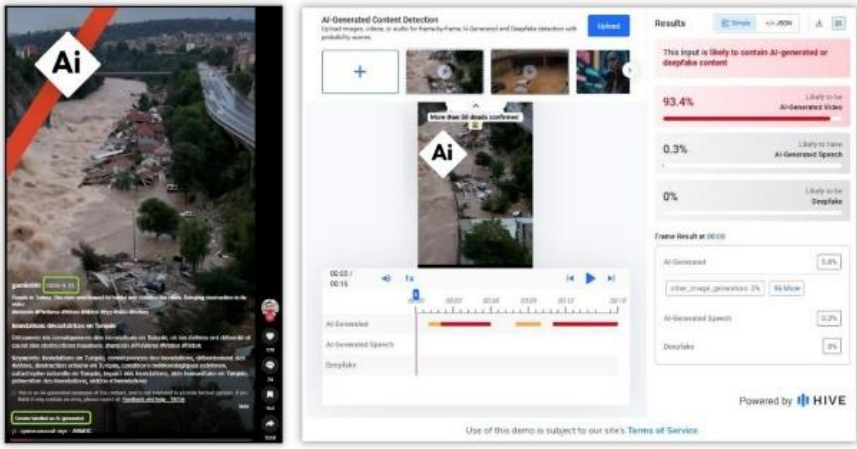

Figure 3. Screenshot of a TikTok post from 2025, annotated to display the publication date and the AI label (left), together with the results of a Hive Moderation analysis conducted on March 12, 2026. AI symbol added by AFP

How Credible Is AFP Fact Check?

The credibility of AFP Fact Check is derived from several independently verifiable factors:

- Institutional status and independence**.** AFP is legally governed by a special French law as an autonomous organization without shareholders. It is financed through the sale of its journalistic content to clients and by financial compensation from the French government solely for the costs associated with fulfilling legally defined public-interest missions. The law explicitly stipulates that AFP is neither a state-owned media organization nor affiliated with any political party [14].
- Independent external certification**.** AFP Fact Check is a certified signatory of the *International Fact-Checking Network* (IFCN) Code of Principles at the Poynter Institute. Consequently, its work is evaluated annually by independent external assessors against a set of 31 criteria, including impartiality, transparency of sources, methodology, and funding [17]. According to the most recent available assessment, more than 75% of AFP's fact-check reports address issues of public interest that may affect the well-being of individuals or society as a whole, thereby fulfilling the IFCN relevance criterion [14].
- Scale and continuity of operations**.** In 2020 alone, AFP Fact Check published more than 7,000 fact-check reports in 18 languages, demonstrating the scale and consistency required for reliable real-time monitoring of viral content [14].
- Platform partnerships**.** AFP is one of the independent fact-checking organizations engaged by Meta platforms (Facebook and Instagram) to verify content within their disinformation mitigation program. Consequently, AFP's labels identifying false content have a direct operational impact on the visibility of such content across these platforms [18].

Despite its high level of institutional credibility, it is important to acknowledge a limitation shared by all fact-checking services, including AFP: regardless of the methodological rigor employed, the verification process requires time—typically several hours to one or two days—whereas AI-generated content during crisis situations, as demonstrated in the preceding chapters, can achieve viral dissemination in less than 24 hours. This structural temporal asymmetry means that even the most credible fact-checking organizations generally operate reactively—exposing disinformation only after it has already reached millions of users—which raises the question

addressed in the following chapter concerning detection tools and the possibilities for early, proactive intervention.

DETECTION TOOLS

Why No Single Tool Is Sufficient on Its Own

Before presenting specific detection tools, it is important to emphasize a finding consistently confirmed by the academic literature: no individual algorithm or tool for detecting synthetic media can guarantee complete accuracy. A comprehensive systematic review published in *Discover Internet of Things* (Springer Nature) analyzed a wide range of detection algorithms—including convolutional neural networks (CNNs), long short-term memory (LSTM) models, transformer-based architectures, and metadata analysis—and concluded that the combination of audio analysis, facial analysis, and metadata examination constitutes a necessary prerequisite for reliable, rapid, and efficient deepfake detection. In contrast, reliance on a single detection technique has proven insufficient due to the rapid evolution of generative models and the limited availability of labeled training data [19]. This conclusion is directly supported by the practices described in the preceding chapters—organizations such as AFP, McAfee, and VERA Files systematically combine multiple tools (Hive Moderation, Attestiv, "Is it AI?", and "AI or Not") with reverse image searching and expert human assessment rather than relying on a single isolated result.

The Most Widely Used Commercial Detection Tools

The market for deepfake detection tools has experienced rapid growth in recent years, reaching an estimated value of approximately USD 581 million in 2025. Among the most frequently cited and widely adopted solutions are:

- Reality Defender—a multimodal detection platform (video, audio, image, and text) based on an ensemble approach that combines multiple models simultaneously. It is primarily used by financial institutions, government agencies, and enterprise security teams. At the end of 2025, the analytical firm Gartner identified Reality Defender as the leading company in the field of deepfake detection.
- Hive AI / Hive Moderation — a tool distinguished by reported detection accuracy exceeding 98% and the ability to identify outputs generated by leading content-generation systems, including Sora, Midjourney, Stable Diffusion, DALL·E, and Kling. Its capability to process large volumes of data makes it particularly suitable for content moderation on platforms serving millions of users. This was the primary tool employed in the analyses cited in the preceding chapters (AFP and McAfee). An example of this tool's report is shown in Figure 4.
- Sensity AI — with a reported detection accuracy of 95–98%, it is widely used by government agencies, cybersecurity companies, and media organizations for detecting face swaps, manipulated audio, and AI-generated images.
- Pindrop (Pindrop Pulse) — a solution specialized in audio deepfake detection, particularly in the context of voice-cloning fraud affecting call centers and financial services.
- Figure 5 presents video and image detection tools.

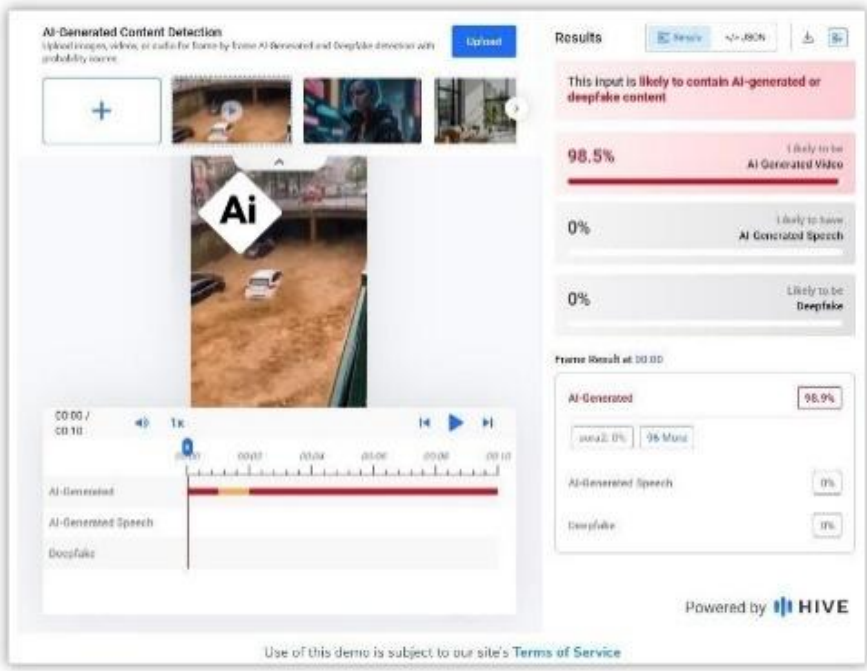

Figure 4. Screenshot of Hive Moderation analysis results, captured on March 12, 2026. AI symbol added by AFP

Video and Image Detection Tools

Tool	Type	Function / Description
InVID-WeVerify	Video / Frame	Frame-by-frame analysis, deepfake detection, and geolocation of video footage. Browser plugin developed with AFP Medialab.
Hive Moderation	Video / Image	Upload video or image to receive an AI-generation probability score. Fast automated screening.
Reality Defender	Video / Audio	Multimodal analysis of both video and audio content. Flags synthetic faces, voice, and scene inconsistencies.
Amped Authenticate	Video / Image	Forensic analysis of metadata, pixel structure, lighting anomalies, and DCT frequency spectrum.
Reverse Image Search	Image / Frame	Google Images / TinEye — traces the original source of video keyframes to expose reused or misattributed footage.

Figure 5. Video and image detection tool overview

It should be noted that the reported accuracy rates and market positions of these tools are derived primarily from technology industry reports and consulting analyses rather than independently peer-reviewed scientific studies. Consequently, these figures should be interpreted as indicative rather than absolute measures of reliability. Table 2 shows an overview of sound detection tools.

Table 2. Sound detection tool overview

Audio Detection Tools	Tool Type	Function / Description
ElevenLabs AI Speech Classifier	Audio	Detects whether an audio sample was generated by ElevenLabs' AI. Accessible via API; first tool of its kind publicly released (2023).
Resemble Detect	Audio	Real-time AI voice detection tool. Analyses audio samples for synthetic speech patterns and voice cloning artifacts.
AI Voice Detector (Hive)	Audio	Upload audio file to detect AI-generated speech. Outputs a probability score distinguishing human from synthetic voice.
Pindrop Pulse	Audio	Forensic audio analysis used in enterprise security contexts. Detects voice spoofing, deepfake audio, and liveness fraud.

Tools Used by Advanced Countries

At the governmental level, the most advanced and longest-running program in this field is led by the United States *Defense Advanced Research Projects Agency* (DARPA). The Media Forensics (MediFor) program, launched in 2016, and its successor, Semantic Forensics (SemaFor), launched in 2020, developed a comprehensive suite of forensic technologies capable of automatically detecting, attributing, and characterizing manipulated multimodal media content, including images, videos, audio recordings, and text [20]. Following the official completion of the SemaFor program in September 2024, DARPA continued transferring the developed technologies to U.S. government agencies and the commercial sector, while further research into media provenance and authenticity was assumed by the *Digital Safety Research Institute* (DSRI), part of *UL Research Institutes* [20]. This model—in which a government agency finances fundamental research and subsequently transfers the resulting technologies to academia, industry, and other governmental bodies through an open catalog of tools—appears, according to available information, to be followed by several other countries as well, although considerably fewer technical details are publicly available regarding their specific implementations.

Concluding Recommendation

Based on the findings presented, we consider it important to emphasize the following: responsible institutional practice during crisis situations should never rely solely on the output of a single detection tool, regardless of the level of accuracy claimed by its developers. Combining at least two or three independent methods—for example, algorithmic image or audio analysis (Hive, Sensity, or Pindrop), reverse image searching and geolocation (as employed by AFP and VERA Files), together with metadata and file provenance analysis (following the principles of the DARPA approach)—substantially reduces the risk of false-negative results, that is, situations in which synthetic content is incorrectly classified as authentic. Furthermore, since all commercial detection tools are based on models trained using previously known content-generation systems, their reliability naturally declines with each new generation of synthetic media generators (such as the Sora system, which, as demonstrated in the Hurricane Melissa case study, successfully bypassed many of the previously established indicators of manipulation). For this reason, even with the best technologies currently available, expert human judgment and institutional coordination—rather than automated detection alone—remain indispensable components of any reliable verification system during emergency situations.

CONCLUSION

This paper has demonstrated that AI-generated video and audio content represents one of the most significant contemporary challenges to crisis communication. The case studies of Hurricane Melissa and the Los Angeles wildfires confirm that false content can now reach millions of views in less than 24 hours—more rapidly than even the most credible fact-checking organizations, such as AFP, are able to complete the verification process. This dynamic is further exacerbated by algorithmic amplification, which systematically rewards emotionally engaging content regardless of its authenticity. The analysis of detection tools has shown that no single technical solution provides complete reliability and that the only dependable approach is the combination of multiple independent methods while maintaining expert human judgment.

A positive aspect of this development is that the same technological progress enabling the creation of increasingly convincing synthetic content is simultaneously driving the rapid advancement of technologies designed to detect it—from government-funded DARPA programs such as SemaFor, through commercial solutions such as Hive and Reality Defender, to regulatory frameworks including the EU AI Act, the Digital Services Act (DSA), and the C2PA initiative for verifying the provenance of digital content. Furthermore, the growing public awareness of the existence of deepfake content—as reflected in the user reactions described in the case studies—indicates a gradual strengthening of societal resilience to this form of manipulation.

The negative aspect, however, remains structurally more difficult to address. The authors of this paper believe that the quality of AI-generated content will continue to improve over the coming years to the point at which the distinction between authentic footage and synthetic media will no longer be recognizable, even to trained experts, let alone the general public—a trend already anticipated by the experts cited in this paper, who warn that telltale indicators such as distorted movements or misspelled signs are gradually disappearing with each new generation of generative models [5]. Should this trend continue at its current pace, detection technologies may permanently lag behind content-generation capabilities, causing the burden of verifying the truth to shift increasingly toward institutional and regulatory mechanisms rather than technology itself.

The consequences of this phenomenon extend far beyond mere informational confusion. During natural disasters, exposure to false content further burdens the psychological state of already vulnerable populations by intensifying fear, uncertainty, and distrust at precisely the moment when psychological stability is essential for responding appropriately to genuine danger. Moreover, the increasingly prominent phenomenon known as the *liar's dividend*—where awareness of the existence of deepfake content leads individuals to dismiss authentic videos and legitimate warnings as fabricated—further erodes public trust in official sources, even when those sources are conveying accurate information. This effect is particularly dangerous during crisis situations, where hesitation in responding to genuine warnings may result in the loss of life.

In the authors' view, the most serious operational risk concerns the work of emergency response and rescue services. When fabricated or incorrectly geolocated content—for example, footage of a "collapsed bridge" or a "flooded neighborhood" that actually originates from a different location or time—is indiscriminately shared and perceived as credible, emergency responders may be redirected to the wrong location while the actual disaster unfolds elsewhere, thereby losing precious time during which lives could otherwise be saved. This scenario is not merely hypothetical: following the earthquake in northwestern England in 2025, Network Rail suspended railway traffic in the affected area on the basis of a fabricated photograph allegedly depicting a collapsed bridge, illustrating how rapidly synthetic content can produce real operational consequences in the field [21].

Based on the findings presented, it can be concluded that effectively countering AI-generated disinformation during crisis situations requires a comprehensive, multi-layered approach combining: (1) the continuous improvement and integration of detection technologies; (2) clear regulatory requirements mandating the labeling of AI-generated content; (3) proactive and timely institutional communication capable of preventing information vacuums; and (4) long-term investment in public digital literacy. Without such an integrated response, the boundary between real and artificially generated disasters risks becoming increasingly difficult to distinguish, with direct consequences for

public safety, the psychological resilience of affected populations, and the effectiveness of emergency response efforts.

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ENGINEERING, TECHNOLOGY AND MATERIALS

INŽENJERSTVO, TEHNOLOGIJE I MATERIJALI

OPTIMIZATION OF INDUSTRIAL DESIGN PROCESSES AND MATERIAL COMPOSITION FOR SUSTAINABLE DESIGN

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ABSTRACT

Sustainable product development has become one of the central challenges of modern society, requiring the integration of environmental and functional aspects throughout the entire design process. The development of distinctive and competitive sustainable industrial designs plays a significant role in high-value-added production. This paper analyzes how industrial design can contribute to product sustainability with special attention to the role of materials and composite systems in achieving a balance between mechanical performance, aesthetics, and environmental requirements. The study combines theoretical analysis with a selected case study from practice in order to identify key strategies for optimizing sustainable product development. For this purpose, the design and development of concrete washbasins were selected. Specially formulated concrete mixtures were developed to achieve an optimal balance between aesthetics, functionality and sustainability. The cast concrete provided high strength, low porosity, and a refined tactile aesthetic. The material composition was enhanced with high-quality pigments and additives, enabling control of color, texture, and surface finish. The results indicate that interdisciplinary collaboration between industrial design, materials engineering, and manufacturing processes is essential for the successful implementation of sustainable design approaches. The presented findings contribute to a broader understanding of how the integration of innovation, advanced materials, and creative design strategies can support environmentally responsible industrial design and promote sustainable innovation in product development.

Keywords: sustainability, industrial design, materials, product development, eco design.

INTRODUCTION

Industrial design is an important field of contemporary design that integrates art, engineering, technology, and user needs to develop functional, aesthetically appealing, and commercially competitive products [1,2]. Its role extends beyond shaping a product's external appearance, encompassing a comprehensive process that involves research, user needs analysis, concept development, material selection, manufacturing processes, ergonomics, functionality, and aesthetic considerations [1,3]. The successful integration of these elements enables the development of products that respond to both technological possibilities and market demands.

This paper explores the fundamental principles of industrial design through the development of a selected sanitary product - a washbasin. Particular attention is given to the relationship between form and function, material selection, manufacturing technology, ergonomics, and aesthetic requirements. The analysis also considers the role of sustainable design in contemporary product development, emphasising the importance of balancing technical performance, user expectations, and environmental considerations.

A review of existing washbasin models indicates a growing tendency towards simplified forms, the use of diverse materials, and greater opportunities for personalisation. These trends highlight the importance of considering aesthetic appearance, functionality, ergonomics, and material properties as interconnected aspects of the design process. Concrete, including microcement-based finishes, represents one of the material approaches used in contemporary washbasin design. In such products, the material serves not only as a structural component but also contributes significantly to their visual character. The availability of different colours, textures, and surface finishes allows the product to be adapted to specific interior design concepts.

The choice of concrete for the proposed washbasin is primarily motivated by its characteristic texture and distinctive sense of solidity and mass. The washbasin is conceived as a sculptural form that establishes a direct relationship with water through everyday use. The contrast between the solidity of concrete and the fluidity of water provides the conceptual basis for a restrained design characterised by clean lines and a minimalist form. This approach allows the washbasin to complement different interior styles while retaining its distinctive sculptural character.

Material selection is a key aspect of product design, as it directly influences strength, durability, weight, appearance, maintenance requirements, and manufacturing processes [4]. The materials most commonly used in commercially available washbasins include sanitary ceramics, porcelain, natural and composite stone, acrylic-based composites, microcement, and concrete. Ceramics and porcelain are widely used due to their hygienic surface properties, resistance to scratching and chemical agents, and relatively easy maintenance. Natural and composite stone offer distinctive aesthetic qualities and a sense of luxury, although their greater weight and specific maintenance requirements may present certain limitations.

The concrete selected for the proposed product is formulated with high-quality pigments and additives that allow precise control over colour, texture, and surface finish [5]. This flexibility enables the creation of individual variations, making each finished piece visually distinctive. In addition to its aesthetic potential, concrete offers several properties relevant to washbasin applications:

- Resistance to moisture, wear, and temperature variations, which contributes to its suitability for everyday use;
- Potential for environmentally responsible production, through the selection of appropriate materials and manufacturing processes aimed at reducing environmental impact;
- Distinctive appearance, resulting from natural variations in texture and colour that make each product unique.

Particular attention must be given to the surface finishing and protection of concrete [5]. Since the washbasin is regularly exposed to water, cleaning agents, and various substances, an

appropriate protective treatment is essential to prevent staining and unwanted changes in appearance. From an aesthetic perspective, the natural texture of concrete can become an integral part of the product's visual identity. The addition of pigments allows different colour shades to be achieved, while various finishing techniques can produce matte, smooth, or more pronounced textured surfaces [8].

Beyond material selection, the functional design of a washbasin requires careful consideration of its geometry and drainage system. Its internal surface must be shaped to direct water towards the drain opening and minimise water accumulation. The drain is therefore one of the key functional elements of the product. The design may also incorporate an overflow opening, which provides an additional drainage route when the basin is filled and is connected to the drainage system.

The main functional requirements of a washbasin include: Stability during use; User safety; Efficient water drainage; Prevention of excessive water splashing outside the basin; Ease of cleaning and maintenance; Resistance to moisture and commonly used cleaning agents; Secure attachment to the supporting structure.

Ergonomics is another essential consideration in washbasin design, particularly because the product is used daily and often several times throughout the day. Its dimensions and installation position should ensure a natural and comfortable user posture. The main ergonomic parameters include: Installation height of the washbasin; Width and depth of the basin; Position of the drain opening; Distance between the basin and the tap. An appropriate installation height allows users to operate the washbasin without excessive bending. If positioned too high, the basin may be uncomfortable to use, whereas an excessively low installation height can result in increased forward bending of the back. The width and depth of the basin are equally important, as they must provide sufficient space for handwashing while taking into account the available bathroom space. Consequently, the design should achieve a balance between user comfort and spatial constraints. Ergonomic considerations also include user safety. The edges of the washbasin should avoid unnecessarily sharp transitions that could pose a risk during everyday use. Rounded edges can contribute not only to a more refined appearance but also to safer and more comfortable interaction with the product.

The main design challenge addressed in this study arises from the need to integrate functional, structural, aesthetic, environmental, and manufacturing requirements within a single sanitary product. In practice, improvements in one product characteristic may adversely affect another [6, 7]. For example, increasing the amount of material may improve structural strength but also increase product weight and material consumption [8]. Similarly, more complex geometry may enhance the visual appeal of the product while complicating mould fabrication and the casting process. Material selection may also involve trade-offs between mechanical performance, aesthetic qualities, and manufacturing requirements. These interdependencies highlight the need for a comprehensive design approach in which different product requirements are considered simultaneously.

In this context, the paper investigates the application of industrial design principles, sustainable design approaches, and computer-aided design (CAD) technologies in product development. Its primary objective is to explore the development of a washbasin that responds to contemporary user needs by integrating aesthetic, functional, technical, and environmental requirements. The theoretical part examines fundamental industrial design principles, with particular emphasis on the relationship between form and function and the role of sustainable design. Consideration is also given to material selection, the rational use of resources, waste reduction, and the potential for minimising environmental impacts. The practical part focuses on the design and development of the washbasin, from initial concept definition and form development to the preparation of technical documentation and 3D modelling using CAD tools. Ergonomic, functional, and aesthetic requirements are considered throughout the design process, alongside the potential application of sustainable materials and manufacturing principles. In addition, a survey was conducted to identify the needs and attitudes of potential users, focusing on

the perceived importance of product aesthetics and functionality, material selection, and attitudes towards sustainable design. By combining theoretical considerations, survey findings, and the practical design process, the paper highlights the importance of integrating industrial design principles and sustainability considerations in contemporary product development.

MATERIALS AND METHODS

Structural development is an important stage in the product design process, as it allows the geometry, functional characteristics, and manufacturing feasibility of the product to be precisely defined. The selected product, the Qadra washbasin, was modelled using AutoCAD software, based on the principles of orthographic projection and technical drawing. The technical documentation includes the top view, front view, side view, bottom view, section A-A, and a three-dimensional (3D) representation of the product. Together, these views provide a comprehensive understanding of the product's external and internal geometry.

The colour of the product is incorporated into the material and the available colour palette is shown in Figure 1. Rather than being applied only to the surface, the pigment is distributed throughout the material. This results in consistent coloration and helps maintain the product's appearance during use (Figure 2). It also reduces the dependence of the final appearance on the condition of the outer surface.



Figure 1. Defined colour palette for the Qadra



Figure 2. The Qadra washbasin

The following functional requirements were considered during the washbasin design process: efficient and controlled water drainage; structural stability; straightforward installation and

suitability for serial production. The washbasin was designed as a compact body with a regular external contour and a centrally positioned drainage opening. The inner surface is shaped to direct water by gravity towards the central drainage point, minimizing water retention. Wall thickness is maintained consistently along the perimeter to provide mechanical strength, more uniform stress distribution, and structural stability during use. The transitions between surfaces are defined by specific radii, which help reduce stress concentrations and facilitate the manufacturing process.

The designed product has a square base with rounded edges. Its external contour is defined by precise linear segments and transition radii. The central opening for the drain fitting is positioned along the axis of symmetry, contributing to the balanced distribution of loads and the overall visual symmetry of the product. The inner volume is shaped as a recessed basin with a gentle slope towards the drainage opening. This geometry is intended to ensure the smooth flow of water and minimize its retention on the surface. The underside is designed to provide stable support and facilitate connection to the installation components.

The selected washbasin is made from specially formulated concrete mixtures developed to provide the required strength, appearance, and functional performance. Concrete offers resistance to moisture, wear, and temperature variations, while pigments and additives allow the colour and surface texture to be controlled. The manufacturing process uses locally sourced materials, with less than 5% of production waste separated for further recycling. Part of the energy demand is supplied by photovoltaic panels, while the material also offers potential for recovery and reuse at the end of the product's service life [5].

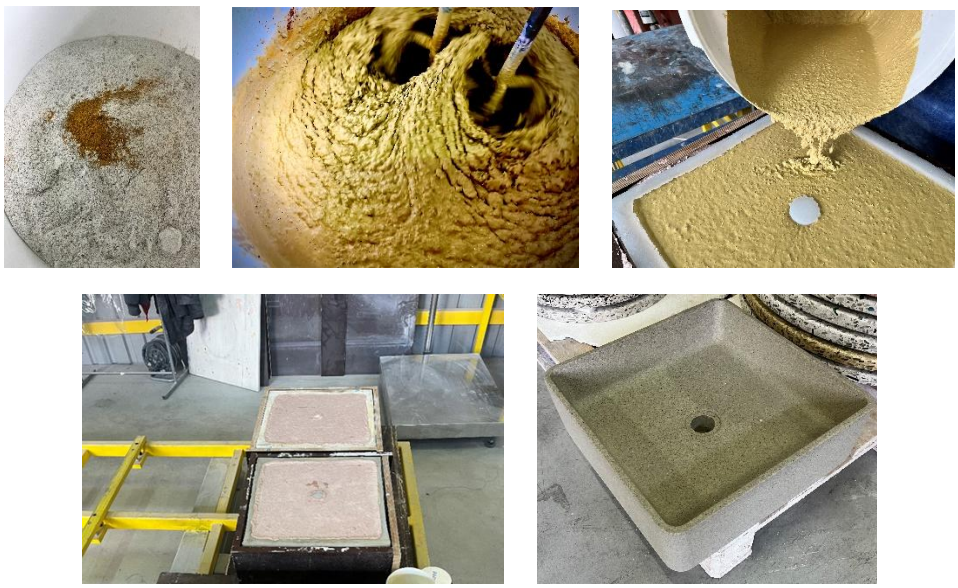

Figure 3. Qadra washbasin manufacturing process

The process begins with the preparation of a mould according to the dimensions and predefined geometry. The mould (Figure 4) must be manufactured with sufficient precision to ensure dimensional accuracy, uniform wall thickness, and the correct positioning of the drainage opening. Particular attention is given to the internal surfaces of the mould, as their finish directly affects the surface quality of the final product.



Figure 4. Mould designed for the Qadra washbasin

The technical properties of the material are an important consideration when selecting it for washbasin production. Table 1 presents the main physical, mechanical, and technical properties of the concrete, including its strength, density, resistance to water, chemicals, temperature variations, and wear, as well as its surface finish properties.

Table 1. Composition and ingredient information for cast concrete

Parameter	Value	Standard
Density (dry material)	2.200 – 2.350 kg/m^3	EN 12390-7/SRPS EN 12390-7
Compressive strength (28 days)	≥ 70 MPa	EN 12390-3/SRPS EN 12390-3
Flexural strength	≥ 12 MPa	EN 12390-5/SRPS EN 12390-5
Water absorption (sealed surface)	< 0.01%	EN 13755
Chemical resistance	Good (pH 5–10, mild chemicals)	ASTM C267
UV resistance	Slight tone variations possible	ISO 4892-2
Thermal shock resistance (uncoated)	Δ < 1 MPa (20–90 °C)	EN 14066
Frost resistance (50 cycles)	No degradation	EN 12390-9/SRPS EN 12390-9
Scratch resistance	6.5–7.5 Moh	Moh UHPC reference
Abrasion resistance	Good, depends on surface finish	EN ISO 5470-1
Thermal stability	Up to +90 °C	EN ISO 10545-8
VOC emissions (after curing)	< 0.05 mg/m³ (Low VOC)	EN ISO 16000-9 / AgBB / LEED v4
Surface finish (sealer)	Water-based, safe for skin and food contact	Food contact

The material composition is another important factor in understanding its physical, mechanical, and functional properties. Cast concrete is a composite material consisting of a cement-based binder, mineral components, pigments, and additives. The selection and proportions of these constituents influence the material's workability, strength, appearance, and suitability for the intended application (Table 2).

Table 2. Composition and ingredient information for cast concrete

Ingredient	CAS Number	EC Number	Concentration (%)	Note
Portland cement	65997-15-1	266-043-4	< 30	In powder form - irritant
Silica (SiO_2)	14808-60-7	238-878-4	30–50	Respirable crystalline fraction
Calcite ($CaCO_3$)	1317-65-3	215-279-6	10–20	Inert filler
Inorganic pigments	/	/	< 5	Fe-oxides, non-reactive
Additives (superplastic.)	/	/	< 2	PCE-based, non-reactive

*Note: The final product is in a solid, inert form. Toxicological properties and hazard classifications refer exclusively to the raw materials in their uncured or processed state.

As part of the study, a survey was conducted among potential users of the designed washbasin. The aim was to examine their attitudes towards the product's aesthetics, functionality, material origin, sustainability, ease of maintenance, and overall perception of contemporary concrete sanitary products. The survey findings were also considered in relation to the technical and design characteristics of the analysed product.

RESULTS AND DISCUSION

Technical drawing and geometric characteristics of the product

The technical drawing of the washbasin comprises several characteristic views that provide a comprehensive representation of the product. The following views and representations were prepared: top view, front view, side view, bottom view, section A-A, three-dimensional (3D) representation of the product. This set of views enables a comprehensive examination of both the external and internal geometry of the component.

The top view provides the basis for dimensioning and proportional analysis of the product. It defines the following features: overall dimensions, position and diameter of the central opening, relationship between the external and internal contours, symmetry of the design.

The main structural features of the washbasin include:

- the external and internal contours;
- wall thickness;
- transition radii;
- the central drainage opening;
- the inclination of the inner basin towards the drainage opening.

The individual views provide complementary information about the product geometry:

- Top view - illustrates the overall dimensions, drainage opening, and design symmetry (Figure 5);
- Front view - defines the height and depth of the basin (Figure 6);
- Side view - shows the product profile and overall structural height (Figure 6);
- Bottom view - indicates the position of the drainage opening and the supporting surface (Figure 5).

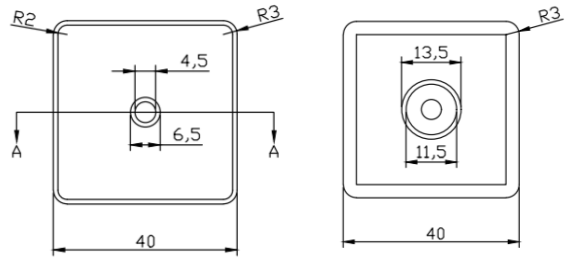

Figure 5. Top (left) and bottom (right) view

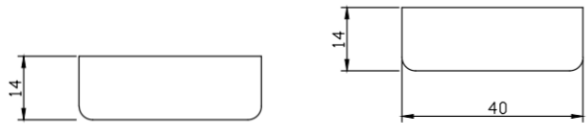

Figure 6. Front (left) and side (right) view

Section A-A represents the most important structural view, as it provides insight into the internal geometry of the washbasin. It illustrates the wall thickness, basin depth, transition radii, and inclination of the inner surface towards the drainage opening. These features are essential for understanding the product's construction and defining its geometric characteristics. The sectional view is presented in Figure 7.

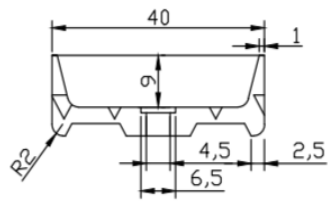

Figure 7. Section A-A

The 3D model provides an overall representation of the washbasin, illustrating its final shape, proportions, and spatial characteristics. It brings together the geometric features defined in the technical drawings, allowing the external form and the relationship between the basin contours to be clearly visualized. The model also provides a better understanding of the product's overall design and complements the technical views presented in the previous figures (Figure 8).

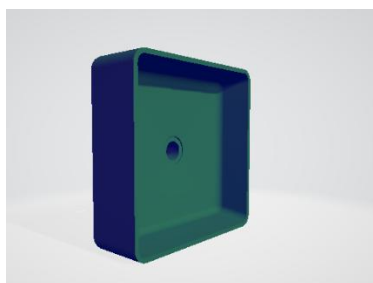

Figure 8. 3D model of the product

Sustainability aspects of the product

Sustainability is considered throughout the development and production of the Crafton washbasin, with particular attention to the selection of raw materials, efficient resource utilization, energy consumption, and the possibilities for material recovery at the end of the product's service life.

Local sourcing of raw materials: Approximately 90% of the raw materials used in production are locally sourced. These include mineral fillers and pigments. The use of locally available materials helps reduce transportation distances and supports a more sustainable supply chain [5].

Efficient material utilization: The production process achieves a material utilization rate of approximately 95%. Less than 5% of the material is separated as production waste, while the remaining material is retained within the production process. This approach reduces material losses and contributes to more efficient resource utilization [5].

Colour integrated throughout the material: Unlike surface-applied finishes, the pigment is incorporated throughout the material structure. This provides consistent coloration across the entire product and helps maintain its appearance even when the surface is exposed to regular use.

Use of renewable energy: Part of the electricity required for production is supplied by photovoltaic panels installed at the manufacturing facility. The use of solar energy helps reduce reliance on conventional electricity sources and contributes to lower environmental impacts associated with manufacturing [5].

Material recovery and reuse: At the end of its service life, the washbasin can be mechanically ground, allowing the recovered material to be considered for reuse in other applications, such as mineral filler in new panels, an additive in concrete-based materials, or secondary aggregate in architectural composites. This possibility provides an opportunity to extend material use beyond the original product.

Surface coating properties: The washbasin is finished with a protective coating designed to provide UV stability and a durable surface. The coating is also intended to meet requirements for applications involving food contact. Its VOC content is an additional environmental consideration in the selection of finishing materials [5].

Recycled packaging: The product is packaged in recycled cardboard, which provides protection during handling and transportation while reducing the need for virgin packaging materials.

Research into user attitudes and requirements in the product development process

As part of this paper, a study was conducted to identify the attitudes, needs, and expectations of potential users regarding the appearance, functionality, and properties of sanitary products, with particular emphasis on the washbasin as the subject of industrial design research. The respondents' answers were analyzed to determine which product properties users consider most important and which aesthetic and functional elements have the greatest influence on their choices. The study included questions concerning the respondents' demographic characteristics, habits, and attitudes.

The research was conducted using a survey. The questionnaire was developed in a digital format, and data were collected from potential users across different age groups. The study included respondents of different genders, ages, education levels, and employment statuses. This approach aimed to ensure a diverse sample and provide a broader understanding of their attitudes and needs. In addition to electronic data collection, some responses were collected through direct contact with respondents, using face-to-face surveys. This enabled the inclusion of respondents who use digital platforms less frequently. Following data collection, the responses were processed, and the results were presented graphically and as percentages.

The sample included respondents with a range of demographic characteristics. The variables analyzed were gender, age, education level, employment status, and monthly income. The sample included approximately equal numbers of male and female respondents (Figure 9). This distribution allows the results to be considered without a pronounced predominance of either gender.

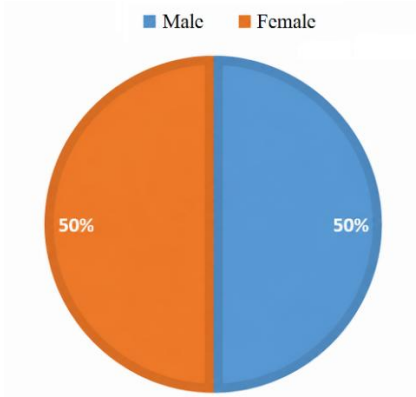

Figure 9. Distribution of respondents by gender

The age distribution shows that several age groups were represented (Figure 10). The largest number of respondents belonged to younger age groups, although older age groups were also included in the study.

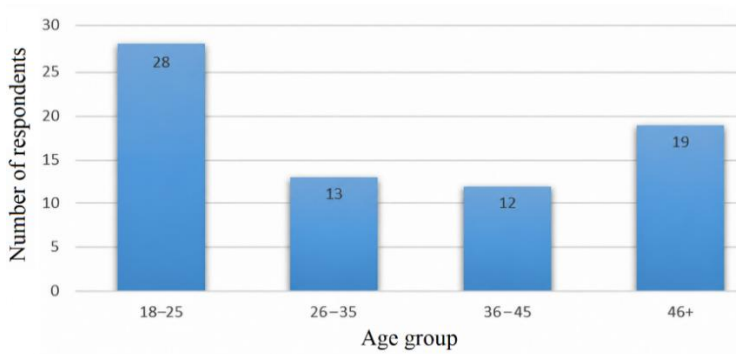

Figure 10. Age distribution of respondents

The analysis of education levels showed that respondents with different educational backgrounds were represented in the sample (Figure 11). Respondents with secondary and college or university education accounted for the largest proportions.

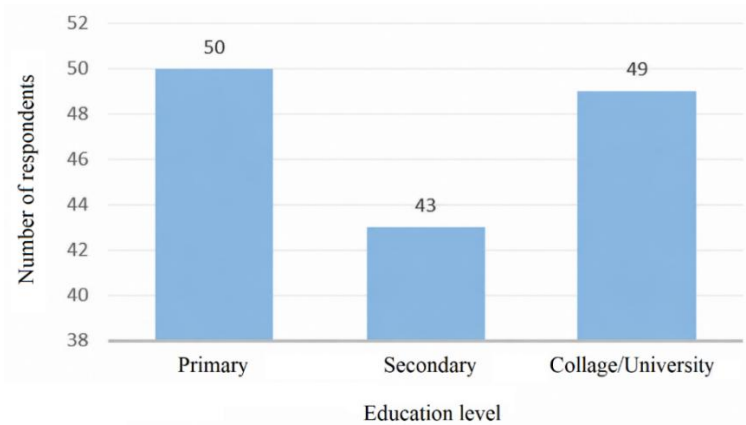

Figure 11. Distribution of respondents by education level

In terms of employment status, respondents were classified as employed, unemployed, pupils and students, or retired (Figure 12).

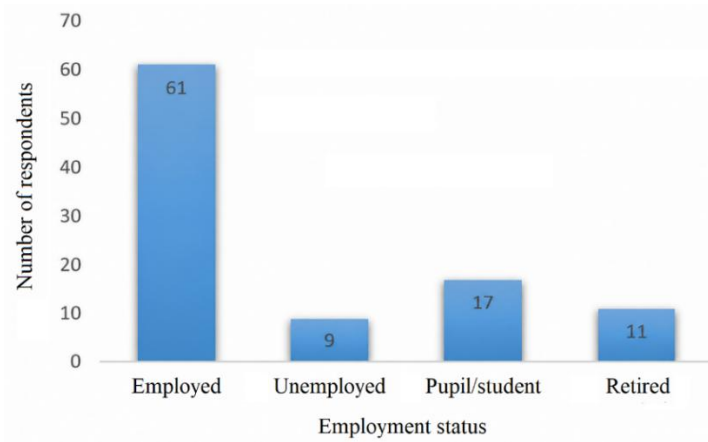

Figure 12. Distribution of respondents by employment status

This sample composition allows the findings to be considered from the perspectives of different groups of potential users.

Following data collection, the results were analyzed for each question. The findings were presented graphically to facilitate comparison. One question concerned the importance of product appearance when selecting sanitary equipment. The results indicate that aesthetic appearance is an important factor for a dominant number of respondents (Figure 13).

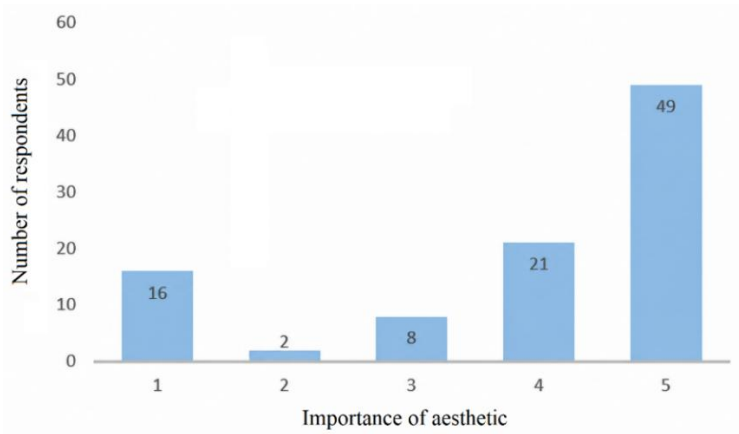

Figure 13. Importance of the washbasin's aesthetic appearance in product selection

This finding indicates that washbasin design should address both functional requirements and the product's visual identity. Form, proportions, lines, and surface finish are elements that can influence users' perceptions of a product.

One section of the survey concerned the choice of material from which the washbasin should be made. The responses to this question were used to examine users' attitudes towards traditional and contemporary materials (Figure 14).

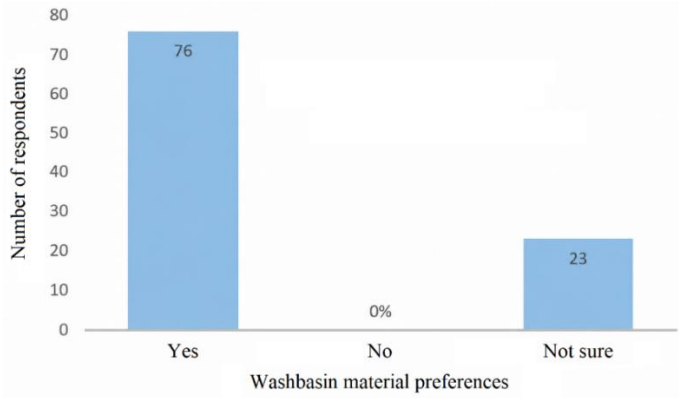

Figure 14. Respondents' preferences regarding washbasin materials

In addition to its visual appearance, the product material should be assessed in terms of moisture resistance, maintenance requirements, durability, and suitability for everyday use. Respondents were also asked to express their views on the importance of the washbasin's functional properties. The results indicate that functionality is one of the primary criteria in product selection and also that product design should be based on a balanced relationship between aesthetics and functionality (Figure 15).

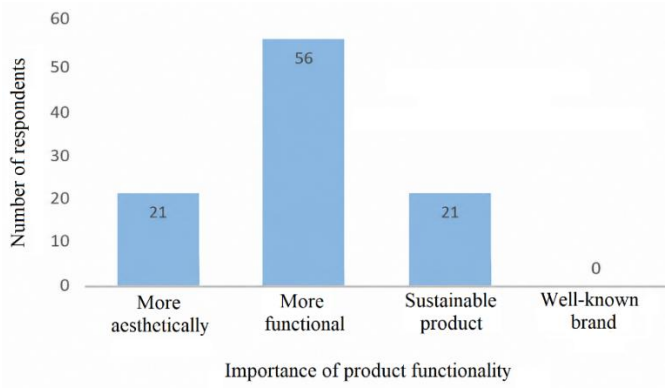

Figure 15. Importance of the selected product's functionality

The analysis of respondents' answers provided insight into the needs and expectations of potential users regarding the appearance and functionality of sanitary products. Based on the findings, particular attention was given to the product's form, proportions, material selection, maintenance requirements, and functional properties. The design process aimed to achieve a balance between visual appeal and practical usability, ensuring that the proposed design addressed both aesthetic considerations and users' functional requirements. Thus, the survey findings provided a basis for and further justification of specific design decisions.

The study provided valuable information on potential users' attitudes, preferences, and needs, enabling the identification of key factors influencing product perception and selection. The results highlighted the importance of an integrated approach to product design, in which aesthetic, functional, and material characteristics are considered collectively. Accordingly, user research served as a link between the design process and the expectations of potential users, helping to ensure that the final product design was informed not only by technical and aesthetic criteria but also by user-oriented considerations.

CONCLUSIONS

The product analysis demonstrated that functionality, design quality, appropriate material selection, and sustainability can be successfully integrated into a single product. The examination of the selected washbasin, including its views and cross-sectional representation, confirmed the functional requirements, structural precision, and consistency of its main design elements. Considering the aesthetic, functional, and material properties together provides a basis for developing a final product that responds not only to technical and design requirements but also to the actual needs of potential users. In this context, user research represents an important part of the product development and design process.

The conducted survey provided insight into the attitudes and preferences of potential users regarding sanitary products. The results indicated that functionality, quality, and durability are the most important factors influencing product selection. However, respondents also considered appearance and material choice to be relevant aspects. Furthermore, the findings revealed a positive attitude towards the use of sustainable materials, highlighting the importance of incorporating environmental considerations into contemporary product design.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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TREATMENT OF TEXTILE DYE WASTEWATER BY SOLAR-POWERED ELECTROOXIDATION

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ABSTRACT

Wastewaters represent one of the biggest problems today as they contain many pollutants, some of which are well-known pollutants, while there are also those whose impact on human health and the ecosystem has not been fully investigated. There are many persistent pollutants that cannot be removed by conventional wastewater treatment technologies, which causes great concern regarding their impact on human health. For this reason, the study, development and implementation of advanced technologies in wastewater treatment are of great importance. In recent years, new advanced oxidation processes based on electrochemical technology - electrochemical advanced oxidation processes (EAOPs), have been developed for the treatment of persistent pollutants. EAOPs are known not only as very efficient technologies but also as large consumers of electricity. In this research EAOP were used for the treatment of textile dye wastewater. In order to eliminate their biggest drawback, instead of being powered by the distribution network, the electrochemical reactor was powered by solar panel. A battery was used to store the energy obtained from the solar panel to ensure continuous operation and avoid energy fluctuations. The key parameters that affect the efficiency of the process, the economic feasibility and the potential for real-scale application were examined.

Keywords: Green energy, EAOPs, electrooxidation, dye removal.

INTRODUCTION

Global industrialization and urbanization have significantly increased both the volume and the complexity of wastewater. Many pollutants, especially micropollutants such as pesticides, pharmaceutical residues and dyes are resistant to removal by conventional wastewater treatment methods (coagulation, biological and chemical oxidation, etc.), thereby posing risks to both ecosystems and human health [1]. Therefore, there is a growing demand for more efficient wastewater treatment (WWT) systems. When selecting an appropriate WWT technology, several criteria must be considered, including efficiency, sustainability, compliance with environmental regulations, and economic viability [2]. By developing advanced technologies, such as advanced oxidation processes (AOPs) it is possible to produce high-quality water. AOPs are based on the formation of highly reactive hydroxyl radicals (OH·) and other oxidants, which degrade pollutants either through mineralization or by transforming them into less toxic by-products [3], [4]. These processes include UV/H_2O_2, ozonation, Fenton and photo-Fenton reactions, as well as electrochemical approaches - are among the most effective methods for wastewater treatment containing organic pollutants.

AOPs in which OH· formation is initiated by electricity are called electrochemical advanced oxidation processes (EAOPs). These processes are based on the electrolytic in situ generation of OH· in an electrochemical reactor (ECR) and include processes such as electrochemical oxidation, electro-Fenton, photoelectrochemical and sono-electrochemical technologies, and capacitive deionization [5]. The most popular and most researched EAOP is electrochemical oxidation/electrooxidation (EO), in which pollutants are oxidized/degraded either directly on the surface of the anode, or indirectly through intermediates. The main advantages of EAOPs include their wide applicability, the complete mineralization of organic pollutants, the potential for integration with solar photovoltaic and thermal energy, the additional production of useful by-products (e.g., H_2), the possibility of automation, ease of handling, the simplicity of equipment, and safe operation [3], [6]. On the other hand, the main drawbacks are their high energy consumption, sensitivity to wastewater composition (e.g., chlorides induce the formation of toxic by-products), and the low conductivity of some wastewaters, which requires the addition of supporting electrolytes (salts). Furthermore, electrode activity may decrease and electrode lifetime may be shortened due to the deposition of organic matter on their surface [7], [8], [9].

Economic analysis of electrochemical WWT systems shows that the main costs are the initial investment and the electricity consumption during the electrolysis process. Investment costs include the design and construction of the ECR system, the provision of electrolytes in the case of low conductivity wastewater, and the procurement of appropriate electrode materials. However, the biggest challenge for the widespread application of EAOP technologies remains the high energy consumption, which also represents the most significant financial burden [10]. Since, energy requirements represent the main limitation for large-scale application of EAOPs the focus has shifted to integrating renewable energy sources. In this sense, solar photovoltaic systems have been developed to allow the direct powering of electrochemical reactors with photovoltaic (PV) panels or PV–battery systems [11]. The direct use of electricity from the PV array to power the ECR could provide energy autonomy for solar EAOPs as it does not require any connection to the grid [12], [13]. In addition, the use of intermediate components for energy storage (batteries) is being investigated for achieving more efficient integrated technologie. Management of PV energy and storage (e.g., redox flow batteries) increases stability and treatment efficiency [14]. It is important to note that PV systems produce direct current (DC), which can be directly used by the EAOPs system.

Although it is still under development for optimization and further improvements, numerous results on independent, so-called "off-grid" PV modules that drive the electrochemical degradation of various organic pollutants at the laboratory/pilot level are readily available in the literature. Successful pilot and industrial-scale implementations exist in textile effluents, olive mill wastewater, hospital effluents, and municipal sewage [15], [16]. These cases show that scale-up is

feasible, but site-specific testing is essential due to variations in pollutant load and water chemistry.

Laboratory testing is a crucial step prior to any scale-up process, as it enables a realistic assessment of the applicability of AOPs depending on the contaminant type, water matrix composition, and intended process scale. To ensure practical relevance, experiments should be conducted in real water matrices and under the same conditions.

From a benchmarking perspective, laboratory experiments provide the basis for evaluating new solutions in terms of cost, energy efficiency, and reliability compared to established processes, supporting decisions on whether to proceed to demonstration or pilot scale. Since traditional scale-up is expensive and time-consuming, a structured three-step approach (theoretical application screening, lab-scale performance testing, and cost and energy comparison with a benchmark process) offers a systematic framework to develop scalable and industrially relevant AOPs [17].

Recent research on wastewater treatment highlights several practical insights for policymakers and plant operators when considering AOPs and EAOPs, more precisely PV-AOPs and PV-EAOPs. EAOPs show strong potential when combined with other conventional WWT methods (e.g., biological treatment). This hybrid approach reduces energy demand and improves biodegradability of effluents, enabling compliance with discharge limits even for persistent organic pollutants and pharmaceuticals [18], [19]. Therefore, it should avoid stand-alone deployment and instead plan for pre/post-treatment integration. Moreover, emerging approaches (e.g., solar STEP processes) enable synergies such as hydrogen production alongside wastewater treatment [6], [20]. These systems should consider not only as treatment units but also as strategic assets within circular economy models.

Energy cost remains a key barrier to the widespread application of these technologies. Studies consistently show that powering electrochemical systems with solar PV or hybrid solar-battery setups improves sustainability and reduces operating costs [3], [14]. Challenges also include electrode fouling, by-product formation, and the need for supporting electrolytes [7], [18]. Proactive maintenance, the selection of durable electrode materials, and process monitoring are critical managerial priorities.

Another important tool in the analysis of the sustainability of WWT systems, in addition to energy analysis, is life cycle assessment (LCA). This analysis can be used to assess resource consumption in a WWT plant and its overall impact on the environment from the very beginning (design and construction of the plant) until the end of the plant's operating life. There are several studies available in the literature on the application of LCA in AOPs for wastewater treatment [8], [21], [22], [23], [24], [25], which conclude that LCA is a useful tool to support decision-making by providing a detailed overview of environmental impacts.

In summary, practice-oriented insights emphasize combining processes, using renewable energy sources, relying on LCA for decision-making, and strategically considering local conditions and long-term benefits, especially regarding energy use and environmental impacts.

METHODOLOGY

The experimental part of the research consists of the EO process powered by electrical energy obtained from a PV array (PV-EO) for the removal of textile azo dye from synthetic wastewater (SWW) prepared in the laboratory. For the research purposes, two different reactors were used. The first reactor (ECR 1) with a smaller capacity was used to determine the key parameters for the EO process, and the second reactor with a larger capacity (ECR 2) was used to optimize the operating parameters. ECR 1, made of glass, had a capacity of 0.5 dm^3, and contained three electrodes of the same dimensions (6 x 5 x 0.2) cm. ECR 1 operates in batch mode. The ECR 2 made of acrylic has a capacity of 1.5 dm^3 of wastewater, with possibility of both batch and recirculating operation modes. The reactor contains eight electrodes (4 anodes and 4 cathodes) of the same dimensions (10 x 12.3 x 0,3) cm and distance between electrodes d=8 mm.

ECR 1 and ECR 2 were powered by electricity obtained from the monocrystalline silicon PV solar panel with a nominal power of 170W, a maximum current of 8.33 A, and a maximum voltage of 20.41 V (SolarFAM, Netherland). The panel was placed on the roof of the Faculty of Technology University of Banja Luka (at an angle of 45°, south oriented). Solar charge controller (MPPT) (SolarFAM, Netherland) was connected between PV and the 12 V battery (MK Powered, 12 V/74 Ah) to ensure that the maximum available electric energy was always drawn from solar cells. The battery was connected directly to output DC voltage regulator to control the current supply to the ECR. The experimental setup for PV-EO process in ECR 1 and ECR 2 is shown in Figure 1.

All experiments were performed at an ambient temperature (≈20°C) with initial SWW volume of 0.4 dm^3 in case ECR 1 and 1 dm^3 of batch and 1.5 dm^3 for recirculating operating mode, in case ECR 2. For the preparation of SWW, Bemacid Red E-TL (BR) dye (CHT GmbH, Germany) was used and sodium chloride, 99.5% NaCl (Lachner, Czech Republic) was added as a supporting electrolyte to increase electrical conductivity of SWW. The initial dye concentration was approximately 100 mg/L. The exact concentration before and after treatment was determined spectrophotometrically (PerkinElmer, LAMBDA 25).

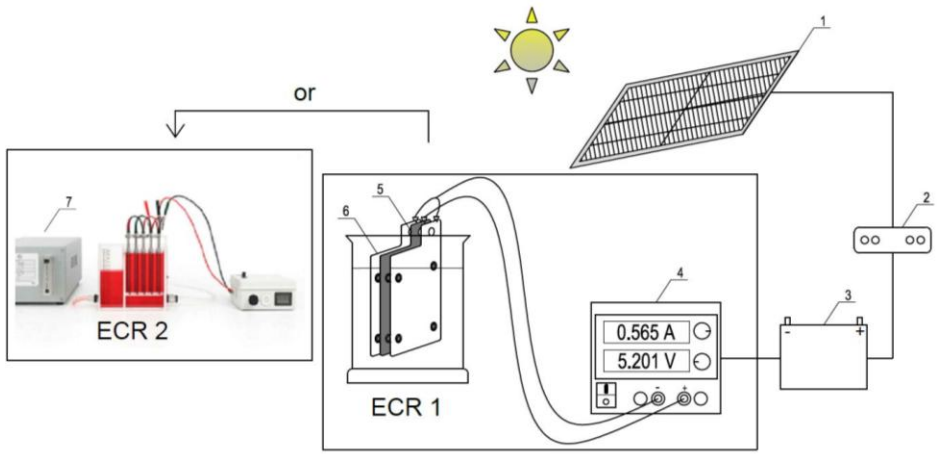

Figure 1. Scheme of PV-EO experimental setup (1- solar panel, 2- MPPT; 3- battery, 4- voltage and current regulator, 5- anode, 6- cathodes, 7- peristaltic pump)

As the electrodes in ECR 1, the following materials were used:

- stainless steel, EN 1.4301 (SS) and graphite felt (GF) were used as cathodes;
- mixed metal oxides (MMO) were used as anodes: Ru mixed oxide on Ti substrate coated with 6g Ru/m^2 (MMO 1) and Ir-Ru mixed oxide on Ti substrate coated with 6g Ru-Ir/m^2 (MMO 2), (Metakem, Germany);
- boron-doped diamond (BDD 1) (Metakem, Germany).

As the electrodes in ECR 2, the following materials were used:

- graphite felt (GF) cathodes;
- boron-doped diamond (BDD 2) anodes (YASA ET (Shanghai) Co., Ltd, China)

Before each experiment, the electrodes were appropriately cleaned depending on the type of material. Different combinations of anode–cathode pairs were placed in the ECR, connected to the output DC regulator, and the current density was adjusted to the desired value.

RESULTS

The results of BR removal from SWW by the PV-EO processes are expressed in terms of removal efficiency (E, %) and calculated according equation (1), where ci and cf are the initial and final concentrations of BR, expressed in mg/L.

$$E = \frac{c_i - c_f}{c_i} \cdot 100\% \quad (1)$$

When operating costs are estimated, in the literature they are most often expressed as the energy required to remove a certain mass of pollutant from the wastewater (kWh/kg of pollutant) or the energy required to treat a specific volume of wastewate (kWh/m^3). Specific energy consumption (W_{sp}) represents one of the most important technological indicators of ECR operation, because it affects the overall cost of treatment. W_{sp} is calculated according to equation (2), where I is current [A], U is voltage on the electrochemical reactor [V], t is the time [h], m is the mass of the removed pollutant [kg], and V is the volume of wastewater [m^3].

$$W_{sp} = \frac{U \cdot I \cdot t}{m_{pollutant}} \left[\frac{kWh}{kg_{pollutant}}\right] \quad \text{or} \quad W_{sp} = \frac{U \cdot I \cdot t}{V_{wastewater}} \left[\frac{kWh}{m^3}\right] \quad (2)$$

In this research, the impact of several important parameters on the efficiency of the EO process was examined, along with the simultaneous calculation of energy consumption. The first part of the research was carried out on a reactor of smaller dimensions (ECR 1), while the second part of the study represents a scale-up using a reactor of larger dimensions (ECR 2).

DISCUSION

The results of the research are presented into two parts. In the first part, the efficiency of PV-EO treatment in a smaller capacity reactor (ECR 1) is presented, while in the second part, the scale-up results are given in a larger capacity reactor (ECR 2).

Efficiency of BR degradation in ECR 1

The choice of anode material is of critical importance for the EO process, since OH· or other oxidizing species are formed on the anode surface. The nature of the anode material affects not only the efficiency of the process, but also the selectivity of the electrode reaction. The anodes used in EO can be classified as “active” and “inactive”. “Active anodes” (low oxygen evolution overpotential) are good electrocatalysts for oxygen evolution (e.g., IrO_2, Pt, RuO_2), and “inactive anodes” (high oxygen evolution overpotential) are poor electrocatalysts for the oxygen evolution [5]. Both active (MMO) and inactive (BDD) anodes were used in this research. The selection of the cathode material in the EO process refers to the selection of a stable, inert material that should prevent accumulation of impurities during the reduction of wastewater on the cathode surface. In the most research, stainless steel or different carbon materials are chosen as the cathode material [26]. Figure 2 shows the efficiency of different electrode pairs in BR degradation during EO treatment. Based on the obtained results shown in Figure 2, it can be observed that treatment is highly efficient, as high dye removal efficiency was achieved in a short time (5 min). The highest efficiency is shown by the BDD anode, while GF proved to be efficient compared to SS. In further research, the most efficient electrode pair was used: BDD - GF.

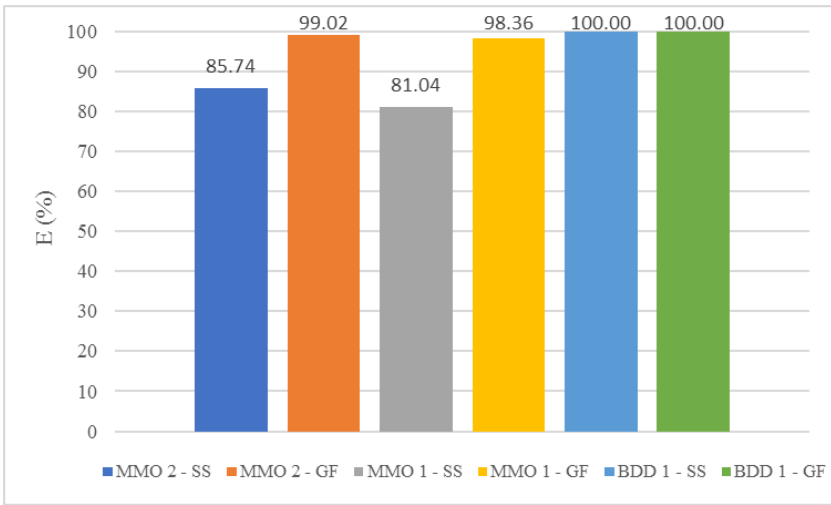

Figure 2. The impact of electrode material on BR dye removal efficiency (t= 5 min; j= 5 mA/cm^2; c_{NaCl}= 1 g/L)

In order to reduce the investment costs of the treatment, reducing the concentration of the supporting electrolyte was considered (Figure 3). Supporting electrolyte is necessary when the conductivity of the wastewater is low. Electrical conductivity is directly related to the voltage on the ECR. When the water conductivity is higher, the voltage on the ECR is lower and, consequently, Wsp is lower, in accordance with equation (2). NaCl was chosen as supporting electrolyte because it is readily available and inexpensive, but also because the generation of active chlorine and other reactive chlorine species (hypochlorite, hypochlorous acid) can occur via indirect oxidation [6], [7], [27]. In this way, in addition to the OH· formed in situ in ECR by the electrolysis of water, these reactive chlorine species enhance the rate of oxidation and the decomposition of organic pollutants in wate. From Figure 4, it can be seen that reducing the NaCl concentration decreases removal efficiency, requiring a longer time for complete dye removal.

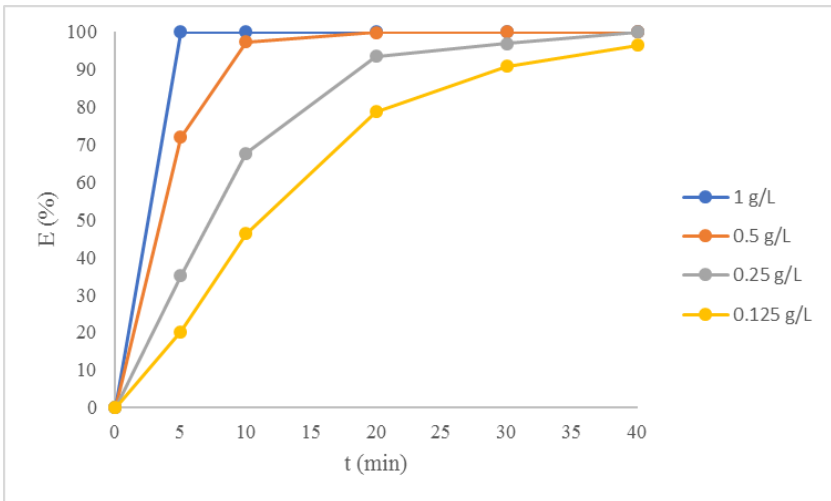

Figure 3. The impact of supporting electrolyte concentration on BR dye removal efficiency at different treatment time (BDD - GF electrode pair; j= 5 mA/cm^2)

As the concentration of supporting electrolyte decreases, the voltage on the ECR increases as expected, which consequently leads to an increase in energy consumption, according to equation (2). Table 1 shows the energy consumption for achieving more than 95% dye removal during the treatment at different concentrations of NaCl.

Table 1. Energy consumption at different concentrations of NaCl

NaCl concentration (g/L)	E (%)	Treatment time (min)	W_{sp} (kWh/kg)	W_{sp} (kWh/m^3)
1	100	5	1.15	0.26
0.5	97.33	10	4.62	1.05
0.25	100	40	17.13	4.00
0.125	96.5	40	20.55	4.20

In EAOPs powered by electricity from the distribution network, extending the treatment time is not desirable, because more energy is consumed, making the process more expensive. In that case, supporting electrolyte concentration is increased in order to reduce the voltage on the reactor and shorten the treatment time, thereby reducing the treatment cost. However, since in these experiments the ECR was supplied with electricity from a solar panel, it allowed the use of lower NaCl concentrations and longer treatment times. In this way, the cost related to the addition of supporting chemicals is reduced. For this reason, the supporting electrolyte concentration of 0.5 g/L for the continuation of the research.

Another important parameter that affects the efficiency of wastewater treatment and energy consumption is the current density. In general, the pollutant degradation rate or the efficiency of mineralization increases with increasing current density up to a certain optimal value. High current densities do not always enhance the oxidation rate or improve pollutant removal efficiency due to the occurrence of the oxygen evolution reaction and/or mass transport limitations. If the current density is above the optimal value it can also lead to an increase in the rate of the OH· consumption, resulting in higher energy consumption [28], [29]. The impact of current density (1.25, 2.5 and 5 mA/cm^2) on the dye removal efficiency by EO was shown in Figure 4.

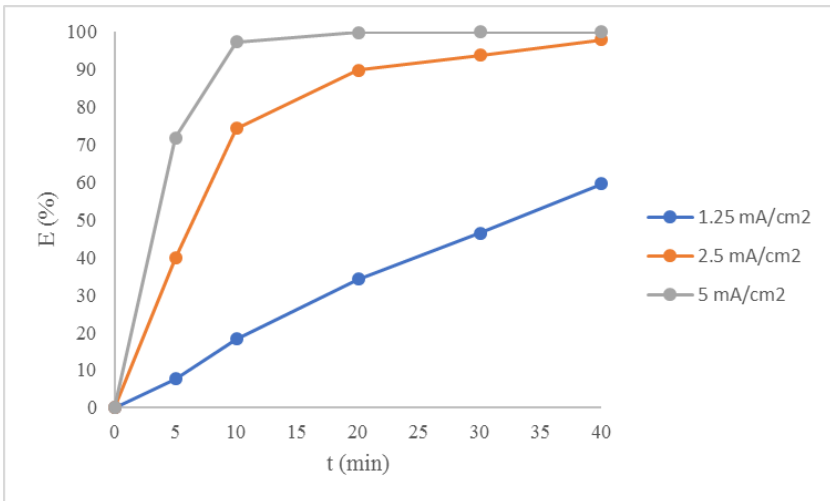

Figure 4. The impact of current density on BR dye removal efficiency at different treatment time (c_{NaCl}= 0.5 g/L; j= 2.5 mA/cm^2; BDD - GF electrode pair)

At higher current densities (2.5 and 5 mA/cm^2), differences in the achieved efficiencies are observed, but for 40 minutes of treatment, almost the same degradation efficiency is achieved. At the lowest tested current density (1.25 mA/cm^2) the process is significantly less efficient. Table 2 shows energy consumption during the treatment at different current densities.

Table 2. Energy consumption at different current densities

Current density (mA/cm^2)	E (%)	Treatment time (min)	W_{sp} (kWh/kg)	W_{sp} (kWh/m^3)
5	97.33	10	4.62	1.05
2.5	98.01	40	2.81	0.68
1.25	59.51	40	2.03	0.26

The current density of 2.5 mA/cm^2 was chosen for further research in ECR 2, because the energy consumption is almost half that at higher current densities, and the efficiency is still satisfactorily high for a relatively short EO treatment time.

Efficiency of BR degradation in ECR 2

After the most important parameters (electrode material, current density, supporting electrolyte concentration) were examined in the ECR 1 and the optimal conditions were selected, the research was continued with a scale-up using a larger-capacity reactor - ECR 2. The goal was to confirm the efficiency of the PV-EO treatment in ECR 2 under the experimental conditions previously selected in ECR 1

The ECR 2 reactor can operate in two modes: batch mode (BM) and recirculation mode (RM). When the reactor operates in BM, the maximum wastewater volume is 1 dm^3, and in RM, it is 1.5 dm^3. It was investigated whether the reactor operating mode affects the efficiency of BR dye removal (Figure 5).

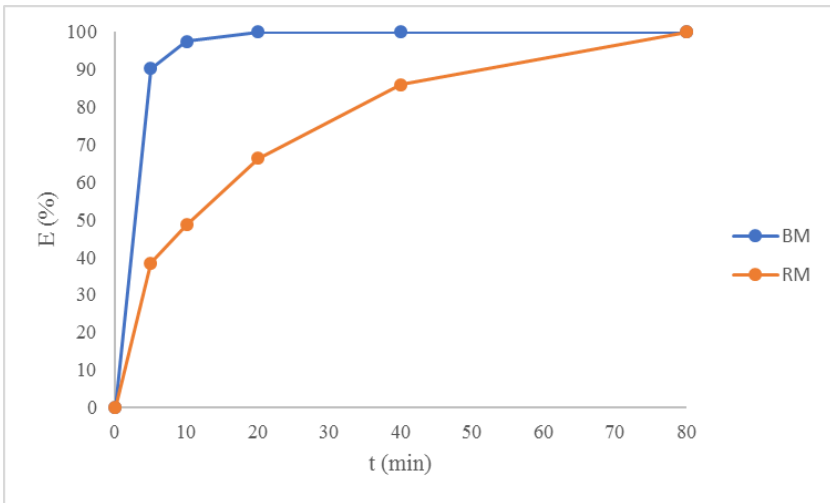

Figure 5. The impact of reactor operation mode on BR dye removal efficiency at different treatment time (BDD - GF electrode pair; c_{NaCl}= 0.5 g/L; j= 2.5 mA/cm^2; 50 dm^3/h flow for RM)

The experiment showed that efficient PV-EO treatment can be achieved in a larger reactor, with a larger amount of wastewater, using the process parameters previously selected as optimal in ECR 1. In ECR 2, 97.5% dye removal was achieved in 10 minutes, and 100% in 20 minutes,

compared to ECR 1 (Figure 4) where, under the same conditions, 98.0% dye removal was achieved in 40 minutes. More electrodes in the reactor results in faster dye degradation.

Based on the diagram shown in Figure 5, it is noticeable that the reactor operating mode has a significant impact on treatment efficiency, particularly at shorter treatment times. Complete (100%) dye removal is achieved in BM in 20 minutes, while in RM, 80 minutes of treatment were necessary for complete dye removal. The lower efficiency in RM is probably due to the shorter contact time with the electrode surface.

Table 3 shows the energy consumption for PV-EO treatment in ECR 1 and ECR 2 in batch operation mode, at c_{NaCl} = 0.5 g/L and j = 2.5 mA/cm^2.

Table 3. Comparison of energy consumption for ECR 1 and ECR 2

Reactor type	E (%)	Treatment time (min)	W_{sp} (kWh/kg)	W_{sp} (kWh/m^3)
ECR 1	98.01	40	2.81	0.68
ECR 2	97.47	10	15.32	1.28

Table 3 clearly shows that the energy consumption is higher in ECR 2, which is expected considering the larger wastewater volume, the greater number of electrodes in the reactor, and the larger electrode surface area.

In order to consider the industrialization of a process, it is useful to estimate the operating cost in terms of energy consumption (kWh/m^3) for treating 1 m^3 of wastewater [30]. The price of electricity varies from country to country. For example, in 2024 the electricity price for industrial use (non-household consumers) in Europe was between 0.0767 - 0.2578 € per kWh [31]. Treatment of 1 m^3 of wastewater containing BR dye as a pollutant, under experimentally determined treatment conditions (c_{NaCl}= 0.5 g/L, j= 2.5 mA/cm^2) costs between 0.098 – 0.323 € for 10 minutes of treatment. In accordance with equation (2), energy consumption can be calculated per 1 kg of removed pollutant. In this case, the energy consumption for removing 1 kg of BR dye under the specified conditions amounts to 1.17 – 3.94 €. This can still be considered as cost-effective, but it should be noted that some treatments could be significantly more expensive. For more polluted wastewater, the treatment would take longer, leading to higher energy consumption.

In order to use energy more efficient and further simplify the process, direct connection of the PV array to the ECR can be implemented, avoiding the use of storage battery systems. This clearly contributes to more efficient energy use (no energy losses in battery charge-discharge cycles) and reduces the investment and maintenance costs of the storage system. But, changes in the intensity of solar radiation during the day lead to significant energy fluctuations, so the ECR is powered by a variable energy source. This power profile can affect the performance and efficiency of WWT [32].

CONCLUSION

The results presented in this paper demonstrate that the degradation of the Bemacid Red E-TL textile dye can be efficiently performed by the electrooxidation process. Moreover, the electrochemical reactor can be powered by renewable energy from a solar panel, making the process efficient, sustainable, and cost-effective. By optimizing the process parameters, such as the concentration of the supporting electrolyte and the applied current density, the treatment duration can be controlled. Shorter treatments would require higher concentrations of supporting electrolyte and higher current density. In this regard, shorter treatments increase costs due to additional chemicals and higher energy requirements, while longer treatments reduce these costs but may shorten electrode lifetime. Process parameters need to be adjusted depending on the type and amount of treated wastewater. However, it can be concluded that EAOPs in combination with

green renewable energy sources have great potential for implementation and scaling up the process to a commercial level.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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INNOVATIVE APPROACH TO SAMPLING OF MICROPLASTICS IN THE MARINE ENVIRONMENT

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ABSTRACT

MARPOL Convention recognises various types of marine pollution, including oil, garbage, sewage, and greenhouse gases pollutions. Garbage-sourced microplastics (MPs), due to their small size and high resistance coupled with their chronic biological effects, pose a serious omnipresent environmental threat. This paper's research was motivated by the lack of methodology innovations in the field of sea environment monitoring and sampling of MPs.

Traditionally, microplastic sampling was conducted using big manta-ray nets, requiring deployment from motor-propelled vessels. Driving the question of possible usage of manta-ray net in combination with unmanned vehicles for a more economical, eco-friendly, flexible and precise approach. The innovative contribution of this research is highlighted through the design of a mini manta-ray net, successfully integrated on Remotely Operated Underwater Vehicles (ROV). Mini manta-ray was constructed in accordance with all relevant technical specifications using a special 300 micron net. First, the prototype was constructed for preliminary testing of structural integrity and stability. Based on experience and the results of preliminary prototype testing, the construction of the final product was used for our first MP sampling using an ROV. Sample of 1.5 liters of seawater obtained from the filtration of 5000 liters of seawater was then sent for laboratory analysis to evaluate system functionality under realistic operational conditions.

Practical testing confirmed stable and functional operational integration of mini manta-ray with ROV. From good water worthiness to positive results from laboratory analysis, indicating reliable sampling performance. The results show realistic functionality and potential for further improvements and optimization of the sampling of microplastics by ROV

Keywords: MARPOL Convention**,** Microplastics (MP), Innovative, Mini manta-ray net, Remotely Operated Underwater Vehicles (ROV).

INTRODUCTION

Oceans and seas are some of the most precious parts of our ecosystem. They are a source of life, food, resources, tourism, climate regulation and transport. However, marine pollution remains one of the major environmental challenges of modern society [1]. Their pollution and preservation are primarily regulated by the International Maritime Organisation (IMO) under the International Convention for the Prevention of Pollution from Ships (MARPOL) [2].

The International Convention for the Prevention of Pollution from Ships (MARPOL) recognizes the following types of pollution: Annex I Regulations for the Prevention of Pollution by Oil (entered into force 2 October 1983), Annex II Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk (entered into force 2 October 1983, provisions took effect from 6 April 1987), Annex III Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form (entered into force 1 July 1992), Annex IV Prevention of Pollution by Sewage from Ships (entered into force 27 September 2003) and Annex V Prevention of Pollution by Garbage from Ships (entered into force 31 December 1988), Annex VI Prevention of Air Pollution from Ships (entered into force 19 May 2005). For the purposes of this research, the most relevant is Annex V (pollution by garbage) as an emerging marine pollutant [3].

Driven by garbage pollution and the degradation of a wide variety of plastic and synthetic objects, including even sea buoys, microplastic pollution has become a widespread problem. Microplastics (MPs) include all plastic fragments smaller than 5 mm [4, 5]. The most common sources of MPs in today's aquatic ecosystems are wastewater treatment plants, fishing, shipping, landfills, illegal dumping, and industrial pollution [6, 7]. Their small size and high resistance make them a serious challenge for environmental protection and preservation, triggering chronic biological effects such as inflammation and affecting the growth and reproduction of organisms [8]. Microplastics are distributed throughout all water depths, from the surface to the seabed, where they attach to and are ingested by marine flora and fauna. In fish, one of the most commonly consumed seafood products, MPs can be found in the gills and even inside the stomach and intestines. However, the highest human intake of MPs through seafood is considered to occur from the consumption of bivalves, as they are eaten whole [9, 10]. An additional concern is that MPs can act as transport surfaces for other contaminants, such as heavy metals, resulting in coupled toxic effects [11, 12].

Today, there are highly diversified types of MPs that can be found in marine environments. Polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polystyrene (PS) are the dominant types due to their widespread use [13]. However, PE and PP are the most commonly found polymers in surface waters because of their lower density, whereas higher-density polymers, such as PVC, tend to sink and become part of the marine sediment [14].

Even today, there are still gaps in research on microplastics. From their movement and transport in our environment as well as their toxic and harmful effects caused by their accumulation. Even a lack of properly standardized sampling and analysis on a global level. Traditionally, they are sampled with manta-ray nets with 300- 350 μm mesh, with notable differences in results depending on the net's mesh size [15, 16]. Their concentration is calculated with the amount of filtered seawater that goes through the frame of the net based on a flow meter. That is then compared to the number of positive MPs found after laboratory analysis in the given sample, giving us X number of MPs per m^3 [17].

Despite the widespread application of conventional microplastic sampling methods, limited methodological innovation and optimization have been introduced in recent years. Traditional microplastic sampling is typically carried out using motor boats towing large manta-ray nets [14]. Although this approach provides reliable sampling results, it also has several limitations. Motor boats contribute to environmental pollution, are unsuitable for sampling in shallow waters, and provide limited manoeuvrability and positioning accuracy during sampling operations. The application of a Remotely Operated Vehicle (ROV) integrated with a compact manta-ray overcomes many of these limitations. Enabling sampling in shallow and difficult-to-access areas

while simplifying and making the sampling process more economically and environmentally sustainable.

Through the development, design and construction of an innovative manta-ray prototype, named *Mini*, surface water sampling was conducted. Sampling was performed using the *Mini* manta-ray integrated with the QY SEA *FIFISH W6* ROV. Sampling was carried out in the Boka Kotorska Bay in Montenegro. Development of the Mini manta-ray, acquisition of the ROV, and laboratory analysis of the collected sample were funded by MARROBO (Interreg IPA CBC Montenegro – Bosnia and Herzegovina, see Acknowledgement).

The sampling of surface water in a micro-location in front of the Maritime Faculty Kotor (PFK) involved filtering seawater through a *Mini* manta-ray that gave a sample of microplastics. Laboratory analysis of the collected sample provided feedback on the concentration of microplastics in surface water levels. Showing us data on area, perimeter, maximum Feret diameter, color distribution of collected microplastic particles, and indicated the level of local microplastic pollution. Results of sampling at depths of up to 10 cm gave us nearly average-level results regarding microplastic concentration in the Mediterranean Sea [18] and operational validation of the *Mini* manta ray prototype.

Grounded in prior research on microplastic particles, their sources, and associated pollutants, this study explores an innovative approach to microplastic particle sampling and the assessment of their concentrations in surface seawater. A laboratory-based analytical methodology was applied to determine the physical composition and characteristics of the collected water samples. The principal objective of this work is to establish a scientific foundation for a more efficient and modern sampling methodology for assessing environmental health based on microplastic concentrations. The study includes the design and construction of a specially optimized manta-ray microplastic sampler for integration with an ROV, followed by its practical validation through the analysis of the collected samples.

The present research has several limitations. A single sample was collected and analysed, representing a preliminary result. Requiring multiple samples for further validation as part of future research, together with a direct comparison with results obtained using traditional sampling methods.

The structure of the paper is organized into four main sections. The second section outlines the research methodology, detailing the data sources and analytical techniques employed. The third section presents the key findings and their interpretation. Finally, the fourth section provides concluding remarks and proposes directions for future research.

METHODOLOGY SECTION

This study follows a structured methodology for the development and evaluation of an innovative microplastic sampling system based on a new Mini Manta-Ray sampler integrated with a Remotely Operated Vehicle (ROV), can be seen in Figure 1. The research was motivated by the growing concern regarding microplastic pollution in the marine environment and the lack of innovative sampling methodologies capable of providing flexible, precise and environmentally sustainable monitoring solutions compared to traditional methods.

A summary of the research methodology is presented in Figure 2. The methodology included the design, fabrication and testing of two Mini Manta-Ray prototypes. The initial prototype was developed for preliminary assessment of structural integrity, hydrodynamic stability and operational compatibility with the ROV platform. Based on the results obtained during experimental testing, an improved prototype was constructed and integrated with the ROV for field sampling operations. Seawater samples were collected using a specially designed 300 μm sampling net and subsequently prepared for laboratory analysis to evaluate the functionality and effectiveness of the developed sampling system under realistic operational conditions.

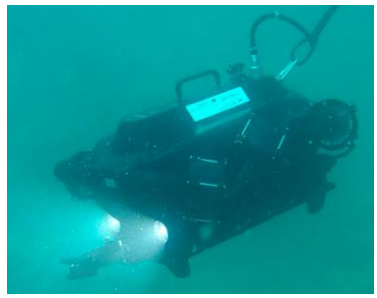

Figure 1. *FIFISH W6* ROV

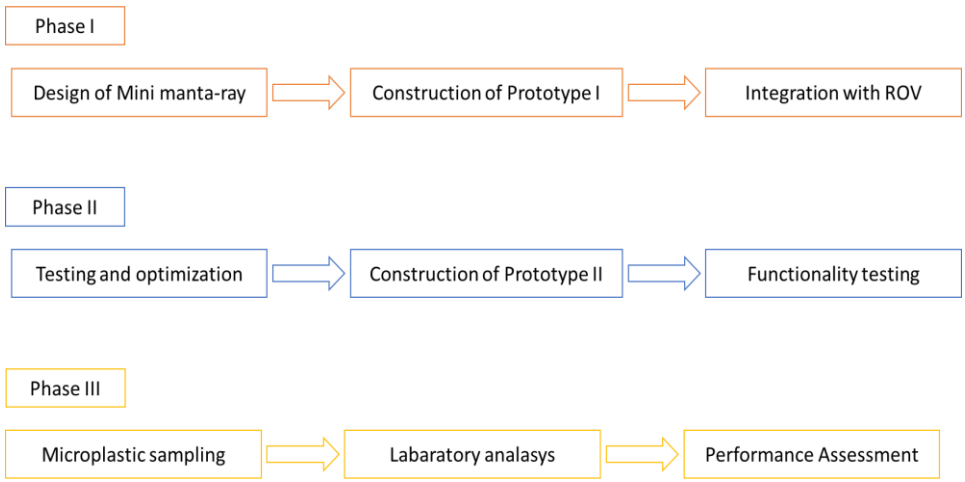

Figure 2. Research methodology summary

Phase I focused on the design and development of the Mini Manta-Ray sampling system. First was the conceptual design stage (Figure 3), followed by the construction of the prototype and its integration with the ROV platform (Figure 4) to assess structural compatibility and operational capability.

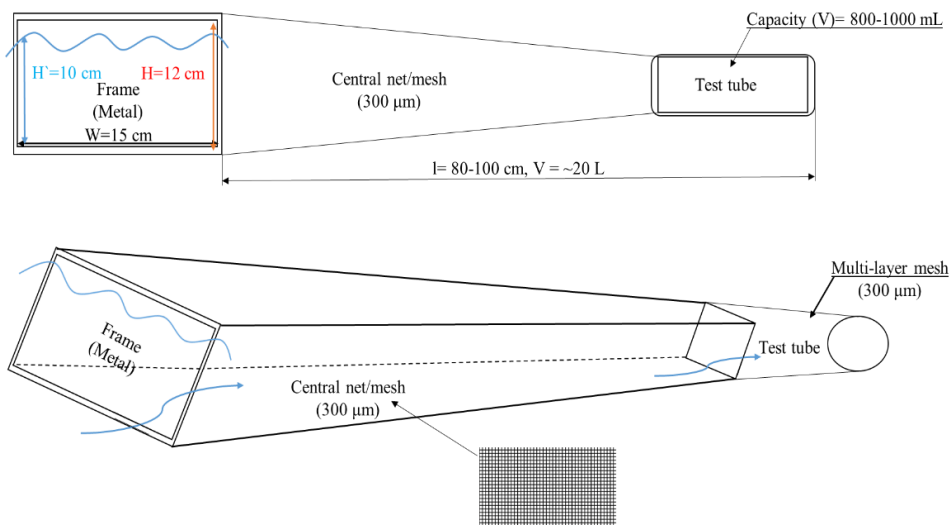

Figure 3. Conceptual design of *Mini* manta-ray



Figure 4. Construction of *Mini* manta-ray prototype I

Phase II involved testing of the initial prototype and optimization of the design based on gathered experience. Followed by the development of an improved Mini Manta-Ray design. With performance assessment of the improved Mini Manta-Ray (Prototype II).

Phase III consisted of the Mini Manta-Ray deployment with ROV *FIFISH W6* for microplastic sampling under real operating conditions (Figure 5). The gathered sample was then taken for laboratory analysis to provide a preliminary validation of this novel methodological approach to microplastic sampling.



Figure 5. Construction and deployment of *Mini Manta-Ray prototype* II for microplastic sampling

Database

A total of 5,000 L of seawater was filtered using the final prototype of the Mini Manta-Ray sampling system integrated on an ROV. Sampling was conducted in the waters surrounding the Faculty of Maritime Studies in Kotor, under relatively stable marine conditions and a seawater temperature of approximately 17 °C.

To estimate the volume of filtered seawater, the flow rate of the sampling system was calculated using the basic parameters presented in Figure 3. First, the opening area ($A = W \times H$) was determined using the opening width (W) and height (H). The estimated volumetric flow rate ($Q = A \times v$) was then calculated using the obtained opening area. Determination of the ROV travelling speed (v) represented the most challenging part, as a flow meter was not available. This limitation was addressed by measuring the time required for the ROV to travel between two predefined reference lines. The total volume of filtered seawater (Vfiltered) was then calculated by multiplying the volumetric flow rate (Q) by the sampling time (t). Although the calculated ROV speed was not 100% accurate, it provided a sufficiently reliable estimate for the purposes of the analysis.

Upon completion of the sampling procedure, the collection net was carefully retrieved and rinsed with fresh water to ensure the removal of all MPs and other potential particles into a sample bottle. The resulting concentrated sample of approximately 1.5 L was then preserved and sent to the Ruđer Bošković Institute in Croatia for laboratory analysis and identification of microplastic particles.

Methods

The collected sample was subjected to laboratory analysis at the Ruđer Bošković Institute. Potential microplastic particles were identified and quantified through visual examination using a stereomicroscope (Nikon SMZ745T, Figure 6). Particle identification was based on visible physical characteristics, including shape, colour, uniformity and the absence of recognizable biological structures.

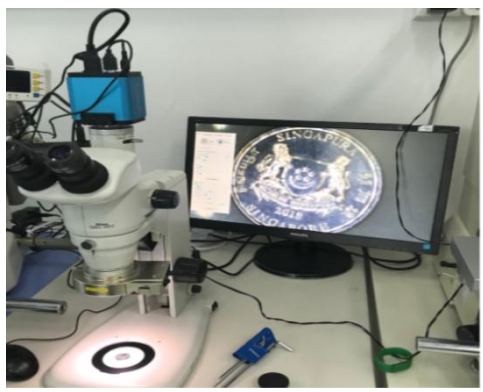

Figure 6. *Nikon SMZ745T*

Image acquisition and particle measurements were performed using *Image J/Fiji* software. Since no spectroscopic confirmation methods, such as FTIR or Raman spectroscopy, were applied, all detected particles were classified as putative microplastics. Therefore, the obtained results represent a preliminary assessment of microplastic presence and should be interpreted as visually identified plastic-like particles (putative microplastic particles) pending further analytical verification.

RESULTS AND DISCUSSION

From a single sampling site in the Kotor area, 5000 L of seawater was filtered with a mini manta-ray net, mesh size 300 μm. A total of 92 putative microplastic particles were identified by visual inspection from a 1,5 L freshwater sample.

The perimeter histogram for the Kotor sample (Figure 7) depicts a strongly right-skewed, unimodal distribution with the highest frequency in the 1–2 mm bin (61 putative particles, 66.3%). Nearly 97% of the putative microplastics have perimeters of 5 mm or less, while only one particle reaches the 20–50 mm range. This pattern reflects a sample dominated by putative microplastics with small-to-moderate perimeters, with a sparse tail of larger, likely elongated or fibrous outliers contributing to the high skewness, high kurtosis, and elevated mean observed in the descriptive statistics.

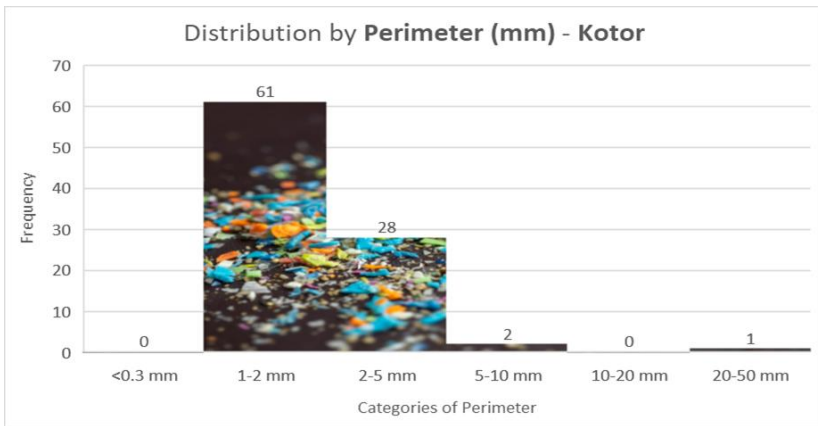

Figure 7. Perimeter histogram

The maximum Feret diameter histogram for the Kotor sample (Figure 8) shows a unimodal, right-skewed distribution with the highest frequency in the 0.5–1 mm bin (36 putative particles, 39.1%). The vast majority (98.9%) of putative microplastics are 2 mm or smaller in their longest dimension, with only one putative particle exceeding 2 mm and none larger than 3 mm. This pattern reflects a sample overwhelmingly composed of small putative microplastics, with moderate positive skew and leptokurtosis driven by a small number of larger outliers, consistent with the descriptive statistics for the Kotor location.

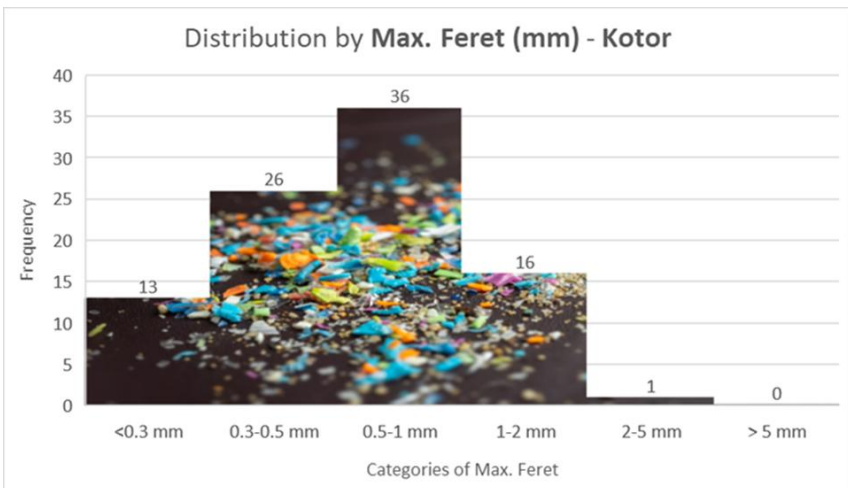

Figure 8. Feret diameter histogram

The area histogram for the Kotor sample (Figure 9) reveals an extremely skewed distribution in which 91 out of 92 putative particles (98.91%) are smaller than 0.5 mm², with only one particle in the 0.5–1 mm² bin and none larger. This pattern demonstrates a sample overwhelmingly dominated by very small putative microplastics, consistent with the low mean (0.04 mm²), median (0.02 mm²), and the strongly right-skewed, extremely leptokurtic distribution described in the summary statistics.

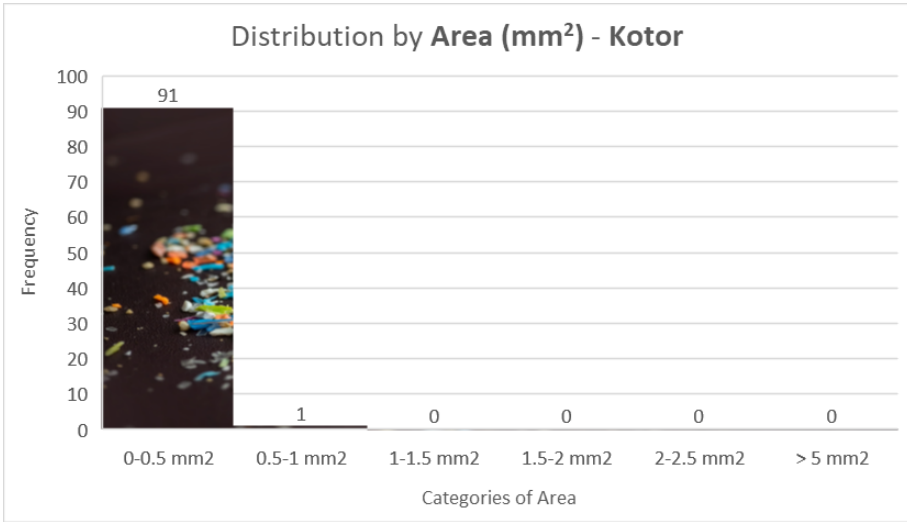

Figure 9. Distribution by area histogram

The color distribution in the Kotor sample (Histogram 10) is highly skewed, with black putative particles dominating overwhelmingly (86 putative particles, 93.5%). Red (4 putative particles, 4.3%) and blue (2 putative particles, 2.2%) appear in trace amounts, while all other colors are absent. This indicates an exceptionally uniform color profile dominated by black putative microplastics at the Kotor site. With a notable mention that 91 out of 92 were fiber-shaped particles, and only one filament.

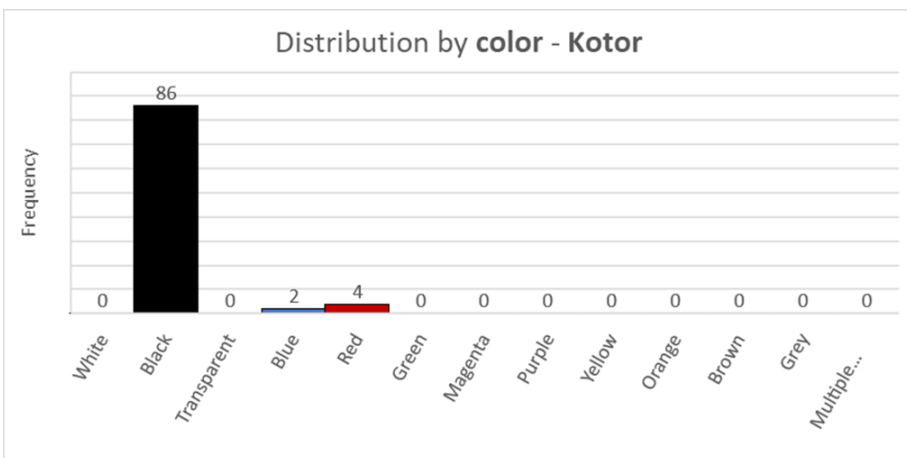

Figure 10. Distribution by color

The analysis of 92 putative microplastic particles collected from 5000 L of seawater in the Kotor area using a 300 µm mesh net reveals a highly uniform, fiber-dominated pollution profile characterized by very small particle sizes. The particles are overwhelmingly tiny, with 98.9% having an area below 0.5 mm² (median 0.02 mm²), a median maximum Feret diameter of 0.55 mm. Almost exclusively black colored and fiber-shaped.

CONCLUSION

The developed Mini Manta-Ray prototype successfully demonstrated its potential as an innovative microplastic sampling system integrated with an ROV platform and represents a preliminary result. Field testing and laboratory analysis confirmed its operational feasibility, sampling capability and potential as an alternative to conventional sampling methods. Future development of *Mini* manta-ray should focus on the integration of a flowmeter for accurate measurement of filtered water volume, as well as the integration of the sampler on a fully autonomous unmanned platform, enabling more efficient, cost-effective and large-scale environmental monitoring. While, at the research level, further validation should be based on a larger number of samples, supported by additional laboratory analyses and direct comparison with traditional sampling methods.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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AN ALGORITHM FOR IMPROVEMENT THE ACCURACY OF PHASOR ESTIMATION IN THE PRESENCE OF A DECAYING DC COMPONENT IN CURRENT SIGNAL

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ABSTRACT

This paper presents a novel and computationally efficient algorithm for improving the accuracy of phasor estimation in the presence of a decaying DC (DDC) component in current signals during transmission-line faults. In digital protective relays, the discrete Fourier transform (DFT) is widely used to estimate the phasor of the fundamental-frequency component. However, the presence of a DDC component in the current signal may introduce significant errors into the estimated phasor parameters. The proposed algorithm compensates for the DFT estimation error caused by the DDC component. The method consists of two stages. In the first stage, the fault-current samples are summed over a one-cycle data window, and the window is successively shifted by one sample to generate a sequence of summed values. In the second stage, a logarithmic transformation is employed to estimate the DDC parameters. The algorithm requires only $N + 4$ samples of the processed signal, where N samples correspond to one period of the fundamental component. In this framework, closed-form analytical expressions are derived for estimating the DDC parameters. The proposed method was evaluated using computer-generated signals, and the simulation results demonstrate strong robustness to noise and higher-order harmonics in the processed current signal.

Keywords: Phasor estimation, Fault current, DFT, Logarithmic transformation, DDC.

INTRODUCTION

Power systems are inherently exposed to fault conditions. Digital protective relays are therefore employed to ensure secure and dependable system operation, and their performance relies heavily on accurate phasor estimation of the fundamental and, in some applications, higher-order

harmonic components. Consequently, phasor estimation remains a key functional requirement in digital and numerical protection algorithms [1].

The principal performance criteria for phasor estimation algorithms are accuracy, response time, and computational complexity. During fault conditions, the measured current signal commonly contains a decaying DC (DDC) component superimposed on the periodic waveform. The presence of this component, together with harmonics and noise, substantially degrades the accuracy and convergence speed of phasor estimation algorithms. As a result, the operating speed and dependability of protection functions may be adversely affected [2].

A variety of digital signal-processing techniques have been employed for phasor estimation, including the discrete Fourier transform (DFT), discrete wavelet transform (DWT), least-squares (LS) methods, and artificial-intelligence-based approaches. Among these, the DFT remains the most widely used algorithm in digital and numerical relays. The DFT provides inherent selectivity with respect to harmonics, exhibits good robustness to white noise, has low computational complexity, converges rapidly, and is straightforward to implement. Nevertheless, because the DDC component is aperiodic and possesses a broad frequency spectrum, it introduces significant errors into DFT-based phasor estimates [3].

In continuous phasor estimation, the DDC component causes oscillatory behavior in the DFT output, making additional compensation techniques necessary in order to achieve the required accuracy and convergence speed [4].

The estimation and removal of the DDC component play a crucial role in DFT-based phasor estimation. Numerous methods have been proposed in the literature to improve the performance of DFT-based estimators under fault conditions. In general, these methods can be classified into two broad groups [5].

The first group is based on filtering the DDC component from the fault-current signal prior to phasor estimation. The DFT is then applied to the filtered signal. In [6], a digital mimic filter was proposed for eliminating the effect of the DDC component. However, complete compensation is achieved only when the actual DDC time constant is equal to the time constant assumed in the mimic filter design. In [7], a Kalman-filter-based approach was proposed for the same purpose, but accurate elimination again depends on the agreement between the actual DDC time constant and the time constant embedded in the state-transition model.

In the second group, the phasor is first estimated by means of the DFT, after which the error introduced by the DDC component is estimated and removed. In [8], the DDC-induced error in the phasor parameters is estimated and compensated using three consecutive phasors calculated by the DFT. Although the algorithm requires only $N + 2$ samples, its performance is sensitive to white noise. In [9], the DDC-induced error is estimated using the output of a second DFT filter tuned to the n-th harmonic; however, the method is also notably sensitive to white noise. In [10], the error introduced by the DDC component is estimated using the outputs of DFT filters applied separately to the even and odd subsets of samples.

In [11], three modified algorithms were proposed for correcting DFT errors caused by DDC components. In the first algorithm, the output of the sine filter is modeled as the sum of a sinusoidal component and a linear function, and the unknown model parameters are estimated by the least-squares method. In the second algorithm, all DDC components at the output of the sine filter are approximated by a single equivalent DDC for each sample index, and the corresponding parameters are then estimated using the Prony method. For this signal model, the Prony method provides efficient and noise-robust parameter estimation. In addition, analytical expressions were derived for the unknown parameters, leading to a computationally efficient implementation. In the third algorithm, the sine-filter output is first processed by a notch filter, which transforms the signal into a simpler form containing only DDC terms. These terms are then approximated by a single equivalent DDC, whose parameters are again estimated using the Prony method, resulting in even more compact analytical expressions.

Motivated by the need for fast and computationally efficient compensation methods, this paper proposes a novel algorithm for improving phasor estimation accuracy in the presence of a

decaying DC component in current signals during transmission-line faults. The proposed method compensates for the DFT estimation error caused by the DDC component in two stages:

- In the first stage, the fault-current samples are summed over a one-cycle data window, and the window is successively shifted by one sample to generate a sequence of summed values.
- In the second stage, a logarithmic transformation is applied to estimate the DDC parameters.

The algorithm requires only $N+4$ samples of the processed signal, where N samples correspond to one fundamental period. Within this framework, closed-form analytical expressions are derived for accurate estimation of the DDC parameters.

The key advantages and scientific contribution of the proposed algorithm, relative to the DFT-based methods published so far, are:

- **Robustness to random noise in the processed signal**, which is generally a weak point of previously published DFT-based methods. Because the DFT distributes a single-tone component across neighboring bins under spectral leakage, broadband random noise raises the noise floor in every bin and directly biases the amplitude and phase estimates; an algorithm that remains accurate under these conditions is therefore of clear practical value for real, noisy measurements.
- **Satisfactory accuracy when the frequency deviates from its nominal value.** This criterion is very rarely used to test algorithms in previously published work, precisely because the proposed algorithms tend to be sensitive to any mismatch between the actual signal frequency and the nominal frequency. Such a mismatch violates the coherent-sampling assumption (an integer number of periods within the analysis window), producing spectral leakage and the picket-fence effect; demonstrating accuracy under off-nominal frequency conditions is thus a demanding and meaningful test of robustness.
- **Robustness to multiple DDC.**
- **Computational simplicity and fast response time**, which makes the method well suited to real-time or embedded implementation, where a low operation count and short processing latency are often as important as the estimation accuracy itself.

PROPOSED ALGORITHM

Discrete Fourier Transform

Assuming that sinusoidal components above the $\left(\frac{N}{2}-1\right)$-th harmonic are sufficiently attenuated by a low-pass filter, the discrete fault-current signal measured by the protective relay can be expressed as:

$$i[n]=\sum_{j=1}^{N/2-1} A_j \cos\left(\frac{2\pi j}{N}n+\varphi_j\right)+D\,\mathrm{e}^{-\frac{nT_s}{\tau}}+e(n) \tag{1}$$

where τ and D denote the time constant and amplitude of the exponentially decaying DC component, respectively; A_j and φ_j represent the amplitude and phase angle of the j-th harmonic component; T_s is the sampling interval; and N is the number of samples per cycle. The phasor corresponding to the fundamental-frequency component is given by:

$$\begin{aligned} I_{RF}&=\frac{2}{N}\sum_{n=0}^{N-1} i[n]\cos\left(\frac{2\pi}{N}n\right)\\ I_{IF}&=\frac{2}{N}\sum_{n=0}^{N-1} i[n]\sin\left(\frac{2\pi}{N}n\right)\end{aligned} \tag{2}$$

where I_{RF} and I_{IF} denote the real and imaginary parts of the fundamental-frequency phasor, respectively. The DFT-based estimate of the phasor can be written as:

$$I_{RF} = A_1 \cos\left(\frac{2\pi}{N}k + \varphi_1\right) + D_{RF}$$
$$I_{IF} = -A_1 \sin\left(\frac{2\pi}{N}k + \varphi_1\right) + D_{IF} \tag{3}$$

where D_{RF} and D_{IF} represent the contributions of the decaying DC component to the real and imaginary parts of the estimated phasor, respectively.

$$D_{RF} = D\left(E^N - 1\right)\frac{E\cos\frac{2\pi}{N} - 1}{E^2 - 2E\cos\frac{2\pi}{N} + 1};\ E = e^{-\frac{T_S}{\tau}} \tag{4}$$

$$D_{IF} = D\left(E^N - 1\right)\frac{-E\sin\frac{2\pi}{N}}{E^2 - 2E\cos\frac{2\pi}{N} + 1};\ E = e^{-\frac{T_S}{\tau}} \tag{5}$$

Although the DFT is simple and computationally efficient, its estimate of the fundamental-frequency phasor is affected by errors introduced by the DDC component.

Estimation of DDC-Induced Errors in the Real and Imaginary Components of the Phasor

By summing the fault-current samples over a one-cycle data window, the following expression is obtained:

$$I_0 = \sum_{n=0}^{N-1} i[n] = \sum_{n=0}^{N-1}\left(\sum_{j=1}^{N/2-1} A_j \cos\left(\frac{2\pi j}{N}n + \varphi_j\right) + D\,\mathrm{e}^{-\frac{nT_s}{\tau}} + e(n)\right) \tag{6}$$

After simplification, the above expression can be written as:

$$I_0 = D\frac{E^N - 1}{E - 1};\ E = e^{-\frac{T_S}{\tau}} \tag{7}$$

By shifting the data window by an arbitrary number of samples, the following sequence is obtained:

$$I_0(k) = \sum_{n=0}^{N-1} i[n+k], \quad k = 0,1,\ldots,m \tag{8}$$

where *m* is the number of consecutive shifts of the data window.
After evaluation, this expression becomes:

$$I_0(k) = CE^k, \quad k = 0,1,\ldots,m \tag{9}$$

where *C* is given by:

$$C = D\frac{E^N - 1}{E - 1} \tag{10}$$

For each k in expression (9), a nonlinear relation is obtained between the unknowns *C, E* and the known $I_0(k)$. This yields an overdetermined nonlinear system of equations:

$$\begin{aligned} I_0[0] &= C \\ I_0[1] &= CE \\ &\vdots \\ I_0[m-1] &= CE^{m-1} \\ I_0[m] &= CE^{m} \end{aligned} \tag{11}$$

Each of the equations of the over-determined system (11) is nonlinear, of power-law form, with unknowns C and E. By taking the logarithm of each of these equations, a linear relation is obtained between the unknowns — which are now log C and log E — allowing the previous nonlinear problem to be solved by the simple method of linear regression, i.e. the least-squares method.

The resulting system can be solved by means of a logarithmic transformation. By applying the logarithm to each equation, the nonlinear system is converted into an overdetermined linear system:

$$\begin{aligned} \log C &= \log I_0[0], \\ \log C + \log E &= \log I_0[1], \\ &\vdots \\ \log C + (m-1)\log E &= \log I_0[m]. \end{aligned} \tag{12}$$

The above overdetermined linear system can be written in matrix form as:

$$\mathbf{A}\cdot\mathbf{X} = \mathbf{Y} \tag{13}$$

where

$$\mathrm{A} = \begin{pmatrix} 1 & 0 \\ 1 & 1 \\ \vdots & \vdots \\ 1 & m-1 \end{pmatrix}, \quad \mathrm{X} = \begin{pmatrix} \log C \\ \log E \end{pmatrix}, \quad \mathrm{Y} = \begin{pmatrix} \log I_0[0] \\ \log I_0[1] \\ \vdots \\ \log I_0[m] \end{pmatrix}. \tag{14}$$

By solving this system using the least-squares method, the following result is obtained:

$$\mathbf{X} = \left(\mathbf{A}^{T}\mathbf{A}\right)^{-1}\mathbf{A}^{T}\mathbf{Y} \tag{15}$$

After simplification, one obtains:

$$\begin{aligned} \log C &= \frac{2}{m(m+1)}\left((2m-1)\sum_{k=1}^{m}\log I_0[k] - 3\sum_{k=1}^{m}(k-1)\log I_0[k]\right) \\ \log E &= \frac{2}{m(m+1)}\left(-3\sum_{k=1}^{m}\log I_0[k] + \frac{6}{m-1}\sum_{k=1}^{m}(k-1)\log I_0[k]\right) \end{aligned} \tag{16}$$

By taking the antilogarithm of the above expressions, the parameters C and E are determined. The DDC-induced contributions to the real and imaginary components of the phasor can then be calculated as:

$$D_{IF} = -\frac{2\cdot C\cdot E\cdot(E-1)\sin\frac{2\pi}{N}}{N\cdot\left(E^2 - 2E\cos\frac{2\pi}{N} + 1\right)} \tag{17}$$

$$D_{RF} = -D_{IF}\frac{E\cos\frac{2\pi}{N}-1}{\sin\frac{2\pi}{N}} \tag{18}$$

Finally, the fundamental-frequency phasor is obtained from:

$$\begin{aligned} A_1 &= \sqrt{\left(I_{RF}-D_{RF}\right)^2+\left(I_{IF}-D_{IF}\right)^2} \\ \varphi_1 &= arctg\frac{-I_{IF}+D_{IF}}{I_{RF}-D_{RF}} \end{aligned} \tag{19}$$

PERFORMANCE EVALUATION OF THE PROPOSED ALGORITHM

To evaluate the performance of the proposed algorithm, several computer-generated test signals were considered under different operating conditions. For all examined signals, the following parameters were defined [5]:

- number of samples per cycle, $N = 32$
- fundamental frequency, $f = 50Hz$
- sampling frequency, $f_S = 1600Hz$
- DDC time constants, τ=0.01s and τ=0.1s
- magnitude of the fundamental component, $A_1 = 1\,p.u.$
- phase angle of the fundamental component, $\varphi_1 = 60^\circ$
- signal-to-noise ratio (SNR) $SNR = 40\ dB$ and $SNR = 20\ dB$.

The noise level relative to the useful signal is measured as the signal-to-noise ratio (SNR — Signal to Noise Ratio) and is expressed in dB (decibels):

$$\mathrm{SNR} = 20\log\frac{A}{\sqrt{2}\sigma} \tag{20}$$

In the above relation, A is the amplitude of the fundamental harmonic, and σ is its standard deviation.

To assess the accuracy and precision of the proposed algorithm in estimating the magnitude of the fundamental current phasor, the mean values and standard deviations of the estimated amplitude were calculated. For comparison, the same statistical measures were also determined for the conventional DFT method without DDC correction. All reported statistics were obtained from 200 simulation runs. The exact amplitude value was $A_1 = 1p.u.$.

Performance Evaluation Under Harmonic Distortion and Noise

To examine the robustness of the proposed algorithm in the presence of harmonic distortion and measurement noise, the following test signal was considered [5]:

$$i[n] = \sum_{j=1}^{N/2-1}\frac{A_j}{n}\cos\left(\frac{2\pi j}{N}n - n\varphi_j\right) + A_1\,\mathrm{e}^{-\frac{nT_s}{\tau}} + white\ \ random\ noise \tag{21}$$

During transmission-line faults, the decaying DC component appears in the fault current as a consequence of the inductive nature of the network. Its time constant typically ranges from 0.5 to 5 cycles. Therefore, two different values of the time constant were used to evaluate the performance of the proposed algorithm.

In the first case, the time constant was set to $\tau = 0,01s$. The corresponding fault current waveform is shown in Figure 1.

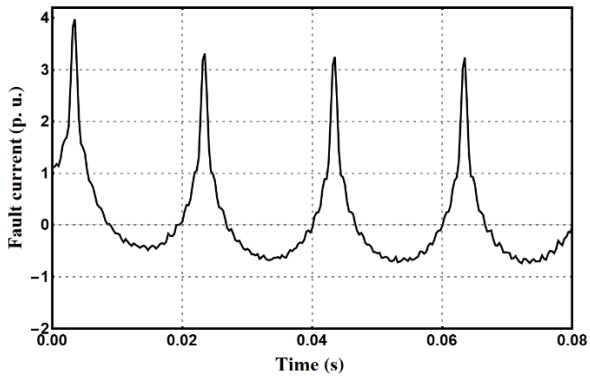

Figure 1. Fault current waveform for $\tau = 0,01s$

Table 1 lists the mean values and standard deviations obtained using the proposed algorithm, the DFT method without correction and algorithm proposed in reference [8].

Table 1. Mean values and standard deviations for the case in which the DDC time constant is set to $\tau = 0,01s$ **.**

Method	Criterion	SNR=20dB	SNR=40dB
Proposed algorithm	mean	0.999686	0.999919
	stand. dev.	0.0242654	0.0022948
DFT without correction	mean	1.27042	1.26941
	stand. dev.	0.0186295	0.0018004
Ref. [8]	mean	1.03498	1.00449
	stand. dev.	0.0266439	0,009898

In the second case, the time constant was set to $\tau = 0,1s$. The corresponding fault current waveform is shown in Figure 2.

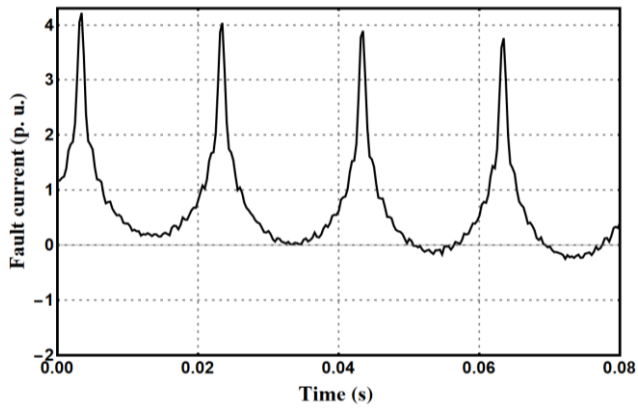

Figure 2. Fault current waveform for $\tau = 0,1s$

Table 2 lists the mean values and standard deviations obtained using the proposed algorithm , the DFT method without correction and algorithm proposed in reference **[8]**.

Table 2. Mean values and standard deviations for the case in which the DDC time constant is set to $\tau = 0,1s$ **.**

Method	Criterion	SNR=20dB	SNR=40dB
Proposed algorithm	mean	0.999167	0.999822
	stand. dev.	0.0229832	0.00221171
DFT without **correction**	mean	1.05458	1.05366
	stand. dev.	0.00170873	0.00184136
Ref. [8]	mean	1.03559	1.00485
	stand. dev.	0.028505	0.010106

The results in Tables 1 and 2 indicate that the proposed algorithm yields mean estimated amplitudes very close to the exact value under both noise levels and for both DDC time constants. In contrast, the conventional DFT method without correction exhibits substantial bias due to the presence of the DDC component.

Performance Evaluation in the Presence of Multiple Decaying DC Components

Current transformers (CTs) are commonly used to measure line currents in power systems. Under fault conditions, the CT secondary current may contain two exponentially decaying DC components, whereas the primary fault current typically contains only one such component. The additional DDC component arises from CT transient behavior and the burden connected to the secondary circuit.

To evaluate the influence of multiple DDC components on the performance of the proposed algorithm, the following test signal was used [5]:

$$i[n] = \sum_{j=1}^{N/2-1} \frac{A_j}{n} \cos\left(\frac{2\pi j}{N} n - n\varphi_j\right) + A_1 \mathrm{e}^{-\frac{nT_s}{\tau}} - 0,1A_1 \mathrm{e}^{-\frac{nT_s}{\tau_s}} + white\ \ random\ noise \quad (22)$$

Because the CT burden is usually small, the second DDC component decays slowly and is therefore characterized by a relatively large time constant. In this study, the time constant of the second DDC component was set to 20 cycles.

Table 3 presents the mean values and standard deviations for the proposed algorithm and the DFT method without correction when the time constant of the primary DDC component is set to $\tau = 0,01s$.

Table 3. Mean values and standard deviations for the case of multiple DDC components, with the primary DDC time constant set to $\tau = 0,01s$

Method	Criterion	SNR=20dB	SNR=40dB
Proposed algorithm	mean	0.99945	0.999655
	stand. dev.	0.020441	0.00220478
DFT without correction	mean	1.26874	1.26803
	stand. dev.	0.0170192	0.00187318
Ref. [8]	mean	1.03473	1.004446
	stand. dev.	0.025	0.01037

Table 4 presents the corresponding results when the time constant of the primary DDC component is set to $\tau = 0,1s$.

Table 4. Mean values and standard deviations for the case of multiple DDC components, with the primary DDC time constant set to $\tau = 0,1s$ **.**

Method	Criterion	SNR=20dB	SNR=40dB
Proposed algorithm	mean	0.999045	0.999632
	stand. dev.	0.023269	0.00224038
DFT without correction	mean	1.05233	1.05218
	stand. dev.	0.000179	0.001712
Ref. [8]	mean	1.08	1.00264
	stand. dev.	0.07716	0.004028

These results show that the proposed method preserves high estimation accuracy even when multiple DDC components are present, whereas the uncorrected DFT estimate remains significantly biased.

Performance Evaluation Under Off-Nominal Frequency Conditions

During transient conditions, the fundamental frequency may deviate from its nominal value, which may introduce both oscillatory and steady-state errors into phasor estimation. To evaluate the performance of the proposed algorithm under off-nominal frequency conditions, the test signal defined in the previous subsection was analyzed for frequencies of 49.5 Hz and 50.5 Hz [5].

Table 5 presents the mean values and standard deviations for the proposed algorithm and the DFT method without correction when the fundamental frequency is set to 49.5 Hz.

Table 5. Mean values and standard deviations for the case in which the fundamental frequency is 49.5 Hz.

Method	Criterion	SNR=20dB	SNR=40dB
Proposed algorithm	Mean	0.980717	0.981039
	stand. dev.	0.0250937	0.00242639
DFT without correction	Mean	1.27629	1.27618
	stand. dev.	0.016757	0.00184741
Ref. [8]	mean	1.0808	1.0225
	stand. dev.	0.06896	0.00851

Table 6 presents the corresponding results when the fundamental frequency is set to 50.5 Hz.

The results under off-nominal frequency conditions indicate that the proposed algorithm continues to outperform the conventional DFT without correction. Nevertheless, a small residual bias is observed, which is expected because the method is derived under nominal-frequency assumptions. This observation is consistent with recent literature, where frequency deviations remain a challenging condition for fixed-window DFT-based estimators.

Table 6. Mean values and standard deviations for the case in which the fundamental frequency is 50.5 Hz.

Method	criterion	SNR=20dB	SNR=40dB
Proposed algorithm	mean	1.02649	1.0259
	stand. dev.	0.023296	0.0024
DFT without correction	mean	1.26445	1.26251
	stand. dev.	0.017128	0.0016267
Ref. [8]	mean	1.11673	1.10318
	stand. dev.	0.091555	0.02006

CONCLUSIONS

This paper presented a novel DFT-based algorithm for improving phasor estimation accuracy in the presence of decaying DC components. The proposed method consists of two sequential processing stages. In the first stage, the fault-current samples are summed over a one-cycle data window, and the window is then successively shifted by one sample to generate a sequence used to estimate the DDC-induced error in the DFT output. In the second stage, the fundamental phasor is accurately determined by removing the estimated DDC contribution from the DFT result.

The simulation results demonstrate that the proposed algorithm provides:

- fast convergence,
- high robustness in the presence of harmonic distortion and noise,

- reliable performance when multiple DDC components are present in the fault-current signal, and
- satisfactory operation under off-nominal frequency conditions.

Because of its fast dynamic response, high estimation accuracy, and robustness under adverse operating conditions, the proposed algorithm appears well suited for real-time protection applications in electric power systems.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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UNDERGROUND COAL GASIFICATION: FROM CONCEPT TO COMMERCIAL APPLICATION

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ABSTRACT

Ensuring a reliable and sustainable energy supply represents one of the most critical environmental, economic and societal challenges of the 21st century. Despite the accelerated transition to renewable energy sources, fossil fuels- especially coal are expected to remain a significant energy component in the foreseeable future. Researches indicates a continued increase in coal demand, underscoring the necessity for more efficient, economically viable, and environmentally acceptable utilization technologies. Underground coal gasification has emerged as a promising in situ technology that enables the exploitation of deep, thin, or otherwise uneconomic coal seams that are not accessible through conventional mining technologies.

A lot of researches point to the potential advantages of UCG over traditional coal mining technologies, including higher recovery rates, reduced land degradation, improved economic performance, and potentially lower greenhouse gas emissions, especially when it is integrated with carbon capture and storage (CCS) technologies. This paper provides a comprehensive overview of the current state of UCG development globally, where we can critically analyze the technological maturity, its economic viability and environmental implications

Keywords: underground coal gasification, clean coal technology, CCS, ecology, coal

INTRODUSTION

Despite the global transition toward renewable energy sources, fossil fuels—particularly coal—are expected to continue playing an important role in the global energy mix over the coming decades. A significant proportion of the world's coal reserves are located at great depths, where conventional mining is technically challenging and economically unfeasible.

Coal extraction at depths exceeding 500 m is economically viable only under favorable geological conditions, while coal deposits located beneath the seabed or within complex geological structures are virtually inaccessible using conventional mining methods. It is estimated that more than 80% of global coal reserves are located under such conditions.

Global coal demand is projected to increase by approximately 20% by 2035, further emphasizing the need for more efficient and environmentally sustainable technologies for coal utilization. At the same time, coal remains one of the major sources of environmental pollution and contributes significantly to increasing atmospheric carbon dioxide (CO_2) concentrations. In this context, the application of Clean Coal Technologies (CCT) represents a key approach to balancing energy demand with environmental protection requirements.

Underground Coal Gasification (UCG), also referred to as *in-situ* coal gasification, is an alternative technology that enables the utilization of otherwise inaccessible coal resources by converting them directly underground into gaseous or liquid fuels. The concept of underground coal gasification is not new. As early as 1862, the renowned chemist Dmitri Mendeleev proposed that, in the future, coal would be burned underground and the resulting gas transported to the surface through pipelines. In 1867, the German scientist William Siemens was the first to publicly present the concept of underground coal combustion before the Society of Chemical Industry in London.

The basic principle of UCG involves drilling several boreholes into the coal seam. After ignition of the coal, one borehole is used to inject oxidizing agents such as air, oxygen, or steam into the gasification zone. The produced synthesis gas (syngas) is then transported to the surface through a second borehole, commonly referred to as the production well.

Table 1 Estimated coal stocks suitable for UCG [1]

Region/State	Coal supplies for underground coal gasification [billion tons]	Amount of gas from underground gasification of stocks [trillion m^3]	Current supplies of natural gas [trillion m^3]
USA	138,1	41,4	5,5
Europe (without Russia)	130,1	21,8	6,0
Russian Federation	87,9	26,3	47,8
China	64,1	19,2	2,4
India	51,8	15,5	1,1
South Africa	48,7	8,2	0,0
Australia	44,0	13,2	2,5
TOTAL	564,7	145,6	65,2

TECHNOLOGY OF UNDERGROUND COAL GASIFICATION

The Underground Coal Gasification (UCG) process consists of four main stages: drilling of boreholes, establishing a connection between the boreholes, initiating the combustion process (ignition), and coal gasification [2].

In its simplest configuration, a UCG system comprises two boreholes: an injection well through which gasification agents (air, oxygen, and/or steam) are injected into the coal seam, and a production well through which the generated synthesis gas (syngas) is extracted. With the advancement of UCG technology, three well configurations have become the most widely applied:

- Linked Vertical Wells (LVW);
- Controlled Retracting Injection Point (CRIP);
- Steeply Dipping Seams (SDS).

In the Linked Vertical Wells (LVW) configuration, the injection and production wells are drilled at a predetermined distance apart, both reaching the target coal seam. A permeable linkage is then established between the two wells, providing a continuous flow path for gases and enabling the uninterrupted gasification process.

The next stage is ignition, during which the coal seam is heated using a combustible gas–oxygen mixture activated by an appropriate ignition source. The duration of this stage depends on the geological and physicochemical characteristics of the coal seam, as well as on the selected operating parameters.

Once a stable combustion reaction has been established, the gasification stage begins. Air or oxygen, usually combined with steam, is continuously injected into the coal seam. Under high-temperature conditions, the coal is converted into synthesis gas (syngas), consisting primarily of hydrogen (H_2), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), and smaller quantities of other gaseous compounds. The produced syngas is transported to the surface through the production well and can subsequently be utilized for electricity generation, heat production, hydrogen production, synthetic fuels, or as a feedstock for the chemical industry.

As the gasification process progresses, the coal is gradually consumed, while the mineral residue (ash) accumulates at the bottom of the gasified zone, forming an underground void known as the **gasification cavity**. When this cavity expands to the production well, the contact between the injected gasification agents and the remaining coal decreases significantly, resulting in a reduction in both the quality and calorific value of the produced syngas. To maintain efficient gasification, the injection point is relocated to a new section of the coal seam, thereby extending the operational life of the gasifier and improving overall resource recovery.

After completion of the gasification process, the cavity is typically flushed with steam and/or water to reduce the concentration of residual contaminants within the coal seam. This post-gasification treatment helps minimize the migration of pollutants into surrounding groundwater aquifers and represents an important measure for environmental protection.

Chemical reactions in UCG

The ICG process occurs in three different zones: drying, pyrolysis and combustion and gasification of solid char.

In the drying zone, wet coal is heated and converted into dry coal by removing moisture attached to it. Upon further heating of coal, the pyrolysis reactions begin at temperatures around 350-400 °C, and coal loses its weight, generating volatile matters and the solid known as char [3].

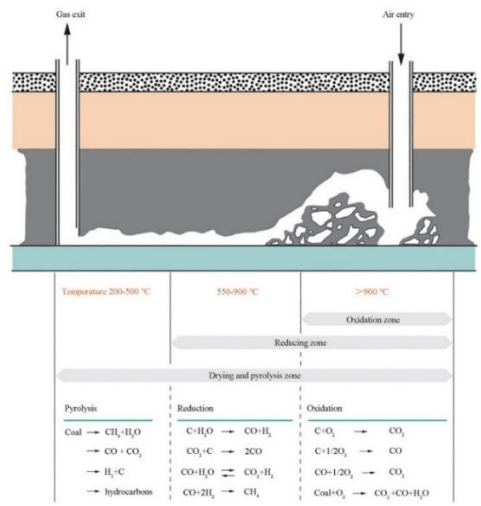

Fig. 1. Schematic of the significant events in underground coal gasification [4]

Finally, the char reacts with the injected/pyrolyzed gases to produce the syngas. The three essential types of char layer reactions which govern the UCG product gas composition are:

- oxidation;
- reduction;
- pyrolysis.

METHODOLOGY

This study was conducted using a comprehensive review methodology aimed at evaluating the historical development, technological progress, environmental performance, and commercial potential of underground coal gasification (UCG). The research is based on the systematic analysis of published scientific literature, technical reports, industrial case studies, and international energy publications. A qualitative comparative approach was adopted to identify the key technological advancements, operational experiences, economic performance, and environmental challenges associated with UCG implementation in different countries.

The review focuses on the evolution of UCG from early experimental projects to recent commercial-scale developments, providing an integrated assessment of its current technological maturity and future prospects.

The analysis included peer-reviewed journal articles indexed in Scopus and Web of Science databases, conference proceedings, books, technical reports, and publications issued by international organizations such as the International Energy Agency (IEA), United Nations Economic Commission for Europe (UNECE), and the International Panel on Climate Change (IPCC). Industrial reports published by companies involved in UCG development were also considered where relevant.

The literature covered publications from the early experimental period of underground coal gasification to the most recent developments published untill 2025.

The reviewed publications were selected according to the following criteria:

- relevance to underground coal gasification technology;
- availability of technical or operational data;
- description of pilot-scale or commercial UCG projects;
- information regarding geological conditions, gasification technologies, environmental impacts, and economic performance;
- publication in recognized scientific journals or by internationally recognized organizations.

Studies with insufficient technical information or duplicated data were excluded from the analysis.

A comparative analysis was performed to evaluate the development of underground coal gasification projects in different countries, including the former Soviet Union, the United States, Europe, Australia, China, and South Africa.

The comparison was based on the following evaluation parameters:

- geological conditions;
- coal seam depth;
- seam thickness;
- gasification agent;
- drilling technology;
- syngas composition;
- heating value;
- coal recovery;
- process efficiency;
- environmental performance;
- commercial applicability.

GLOBAL TECHNOLOGICAL DEVELOPMENT

Development of Underground Coal Gasification (UCG) Technology in USSR

The Soviet Union was the pioneer in the development of Underground Coal Gasification (UCG), conducting the world's first experimental UCG trials in 1933. Three initial experiments were carried out in the Moscow Basin, including two in lignite seams and one in anthracite, while two additional experiments were performed in the Donets Basin. At the Donbas coalfield, preparatory work began at the Gorlovskaya experimental station in 1933, and in 1935 the world's first successful underground coal gasification process was achieved.

The earliest experiments replicated the principles of conventional surface gasification technology by constructing underground mine workings and creating artificial fractures using explosives. The Gorlovskaya station represents the first stage in the development of UCG technology, which focused primarily on testing different gasification techniques and operational methods. During the second stage of development, research shifted towards achieving reliable and continuous underground gasification without prior mining preparation of the coal seam.

By the early 1940s, it had become evident that the construction of underground gasification chambers through conventional mining methods was economically expensive. Furthermore, maintaining gasifier sealing and ensuring stable gasification conditions proved technically challenging. Consequently, UCG development expanded to several major coal basins, including the Donets, Kuznetsk, Moscow, Dnieper, and Angren basins, where a total of five industrial-scale production stations and two experimental stations were established.

Air was the most commonly used gasification agent, while oxygen-enriched air was applied at the Lisichansk station in the Donets Basin. Approximately 25% of the generated heat was lost through the evaporation of formation water. Increasing the oxygen concentration helped maintain the high temperatures required for efficient gasification. Experiments were conducted under a wide range of geological conditions involving different coal types, seam thicknesses ranging from 0.8 to 22 m, depths between 30 and 350 m, ash contents from 2.3% to 34.3%, and calorific values between 7.95 and 30.64 MJ/kg.

Overall, approximately 14 million tons of coal were gasified, producing more than 40 billion Nm^3 of product gas. The syngas was utilized for electricity generation, district heating systems, and as a feedstock for the chemical industry. Depending on coal quality, gas yields varied between 1.5 and 5.5 Nm^3 per kilogram of coal gasified.

At the Moscow Basin station, filtration gasification and hydraulic fracturing techniques were successfully applied. The produced gas supplied the boiler plants of the city of Tula. After removal of sulphur compounds from the syngas, approximately 22,000 tons of elemental sulphur and 47,000 tons of sodium thiosulphate were recovered as valuable by-products. The station remained in continuous operation for 24 years before being closed in 1964 following depletion of the coal reserves.

The Yuzhno-Abinsk station was developed in steeply dipping bituminous coal seams (50–60°) with medium (1.8–3.0 m) and thick (8.0–9.0 m) seam thicknesses at a depth of approximately 350 m. The produced gas supplied industrial facilities located within a radius of 15–20 km around the city of Kiselyovsk. Maximum gas production reached approximately 70,000 Nm^3/h, while the highest annual production exceeded 450 million Nm^3, corresponding to the gasification of approximately 190,000 tons of coal.

Compressed air was injected at various operating pressures, including low pressure (approximately 25 bar), medium pressure (up to 80 bar), and high pressure (up to 500 bar). The produced gas reached temperatures of approximately 700°C upon arrival at the surface. Primary cooling was achieved within the production wells through water injection, after which the gas passed through cascade scrubbers where it was further cooled, cleaned of tar and dust, and stripped of excess steam depending on combustion-front conditions. The hydrogen concentration in the produced gas was approximately twice the normal level owing to the thermal decomposition of steam. During the operational lifetime of the station, three different underground gasifier

configurations were developed and tested, each demonstrating varying degrees of technical success.

Table. 2 Production results of underground gasification in the USSR stations

Parameter	Unit	Yuzhno-Abinsk	Podmoskovnaya	Angren
Years of operation	years	37	24	31
Operating period	year	1955–…	1940–1964	1961–…
Coal calorific value	MJ/kg	29.09	11.39	15.07
Coal type	–	Bituminous coal	Lignite	Lignite
Syngas calorific value	MJ/Nm³	4.19	3.35	3.52
Specific gas yield	Nm³/kg coal	4.9	2.3	3.0
Gasification efficiency	%	70	69	70
Gas composition				
Water vapour (H_2O)	%	0.02	1.2	0.4
Carbon dioxide (CO_2)	%	13.7	17.6	19.5
Higher hydrocarbons (C_2H_m)	%	0.2	0.2	0.3
Oxygen (O_2)	%	0.2	0.5	0.6
Hydrogen (H_2)	%	14.9	15.2	17.0
Carbon monoxide (CO)	%	11.8	6.0	5.4
Methane (CH_4)	%	2.7	1.5	2.0
Nitrogen (N_2)	%	56.48	57.8	54.8
Coal gasified	$\times 10^3$ t	2	5	6
Syngas produced	$\times 10^6$ Nm³	7	5	16
Coal recovery	%	50.3	29.4	62.2

The average annual operating parameters of the station were as follows:

- **Syngas production:** 280 million Nm³/year
- **Average calorific value of syngas:** 3.79 MJ/Nm³
- **Coal gasified:** 66,100 t/year
- **Coal recovery (gasification efficiency):** 43.4%
- **Actual-to-designed production capacity:** 56.0%

The Angren UCG station was developed for the gasification of thick lignite seams ranging from 6 to 20 m in thickness. The project demonstrated that syngas produced from underground coal gasification could be economically utilized for electricity generation in thermal power plants. The total proven coal reserves amounted to approximately 20 million tons, of which about 12 million tons were considered suitable for underground gasification. The coal seams were characterized by low groundwater saturation and low permeability.

Directional drilling technology was applied, with borehole lengths reaching up to 65 m. Well-linking operations required injection pressures ranging from 300 to 600 bar, whereas gasification itself was conducted at relatively low operating pressures of 20–60 bar. The maximum

annual gas production reached approximately 1.41 billion Nm³, corresponding to the gasification of about 600,000 t of lignite.

In 1981, energy costs accounted for approximately 34.5% of the total syngas production costs, while compressed air represented approximately 67% of the total energy consumption associated with the process.

The average annual operating parameters of the Angren station were as follows:

- **Syngas production:** 299 million Nm³/year
- **Average calorific value of syngas:** 2.89 MJ/Nm³
- **Coal gasified:** 102,000 t/year
- **Coal losses:** 25,400 t/year
- **Specific gas yield:** 2.96 Nm³/kg of coal gasified
- **Gas production per unit volume of injected air:** 1.18 Nm³/Nm³ of air
- **Gas losses relative to the theoretical yield:** 7.8%
- **Syngas not meeting quality specifications:** 23.4 million Nm³/year

Development of Underground Coal Gasification (UCG) Technology in North America

North America, particularly the United States and Canada, has played a role key in the scientific and technological development of Underground Coal Gasification (UCG). Unlike European research, which primarily focused on the application of UCG in deep coal deposits, the U.S. program was organized as a national research initiative aimed at developing different technological concepts, optimizing process parameters, and establishing the foundation for future commercial implementation.

Beginning of organized research

In the early 1970s, the U.S. Department of Energy established three specialized research programs, each dedicated to investigating a different category of coal deposits:

- Eastern coal deposits—thin seams (up to approximately 3 m), gently dipping, containing high-quality bituminous coal;
- Western coal deposits—thick sub-bituminous coal seams;
- Lignite deposits—with relatively low calorific value.
- This approach enabled the development of UCG technologies specifically adapted to different geological conditions and coal types.

MERC – Princetown research program

The Morgantown Energy Research Center (MERC) was responsible for research on eastern coal deposits. Two pilot projects were conducted at the Pricetown experimental site, with the most significant results achieved during the Pricetown II experiment.

Within this project, the Longwall Generator Concept was developed, inspired by the longwall underground mining method. The basic concept was based on allowing the gasification front to advance naturally along the coal seam, thereby increasing coal recovery. The connection between injection and production wells was established using directional drilling, significantly reducing the number of wells required while improving process control and roof stability. Despite the encouraging technical results, the program was terminated in 1983 following reductions in federal funding for fossil energy research

Lawrence Livermore Laboratory Program

In parallel with MERC, Lawrence Livermore Laboratory (LLL) initiated its own UCG research program in 1972. The primary objective was to develop an *in situ* gasification technology capable of producing medium-calorific-value syngas suitable for subsequent industrial processing.

The initial concept involved the use of controlled explosive charges to create highly permeable zones within deep coal seams. Later, additional techniques, including reverse combustion linking and directional drilling, were incorporated into the research program.

Three pilot tests were conducted at the Hoe Creek experimental site. During the third experiment, a system consisting of five vertical wells connected by a horizontal directional borehole within the coal seam was implemented. Although reverse combustion did not produce the expected results, oxygen-enriched air successfully established communication between the wells at an average propagation rate of approximately 44 m/day. Over a period of 47 days, approximately 3,900 t of coal were gasified, producing syngas with an average calorific value of 7.4 MJ/m³ and a composition of approximately 37% H_2, 11% CO, 5% CH_4, and 44% CO_2.

Hanna Experiments

The most comprehensive U.S. UCG research program was conducted by the Laramie Energy Research Center at the Hanna experimental site in Wyoming. Beginning in the mid-1970s, four successive field experiments significantly improved the understanding of underground coal gasification processes.

During the Hanna II experiment, researchers found that increasing the air injection rate had little influence on the composition or calorific value of the produced syngas. Instead, the position of the channel connecting the injection and production wells proved to be much more important, as it facilitated the continuous involvement of fresh coal within the reaction zone.

The third phase of the program investigated the influence of operating pressure. Lower operating pressures resulted in increased groundwater inflow, which reduced the calorific value of the produced syngas.

Hanna III, conducted in 1977, represented the first U.S. experiment specifically designed to investigate the environmental impact of UCG on groundwater systems. It also demonstrated that insufficient water availability within the reaction zone caused excessive temperature increases and a gradual deterioration of syngas quality.

The Hanna IV experiment evaluated larger spacing between injection and production wells together with the influence of injected air volume on the width of the reaction zone. Energy balance analyses indicated that approximately 66% of the coal energy was converted into syngas, about 18% remained underground, while the remaining energy was lost through heat transfer to the surrounding rock mass.

Rawlins – Gasification of Steeply Dipping Coal Seams

A separate direction of U.S. UCG research was represented by the Rawlins experiments conducted by Gulf Research and Development Company and TRW Systems Inc. in Wyoming. Their objective was to develop UCG technology for steeply dipping coal seams (>35°), which were considered uneconomic using conventional underground mining methods.

During the Rawlins I experiment (1979), approximately 980 t of coal were gasified over a 30-day period, producing syngas with an average calorific value of 5.6 MJ/m³. Approximately 80% of the coal energy was converted into gaseous products. The experiments also demonstrated that increasing operating pressure reduced the concentration of solid particles in the produced gas.

Even better results were obtained during Rawlins II (1981). Coal gasification rates exceeded 180 t/day, while syngas composition could be effectively controlled by adjusting the oxygen-to-steam ratio together with operating pressure. The produced syngas contained approximately 23% methane, and higher operating pressures further increased its calorific value.

The experiments demonstrated that the highest coal recovery (approximately 88%) was achieved using inclined injection wells drilled along the dip direction of the coal seam. They also confirmed that oxygen–steam mixtures are substantially more effective gasification agents than air because they produce medium-calorific-value syngas with higher hydrogen and methane contents and virtually no nitrogen dilution, resulting in significantly improved gas quality.

Modern Development of UCG in North America

Throughout the 1980s and early 1990s, the United States was the global leader in UCG research and development. However, the sharp decline in natural gas prices during the mid-1990s resulted in the termination of most research programs.

Interest in UCG re-emerged around 2005 when Lawrence Livermore National Laboratory (LLNL), with financial support from the U.S. Department of Energy (DOE), initiated a new generation of research focused on developing integrated three-dimensional numerical models for simulating underground gasifier growth. Modern modelling approaches integrate chemical reactions, geomechanics, heat transfer, groundwater flow, and fluid dynamics, allowing significantly more accurate simulation of the complete gasification process (Burton, 2007).

At the same time, private companies including Linc Energy, Carbon Energy, Laurus Energy, and Ergo Exergy initiated preparations for several commercial-scale pilot projects in Wyoming, North Dakota, Alaska, and Alberta. (Zamzow, 2010). Many of these projects were designed to integrate UCG with carbon capture and storage (CCS) technologies as well as Gas-to-Liquids (GTL) fuel production.

In Canada, the most significant project was the Swan Hills Synfuels pilot, conducted within the Manville coal formation at a depth of approximately 1,400 m, representing the deepest UCG field experiment performed worldwide. The project demonstrated that syngas with a calorific value of approximately 10 MJ/m³ could be successfully produced even at such depths, confirming the technical feasibility of deep underground coal gasification.

Current UCG research in North America is increasingly focused on integrating underground coal gasification with hydrogen production, synthetic liquid fuel production, and CCS technologies. Consequently, the knowledge and experience gained through U.S. and Canadian experimental programs constitute one of the most important scientific foundations for the future commercialization of underground coal gasification (Yang, 2016).

Development of Underground coal gasification technology in Europe

The development of Underground Coal Gasification (UCG) technology in Europe has been closely linked to global energy demand, the availability of fossil fuels, and advances in mining technology. Following the successful experiments conducted in the former Soviet Union, interest in this technology expanded to Western Europe, where intensive research began after the Second World War with the aim of utilizing deep and economically unmineable coal reserves.

The first European experimental investigations were carried out between 1944 and 1959 in Belgium, France, the United Kingdom, Italy, Poland, and Czechoslovakia. During this initial phase, experiments were mainly conducted in thin and relatively shallow coal seams, with access to the coal deposits provided through underground mine workings or a combination of underground workings and vertical boreholes. Air at low pressure (1.2–1.5 bar) was commonly used as the gasification agent, resulting in the production of low-calorific syngas with a heating value generally not exceeding 2.6 MJ/Nm³. The produced gas contained high concentrations of carbon dioxide and relatively low concentrations of carbon monoxide due to the limited interaction between the gasification agent and the coal seam. Coal recovery during this period rarely exceeded 50%.

The development of the technology was interrupted in the early 1960s due to the sharp decline in crude oil prices, which significantly reduced interest in alternative energy production technologies. A new wave of research began in 1974, immediately following the first global oil crisis, when the need to utilize domestic energy resources once again became a strategic priority.

During this new phase of development, European research focused on the gasification of deep hard coal seams, typically at depths exceeding 800 m. Unlike the earlier experiments, advanced technologies such as hydraulic fracturing, reverse combustion linking, and directional drilling were introduced. As a result, Western Europe became a leading region in the development of UCG for deep coal deposits, significantly surpassing the depths achieved in contemporary Soviet and U.S. experiments, which generally did not exceed 350 m.

The most significant European project of this period was the Belgian–German experiment at Thulin, initiated in 1978. The primary objective of the project was to demonstrate the feasibility of commercial UCG application under typical European geological conditions and to produce syngas suitable for electricity generation, fuel gas production, and chemical products such as methanol. The project also investigated the operational lifetime of the underground gasifier, the optimum gasification chamber width, and the efficiency of different gasification methods. In addition to field experiments, the project included laboratory investigations and mathematical modelling to improve the understanding of the physical and chemical processes occurring within the underground gasifier.

Between 1982 and 1984, several attempts were made to connect vertical process wells using the reverse combustion linking method in a coal seam approximately 1.5 m thick at a depth of 860 m. These experiments demonstrated that coal behaviour at great depths differs substantially from that observed in shallow deposits. High lithostatic pressure compressed the coal and significantly reduced its natural permeability, preventing the formation of the branched combustion front required for successful well linkage. Although a thermally altered (distilled) coal zone with improved permeability developed around the injection wells, this proved insufficient for successful application of the reverse combustion method.

Following the failure of reverse combustion linking, short-radius directional horizontal drilling was introduced in 1986, representing a major technological breakthrough. Combined with the injection of oxygen and water at high pressures (190–270 bar), this approach produced syngas with a calorific value ranging from 7.1 to 11.0 MJ/Nm³ and a methane content of 17–25.5%. Gas production rates reached 92–177 Nm³/h. During the experiments, approximately 8,638 t of coal were included within the gasification area, of which about 3,835 t were successfully gasified, corresponding to a coal recovery of 44.4%. The overall energy conversion efficiency from coal to syngas reached approximately 44.8%, with around 20% of the original coal energy converted into useful fuel gas, while the remainder was lost as ungasified coal or heat transferred to the surrounding rock.

The Thulin experiments demonstrated several important technical advantages. High injection pressures enabled the production of syngas with a relatively high methane concentration without significantly reducing its calorific value. Furthermore, oxygen and foamed water proved to be suitable gasification agents that could be compressed and transported using relatively simple equipment. It was also established that lateral expansion of the gasifier created a natural filtration zone composed of residual coal, preventing direct oxygen breakthrough into the production well and thereby avoiding combustion of the produced syngas.

Alongside the technical investigations, comprehensive economic assessments were conducted. These studies showed that the largest share of UCG investment costs was associated with drilling, well completion, and maintenance of the technological wells, whereas surface installations represented a considerably smaller proportion of the total capital investment. The analyses also indicated that drilling costs could be progressively reduced through operational experience, improved geological knowledge, and optimization of drilling procedures.

The European working group concluded that the most economically attractive application of UCG-derived syngas was electricity generation. For a power plant with an installed capacity of approximately 300 MW, the required investment was estimated at around 196 million ECU. Economic evaluations indicated that UCG could become competitive with conventional coal-fired power plants when applied to coal deposits at depths of approximately 1,000 m, with gasifier widths exceeding 30 m and a geometric recovery factor of about 0.75.

During the 1990s, UCG activities in Europe declined once again, mainly due to stabilized energy prices and the limited technological maturity of the process. Nevertheless, research activities did not cease completely. In Russia, efforts continued to improve gasifier designs and operating parameters, resulting in several patented technological innovations. In Ukraine, research continuity was maintained through the development of hydrogen production technologies based on syngas and active participation in European collaborative research programs.

Since the beginning of the twenty-first century, interest in UCG has increased again, largely driven by the need to reduce greenhouse gas emissions and improve the utilization of deep coal resources. Between 2007 and 2014, the European Union funded several major projects, including HUGE and HUGE2, involving Poland, Ukraine, and numerous European research institutions. These projects focused on hydrogen-rich syngas production, process modelling, groundwater impact assessment, operational safety, and the integration of UCG with carbon capture and storage (CCS) technologies. During the same period, Bulgaria conducted a comprehensive feasibility study for the application of UCG in the Dobrudzha coal deposit, while Hungary initiated activities aimed at constructing a pilot UCG facility in the Mecsek region [5].

The United Kingdom also renewed interest in offshore coal resources by issuing several exploration licences for potential UCG projects in coastal offshore areas [6].

Development of Underground coal gasification technology in Australia

Australia is one of the countries that achieved the greatest progress in the practical application of Underground Coal Gasification (UCG) technology during the early twenty-first century. From the late 1990s until 2012, the country became the world's leading demonstration site for UCG, with several pilot projects confirming both the technical feasibility of the technology and its potential for commercial deployment.

The development of UCG in Australia began with the Chinchilla project, located approximately 350 km west of Brisbane in the state of Queensland. Site selection commenced in November 1997, while construction activities were completed by the end of 1999, when syngas production also began. The pilot project officially operated from 1999 to 2003, although preparatory activities had started in 1997, and it is widely regarded as the largest Western demonstration project for underground coal gasification.

The UCG technology was developed through a collaboration between the Canadian company Ergo Exergy Technologies Inc. and the Australian company Linc Energy Ltd. Ergo Exergy provided the technological concept and engineering design of the underground gasifier, whereas Linc Energy was responsible for constructing and operating the demonstration facility. The project represented the first integrated application of UCG combined with technologies for electricity generation and synthetic liquid fuel production.

The long-term strategy envisioned two principal applications for the produced syngas: electricity generation using an Integrated Gasification Combined Cycle (IGCC) power plant and the production of liquid fuels through Fischer–Tropsch synthesis, commonly referred to as Gas-to-Liquids (GTL) technology.

To support these objectives, a syngas treatment and cleaning facility was constructed. After leaving the underground gasifier, the syngas was first cooled, allowing condensable liquid products to be separated for storage or further commercial processing. The gas was subsequently purified using sintered metal filters to remove particulate matter and other impurities, making it suitable for use in a gas turbine. In addition, a pilot-scale gas-cleaning unit was built to simulate the operating conditions of a future commercial plant.

Because of the specific geological characteristics of the Chinchilla coal deposit, particularly its relatively shallow depth and the higher permeability of the overlying strata, the produced syngas had to be compressed before entering the gas turbine. A gas compressor was therefore installed to increase the gas pressure to the required operating level. The separated process water was recycled for syngas cooling, compressor cooling, and as part of the water cycle intended for the future steam turbine. Studies indicated that in deeper coal seams or formations with lower permeability, the gasification process could operate at considerably higher pressures, thereby eliminating the need for additional gas compression.

The project also included plans for constructing a demonstration IGCC power plant with an installed capacity of 70 MW, intended to minimize initial capital investment while generating sufficient technical and economic data for future commercial development. The long-term

objective was to expand the facility gradually to approximately 400 MW, which was considered the optimum capacity for commercial operation.

During the experimental program, nine technological wells were drilled to gasify a coal seam approximately 10 m thick at a depth of about 140 m. Syngas production reached approximately 80,000 Nm^3/h, corresponding to an electricity generation potential of about 70 MW. Approximately 35,000 t of coal were gasified during the trials, producing more than 80 million Nm^3 of syngas with an outlet temperature of around 300°C. These results represented one of the most successful demonstrations of UCG worldwide and confirmed the possibility of stable and long-term process control.

Parallel to the activities of Linc Energy, Carbon Energy Ltd. developed its own underground coal gasification technology and constructed two experimental gasifiers. The produced syngas was successfully used to operate a 1 MW demonstration power plant, providing further evidence of the practical applicability of UCG for electricity generation [7].

During the same period, other companies, including Cougar Energy, also initiated the development of their own UCG projects. However, following environmental problems associated with the Kingaroy pilot project, comprehensive scientific investigations were undertaken to assess potential impacts on groundwater resources and the surrounding environment. As a consequence, the Government of Queensland introduced significantly stricter regulatory requirements for future UCG developments.

An independent scientific assessment of environmental risks was subsequently completed, after which every project developer was required to demonstrate the feasibility of safe underground gasifier closure and site rehabilitation (decommissioning) before obtaining approval for new UCG operations. Through these measures, Australia established one of the world's most stringent regulatory frameworks governing underground coal gasification.

Despite the introduction of stricter environmental regulations, Australia continued investing actively in carbon capture and storage (CCS) technologies. A particularly important initiative is the CarbonNet project in the state of Victoria, which aims to develop large-scale CO_2 storage infrastructure and facilitate the integration of UCG with greenhouse gas emission reduction technologies. Australia has also established active scientific collaboration with several European research institutions in the field of integrated UCG–CCS systems.

The experience gained from the Chinchilla project, together with other Australian demonstration projects, provides an important foundation for the modern development of underground coal gasification. These projects demonstrated that UCG can successfully operate under near-commercial conditions while simultaneously confirming that its long-term implementation requires rigorous environmental monitoring, an appropriate regulatory framework, and integration with carbon capture and storage technologies to minimize greenhouse gas emissions

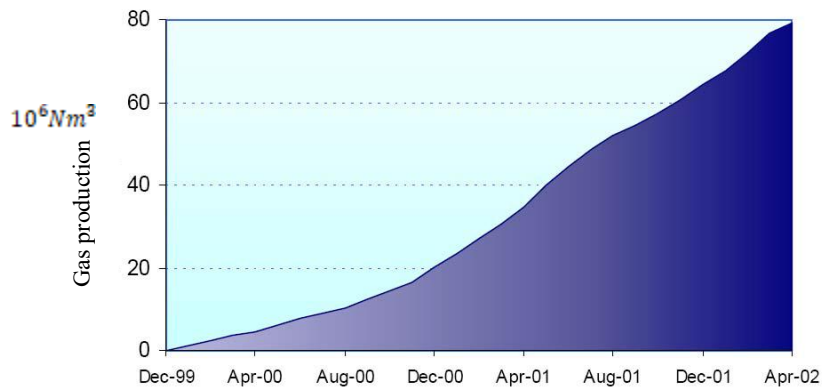

Fig. 2 History of production of gas in Chincila [8]

Development of Underground coal gasification technology in Asia

Asia is one of the regions with the greatest potential for the development and application of Underground Coal Gasification (UCG) technology, primarily due to its vast coal reserves and the increasing demand for cleaner energy technologies. The most significant progress in UCG development has been achieved in **China, India, and Pakistan**, where research has focused on the utilization of deep, inaccessible, and economically unmineable coal resources.

Development of UCG technology in China

China possesses one of the world's largest coal resource bases. Its proven coal reserves are estimated at approximately **114.5 billion tones**. However, due to the limitations of conventional mining methods, nearly **50%** of the country's coal resources are considered uneconomical for traditional extraction. This has been one of the principal drivers behind China's growing interest in Underground Coal Gasification as an alternative method for exploiting deep coal deposits.

Interest in UCG has also been stimulated by China's national strategy to reduce pollution associated with coal-fired power generation. UCG enables the production of synthesis gas (syngas) underground, potentially reducing the need for surface mining operations while providing improved control of environmental emissions.

To date, approximately **15 experimental UCG projects** have been implemented in China. A major contribution has been made by the **Underground Coal Gasification Research Centre** at the **China University of Mining and Technology – Beijing (CUMTB)**. The research center conducts theoretical studies, laboratory investigations, numerical modelling, and field-scale experiments aimed at optimizing the gasification process, improving process control, and evaluating environmental impacts.

In cooperation with the Chinese coal industry, CUMTB has played an active role in advancing the development and commercialization of UCG technology. Owing to the strategic importance of UCG, China has also sought to strengthen international collaboration with countries and organizations experienced in underground coal gasification.

One of the leading Chinese companies involved in UCG development is **ENN Group**, a subsidiary of **XinAo Group**, one of China's largest private energy companies. The company collaborates with CUMTB as well as with research institutions and industrial partners from Uzbekistan, the United States, Australia, South Africa, and the European Union to accelerate the development and commercial deployment of UCG technology.

In 2011, an important international partnership was established between the British company **Seamwell International Ltd.** and the **Chinese Energy Conservation and Environmental Protection Group (CECEP)**. The project proposed the underground gasification of approximately **6 million tonnes of coal annually** in the **Yi He coalfield** in Inner Mongolia, with the objective of generating approximately **1,000 MW** of electricity over a projected operating period of **25 years**. In addition, the Australian company **Carbon Energy Ltd.** developed a commercial UCG project in the **Haoqin coalfield** located in the **Xiwuqi region of Inner Mongolia**. The project was implemented through a **Technology License Agreement (TLA)** with **Zhengzhou Coal Industry Group Co. Ltd.**, under which Carbon Energy was selected as the exclusive technology partner for underground coal gasification in China [9].

Development of UCG technology in India

India, one of the world's largest producers and consumers of coal, has also shown considerable interest in the development of Underground Coal Gasification technology. Particular attention has been directed toward the utilization of lignite and coal deposits that cannot be economically extracted using conventional mining techniques.

In 2005, **Neyveli Lignite Corporation** launched a national UCG program supported by the **Ministry of Coal of India** to identify suitable locations for pilot UCG projects. The program included the selection of appropriate coal blocks, pilot-scale testing, and evaluation of the calorific value of the produced synthesis gas.

Subsequently, the **Central Mine Planning & Design Institute Limited (CMPDI)** prepared comprehensive geological and technical assessments for five potential UCG sites. To provide an independent technical evaluation, the **Skochinsky Institute of Mining (SIM)** of Russia was commissioned to review the project.
Among the investigated locations, the **Kasta Block** within the **Raniganj Coalfield** was identified as the most promising site, where exploration drilling was completed in preparation for a pilot UCG project. In addition, **Coal India Limited (CIL)** identified two further coal blocks suitable for future commercial UCG development: **Kaitha Block** and **Thesgora "C" Block** (Khads, 2007).

Development of UCG technology in Pakistan

In Pakistan, UCG development is closely associated with the enormous reserves of low-grade lignite located in the **Thar Coalfield**, one of the country's largest untapped energy resources.

In December 2009, the **Thar Coal and Energy Board (TCEB)** established a public–private partnership with international companies and research institutions from China, Germany, and South Africa to investigate the geological, hydrogeological, environmental, and social aspects of utilizing the Thar coal resources.

The primary objective of the program was to develop a production system capable of utilizing approximately **6.5 million tonnes of coal annually** and supporting the construction of power generation facilities with a capacity of approximately **1,200 MW**. In 2010, a UCG pilot project was initiated in **Block V of the Thar Coalfield**, where the reserves of low-grade lignite are estimated at approximately **1.4 billion tonnes** (Khurshid, 2011).

The project included the construction of two pilot power plants, each with a generating capacity of **5 MW**, with the long-term objective of producing approximately **8,000 MW** of electricity from the Thar coal resources. However, several technical challenges emerged during the construction and commissioning phases, particularly concerning:

- establishing a stable linkage between injection and production wells;
- groundwater inflow into the gasification zone;
- characterization of surrounding aquifers;
- controlled ignition and stabilization of the underground gasification process.

Despite these technical challenges, the project represents an important milestone in the development of UCG technology in South Asia and demonstrates the potential for utilizing extensive but otherwise inaccessible coal resources through advanced underground gasification technologies.

Table 3 Globally significant underground coal gasification tests (Perkins, Underground coal gasification-Part I: field demonstrations and process performance, 2018) (L. Jiang, 2022)

Country	Site	Startup year	Coal type	Technique	Injected gas	Seam depth(m)	Seam thickness(m)
Former	Lisichansk	1935	Bit.	SDB	Air	30	1
U.S.S.R.	Podmoskovna	1947	L	LVW	Air	55	3
	Yuzno-Abinskaja	1955	Bit.	SDB	Air	~100	3
	Shatskaya	1959	L	LVW	Air	50	2
	Angrenskaja	1961	L	LVW	Air	150	9
USA	Hanna I	1973	HVC	LVW	Air	120	9
	Hanna II	1975	HVC	LVW	Air	85	9
	Hanna III	1977	HVC	LVW	Air	85	9
	Hoe Creek I	1976	HVC	LVW	Air	40	8
	Hoe Creek IIA	1977	HVC	LVW	Air	40	8
	Hoe Creek IIB	1977	HVC	LVW	O_2/H_2O	40	8
	Hoe Creek IIIA	1979	HVC	LVW	Air	40	8
	Hoe Creek IIIB	1979	HVC	LVW	O_2/H_2O	40	8
	Pricetown I	1979	Bit.	LVW	Air	270	2
	Rawlins IA	1979	SB	SDB	Air	105	18
	Rawlins IB	1979	SB	SDB	O_2/H_2O	105	18
	Centralia A	1984	SBC	K-CRIP	O_2/H_2O	75	6
	Centralia B	1984	SBC	LVW	O_2/H_2O	75	6
	Rocky Mountain IA	1987	SB	K-CRIP	O_2/H_2O	110	7
	Rocky Mountain IB	1987	SB	LVW	O_2/H_2O	110	7
UK	Newman-Spinney P5	1949	SB	BH	Air	75	1
Belgium	Thulin	1986	A	LVW	Air	860	6
Spain	El Tremedal	1997	SB	L-CRIP	O_2/H_2O	580	2
Poland	Wieczorek	2014	SB	SM	Air, O_2, CO_2	464	5.5
China	Xinhe	1994	Bit.	LT	Air/Steam	80	3.5
	Liuzhuang	1996	HVC	LT	Air/Steam	100	3
	Xinwen	2000	HVC	LT	Air/Steam	100	1.8
	Feichang	2001	Bit.	LT	Air	90	1.5
	Xiyang	2001	A	LT	Air/Steam	190	6
Australia	Chinchilla G1	2000	SB	LVW	Air	132	10
	Chinchilla G3	2007	SB	LVW	Air	132	10
	Chinchilla G4	2009	SB	P-CRIP	Air	132	10
	Chinchilla G5	2011	SB	L-CRIP	Air&O_2/H_2O	132	5.5
	Bloodwood Ck, Panel 1	2009	SB	P-CRIP	Air&O_2/H_2O	200	9
	Bloodwood Ck, Panel 2	2011	SB	P-CRIP	Air	200	9
Canada	Swan Hills	2011	HVB	L-CRIP	O_2/H_2O	1400	4.5

Guide to symbols Coal type: L = lignite, SB = subbituminous, SBC = subbituminous C, Bit. = bituminous, HVB = high volatile bituminous B, A = Anthracite. Technique: LVW = linked vertical wells, CRIP = controlled retracting injecting point, L-CRIP = linear CRIP, P-CRIP = parallel CRIP, K-CRIP=Knife-edge CRIP, SDB = steeply dipping beds, BH = borehole method, LT = long tunnel, SM = shaft method.

Underground coal gasification in South Africa

South Africa is one of the African countries with considerable interest in the development and application of Underground Coal Gasification (UCG) technology, primarily due to its extensive coal reserves and the need to secure additional energy resources while reducing environmental impacts.

The first investigations into the application of UCG in South Africa were initiated by **Eskom**, one of the country's largest electricity producers. In 2007, Eskom commissioned a pilot UCG project adjacent to the **Majuba Power Station** in the Mpumalanga Province. The pilot plant was designed with a capacity of approximately **3 MW** to evaluate the technical feasibility of the gasification process and to assess the potential utilization of the produced synthesis gas (syngas) within the power generation sector.

In 2010, the syngas produced through the UCG process was successfully utilized for **co-firing with coal** at the Majuba Power Station, demonstrating the feasibility of integrating underground coal gasification with existing coal-fired power plants [10].

The **Majuba coal deposit** consists of bituminous coal seams ranging from **1.8 to 4.5 m** in thickness and located at depths of approximately **250–380 m**. These geological characteristics make the deposit well suited for UCG technology, particularly because they enable the exploitation of coal resources that are difficult or uneconomical to recover using conventional mining methods.

In addition to Eskom's activities, **Sasol Limited**, internationally recognized for its Coal-to-Liquids (CTL) technology, has investigated the potential application of UCG as a source of syngas for its Gas-to-Liquids (GTL) processes at the **Secunda** complex. Sasol and Eskom established a

collaborative initiative with an estimated value of approximately **ZAR 1 billion**, aiming to support the development and future commercialization of UCG technology in South Africa.

Besides the Eskom and Sasol initiatives, several other UCG projects have been considered across Africa. Among these are the Sub-Saharan Africa project developed through collaboration between **Linc Energy** and **Exxaro Resources**, as well as the **Theunissen Project**, initiated by **Africary Holdings Ltd.** These initiatives reflect the growing interest in evaluating UCG as a viable technology for the utilization of deep and otherwise inaccessible coal resources.

The experience gained in South Africa demonstrates that UCG technology has significant potential for exploiting deep and economically unmineable coal reserves, particularly in countries where coal remains a major component of the energy mix. However, the successful commercial deployment of the technology will depend on further improvements in process control, groundwater protection, environmental monitoring, and the implementation of robust regulatory frameworks that ensure safe and sustainable operation.



Figure 3. Worldwide underground coal gasification: a snapshot (Yang, Recent Development on Underground Coal Gasification and Subsequent CO2 Storage, 2016)

CHALLEMGES FOR THE COMMERCIALIZATION OF UNDERGROUND COAL GASIFICATION

Despite decades of development and significant technological progress, Underground Coal Gasification (UCG) has not yet achieved widespread commercial deployment. Recent studies indicate that the successful implementation of UCG depends not only on the technical feasibility of the process but also on its economic viability, environmental risk management, regulatory frameworks, and social acceptance [11].

In recent years, substantial improvements have been achieved in controlling the gasification process through the application of advanced numerical modelling, Computational Fluid Dynamics (CFD) simulations, Digital Twin technology, artificial intelligence, and real-time monitoring systems. These technologies enable better control of the combustion zone, a more stable syngas composition, higher energy efficiency, and improved utilization of coal resources. Furthermore, advances in directional drilling and modern well-linking technologies have significantly enhanced the reliability and controllability of the UCG process.

The greatest challenges to commercialization remain closely related to environmental protection. Particular attention is focused on the potential contamination of groundwater by organic compounds, phenols, benzene, polycyclic aromatic hydrocarbons (PAHs), and other gasification by-products, as well as on controlling land subsidence and preventing syngas migration into surrounding geological formations. Consequently, modern UCG projects incorporate continuous hydrogeological monitoring, geophysical surveys, three-dimensional

geomechanical modelling, and groundwater quality monitoring throughout the entire project life cycle [11].

Practical experience demonstrates that UCG is a highly site-specific technology. Therefore, selecting a suitable coal deposit is one of the most critical prerequisites for successful commercial operation. The assessment of coal seam suitability requires comprehensive evaluation of seam thickness and depth, physical and mechanical properties, structural and tectonic characteristics, hydrogeological conditions, surrounding rock permeability, and the potential risk of surface subsidence. Today, such assessments are increasingly performed using integrated geological–geomechanical models and multi-criteria decision-making methods.

An additional challenge is gaining public confidence and ensuring the social acceptance of the technology. The failures of several UCG projects in the past have highlighted the importance of transparent monitoring, well-defined regulatory frameworks, and continuous communication with local communities. Modern UCG development concepts are based on the principles of sustainable resource management, comprehensive risk assessment, and compliance with environmental regulations aimed at minimizing environmental impacts.

Economic viability represents another key factor influencing the future development of UCG. Syngas produced through underground coal gasification is no longer considered solely as a fuel for electricity generation but also as a valuable feedstock for the production of hydrogen, ammonia, methanol, synthetic liquid fuels, and other high-value chemical products. Particular emphasis is currently placed on integrating UCG with blue hydrogen production, carbon capture and storage (CCS), and low-carbon fuel technologies, which could substantially improve both the economic performance and environmental sustainability of the process.

In the future, the greatest potential for the commercial application of UCG is expected in countries possessing large reserves of deep, unmineable coal deposits and facing increasing demand for domestic energy resources, such as China, India, Australia, and South Africa. Nevertheless, broader commercialization will depend on the successful integration of advanced monitoring technologies, digitalization, risk management strategies, and greenhouse gas emission reduction technologies, together with the establishment of stable regulatory frameworks capable of enhancing investor confidence.

CONCLUSION

The analysis of the historical development of Underground Coal Gasification (UCG) demonstrates that, although the concept has been known for more than a century, significant technological progress has been achieved only during the last few decades, driven by advances in directional drilling, modern process control techniques, numerical modelling, and integration with advanced energy technologies.

The experience gained from the former Soviet Union, the United States, Europe, Australia, China, India, Pakistan, and South Africa confirms that UCG is a technically feasible technology capable of providing stable syngas production for applications such as electricity generation, hydrogen production, synthetic liquid fuels, and a wide range of chemical products. In particular, recent demonstration projects indicate that the technology is steadily progressing toward higher levels of technological maturity.

At the same time, the analysis shows that the commercialization of UCG continues to face significant challenges. The most critical issues include ensuring reliable control of the gasification process, protecting groundwater resources, controlling greenhouse gas emissions, managing the risk of surface subsidence, and establishing appropriate legal and regulatory frameworks. The economic viability of UCG projects depends largely on geological conditions, coal seam depth and thickness, coal quality, energy market prices, and the potential integration of UCG with hydrogen production and Carbon Capture and Storage (CCS) technologies.

Recent research indicates that integrating UCG with CCS, hydrogen production, and advanced digital modelling and real-time monitoring systems can significantly reduce CO_2 emissions while improving the overall energy efficiency of the process. In the context of the

global energy transition, UCG has the potential to serve as a transitional technology, enabling the more sustainable utilization of existing coal resources, particularly in countries with substantial reserves of deep and otherwise unmineable coal deposits.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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SEISMIC EFFECTS OF BLASTING AND THEIR INFLUENCE ON THE STABILITY OF SLOPES IN SURFACE MINES

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ABSTRACT

Blasting represents a fundamental technological operation in the surface exploitation of mineral resources; however, it also generates dynamic loads that can affect on the stability of bench slopes. During mass blasting operations in open pit mines, seismic vibrations are generated, leading to damage in the rock mass and the formation of secondary fractures that propagate into the depth of the rock massif. This process disturbs the equilibrium state of the rock mass and consequently affects the bench slopes. This paper analyzes the seismic effects of explosive blasting and their influence on the geomechanical stability of slopes in an open pit mines.

Keywords: blasting, seismic effects, seismic waves, slope stability, open pit mines.

INTRODUSTION

Surface mining of mineral resources is based on the systematic excavation of rock masses through the use of explosives. The increasing number of low-grade deposits, along with the growing demand for useful mineral resources, necessitates the use of larger quantities of explosives during blasting operations. As a rule, this approach yields greater economic efficiency compared to frequent blasting with smaller explosive charges.

However, blasting with large quantities of explosives generates stronger seismic vibrations, which may cause damage to mining facilities and affect the stability of bench slopes.

During blasting, in the initial phase, the explosive is transformed into a highly compressed gaseous state, followed by the expansion of these gases, during which potential energy is converted into mechanical work. This energy crushes the rock mass near the blast site, creates cracks and permanent deformations at greater distances, and further away it manifests as elastic deformation.

Seismic waves propagate through the medium as a result of this deformation transfer, causing oscillations of the ground and of all structures located on it.

The seismic oscillations induced by blasting are quite similar to those generated by earthquakes; therefore, many principles from seismology, as well as appropriate measuring instruments, can be applied for their analysis. The primary difference between these two phenomena lies in the duration and period of oscillations. In blasting, the duration of oscillations is significantly shorter, typically ranging from 0.004 to 0.25 seconds. There is also a difference in the range of represented frequencies, i.e. significantly a wider spectrum of frequencies is represented in the records of oscillations due to earthquakes in relation with blasting. In figure 1, three records of oscillations caused by blasting, nuclear explosion and earthquake are presented.

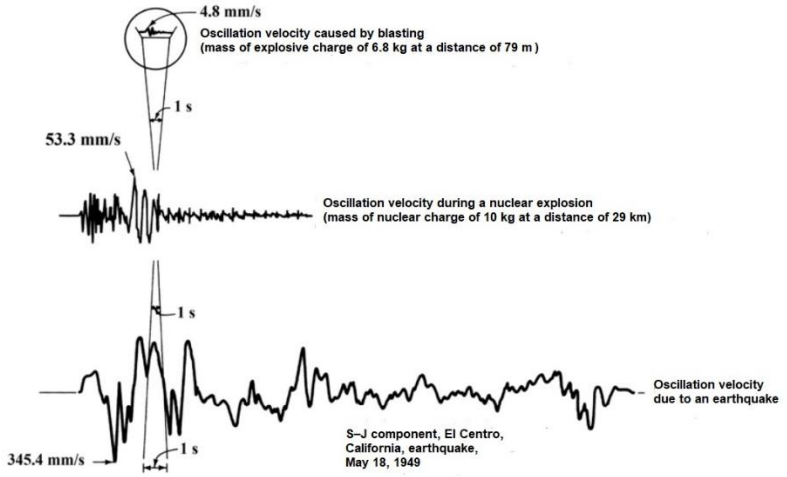

Figure 1. Comparison of records of oscillation velocities from blasting, nuclear explosion and earthquake [1] (Dowding, 1996)

The seismic effects of blasting are influenced by several factors, the most important being: the quantity of explosives used, the distance from the blast site, the type of explosive, the geometric distribution of energy within the blast field, the initiation method, geological and structural characteristics of the ground, and the condition of nearby structures.

Methods for monitoring the impact of blasting on slope stability can be classified into: simple methods, geodetic methods, and geophysical methods.

Simple methods involve visual observation of slopes in open pit mines, photographic documentation before and after blasting, high-speed camera recording immediately prior to blasting, inspection of rock masses along final contours through boreholes using optical instruments, and analysis of slope disturbance through drilling rate and water displacement from boreholes and fractures.

Geodetic methods enable the determination of deformations in working and final bench slopes during blasting. Bench profiles are established along the final contours of the open pit, both at the surface and at depth, where reference points (benchmarks) are installed. Using geodetic instruments, displacements are recorded and monitored.

Geophysical methods register oscillations of the rock mass in working and final slopes by monitoring particle velocity and acceleration within the ground. Stresses generated in the rock mass are measured using piezoelectric and pressure sensors installed in boreholes filled with water, gypsum, or other materials. In addition, acoustic methods are used to determine the degree of disturbance in working and final slopes. These methods evaluate the velocity of wave propagation through the rock mass and assess its degree of fracturing.

METHODOLOGY

The research presented in this paper is based on a combined approach that includes theoretical analysis, empirical relationships, and modern monitoring methods for seismic effects induced by explosive blasting in surface mines.

In the first phase, an analysis of the physical processes occurring during explosive detonation was conducted, with particular emphasis on the generation and propagation of seismic waves through the rock mass. Key factors influencing the intensity of seismic effects were examined, including the explosive charge, the distance from the blasting site, the geomechanical properties of the rock mass, and the initiation method.

In the second phase, empirical mathematical models were applied for quantitative assessment of seismic parameters, with special focus on:

- the relationship between oscillation amplitude, explosive charge, and distance;
- the Sadowski equation for determining the peak particle velocity (PPV);
- the evaluation of elastic and plastic deformation zones within the rock mass.

In the third phase, the influence of seismic waves on the stability of bench slopes was analyzed by defining critical values of particle velocity and correlating them with the degree of damage (cracking, sliding, and rockfall occurrences).

Additionally, several monitoring methods were applied to assess slope conditions:

- visual and observational methods,
- geodetic methods for displacement measurements,
- geophysical methods for recording vibrations and stresses,
- acoustic methods for evaluating rock mass fracturing.

Within the framework of modern research, the application of an alternative monitoring system based on audio recorders and DAQ technology was also analyzed. This system enables real-time acquisition and processing of seismic data. It includes the use of geophones, high-resolution analog-to-digital conversion, and a mobile platform suitable for field deployment.

By integrating theoretical models with experimental data, a comprehensive assessment of the dynamic impact of blasting on slope stability in surface mines was achieved.

INDUCED SEISMICITY DURING MINING

During blasting, shock elastic-plastic and elastic waves occur in rock masses. In the immediate vicinity of the borehole, during the blasting itself, the rock mass is destroyed. The distance at which elastic waves occur is given by the following empirical formula:

$$r = 0.12\sqrt[3]{Q}$$

Where:
r- distance where elastic deformations appear [m]
Q- explosive charge [kg]

In engineering practice, particularly from the perspective of blast-induced seismicity, special attention is given to the zone of elastic deformation, i.e., the zone through which seismic waves propagate. Compared to the crushing zone and the zone of permanent (plastic) deformations, this zone is significantly larger and may encompass a substantial volume of the rock mass.

Seismic waves generated during blasting, especially in cases of inadequately designed charging and initiation patterns, can be detected at distances of several tens of kilometers from the detonation site. This creates a potential risk front for the wider surroundings, including structures, infrastructure, bench slopes, and natural geostructures.

The relationship between the oscillation amplitude, the explosive charge per delay, and the distance of the observation point from the blast field is given by the following equation

:

$$A = 392.3\sqrt[3]{0.45 \cdot Q^2} \cdot (0.07e^{-0.00045r} + 0.001)$$

Where:

A- displacement amplitude [cm]
Q- explosive charge [kg]
r- distance from the blastingfield [m]

This equation is used for distance from 150 to 2000 meters.
The speed of oscillations at the observation site is given by the following Sadowskki formula:

$$V = K(\frac{\sqrt[3]{Q})^n}{r})$$

Where:

V- maximim particle oscillation speed [cm/s],
r- distance from the observation point to the blastingfield [m],
Q- amount of explosive charge [kg],
K- seismoacoustic constant determined by field measurement,
n- exponent determined by soil characteristics and blasting conditions and determined by field measurement.

The application of this dependence allows for a quantitative assessment of the seismic action of blasting and provides a basis for analyzing the dynamic stability of the slopes of open pit mines.

INFLUENCE OF SEISMIC WAVES ON THE STABILITY OF BENCH SLOPES IN OPEN PIT MINES

The propagation of seismic waves along bench slopes in open pit mines is fundamentally similar to their propagation through a rock mass with a horizontal free surface. However, due to the presence of an inclined free surface, certain additional physical phenomena occur, which significantly influence the attenuation and distribution of seismic energy.

In contrast to horizontally layered media, the existence of a slope introduces complex wave interactions, including reflection, refraction, diffraction, and mode conversion at the free surface. These processes lead to additional scattering and partial absorption of seismic energy, resulting in increased attenuation of vibration amplitudes along the slope. Furthermore, geometric spreading of waves becomes more pronounced due to the irregular topography, which additionally contributes to energy dissipation.

It is also important to note that local geological and structural conditions—such as discontinuities, joints, bedding planes, and faults—can further amplify or dampen seismic wave propagation. In some cases, these discontinuities may act as waveguides, facilitating the transmission of energy over greater distances, while in other cases they contribute to rapid attenuation. The particle velocity at the surface of a bench slope, which represents one of the most important parameters for evaluating the impact of blasting on slope stability, can be determined using the well-known Sadowski empirical relationship. This relationship establishes a correlation between the particle velocity, the explosive charge, and the distance from the detonation point, while also implicitly accounting for geological conditions.

For distance from 5 to 70 m from the blasting site and millisecond delay intervals of 15-50 ms, the following expression can be applied:

$$\boldsymbol{v} = \frac{\boldsymbol{k_1}}{\sqrt[3]{\boldsymbol{n}}} \cdot \sqrt{\frac{\boldsymbol{Q}}{\boldsymbol{L}}} \cdot \frac{\boldsymbol{e^{-0.032}}}{\boldsymbol{r}} (\frac{\boldsymbol{cm}}{\boldsymbol{s}})$$

Where:

κ_1- proportionality coefficient, which depends on rock properties; for hard rocks(f>14), it typically ranges from 300-700,

n- number of delay intervals in millisecond blasting,

Q- explosive charge per block (kg),

L- length of the blasted block (m) and

e- base of the natural logarithm

The value of particle velocity is directly related to the intensity of seismic loading acting on the slope. Higher velocities indicate stronger dynamic effects, which may lead to the initiation or propagation of fractures, reduction of shear strength along discontinuities, and ultimately to slope instability.

The relationship between particle oscillation, stress induced by seismic waves, and deformation of bench slopes can be more comprehensively expressed as a functional dependence on several key parameters

$$v = f(Q, r, C, \gamma)$$

Where:

C- velocity of wave propagation through the rock mass

γ- density of the rock (g/cm^3)

These parameters together define the acoustic impedance of the medium, which plays a crucial role in the transmission and reflection of seismic energy. A higher acoustic impedance generally results in more efficient transmission of seismic waves, thereby increasing their potencial impact on slope stability.

Numeous studies have shown that the extent of demage within the rock mass, particularly in working and final bench slopes, is strongly dependent on the explosive charge and the distance from the blast. This relationship is commonly expressed through empirical formulas derived from field observation. One such widely used expression is:

$$r_z = k_p \sqrt[3]{Q}$$

r_z- distance from the zone of complete crushing to the farthest extent of deep cracking (m)

k_p- proportionality coefficient, depent on geological conditions and blasting parameters

Q- explosive charge mass per delay (kg), considering one borehole in single row blasting and two boreholes in doble-row blasting.

Table 1.

Degree of rock fragility	Rocks		
	Easily blastable	Moderately blastable	Difficult to blast
Soft	2.0-1.0	1.2-0.6	0.7-0.2
Medium soft	1.3-0.8	0,7-0.2	0.25-0
Tough (hard)	0.8-0.6	0.4-0.1	0.1-0

According to N.I. Okhramenku, the size of the deep crack zone depends on the mass of the explosive charge per unit length of the block neing mined and the deceleration interval.

$$r_z = k_p \sqrt[3]{\frac{Q}{L}}$$

Where:

k_p- proportionality coefficient
Q- mass of explosive charge in the block (kg) and
L- length of the block being blasting (m).

Table 2.

Number of rows of boreholes	Proportionality coefficient depending on the deceleration interval					
	10	20	30	40	50	60
2	1.5	1.4	1.3	1.25	1.1	1.0
3	-	1.5	1.4	1.35	1.2	1.1
4	-	2.0	1.8	1.6	1.4	1.2

In existing empirical models, bench deformations are most often not directly correlated with the parameters of seismic waves. However, if the analysis incorporates the particle velocity at the slope surface, the acoustic properties of the rock mass, and the critical stress levels at which deformations occur, it becomes possible to establish a direct functional relationship between the parameters of the seismic wave and the degree of deformation of bench slopes in open pit mines.

By integrating these parameters, a more quantitative assessment of the dynamic impact of blasting can be achieved. In this context, slope deformations can be analyzed as a function of the intensity of ground motion, i.e., as a function of the amplitude and energy characteristics of seismic waves. The dependence of slope deformations on the degree of seismic excitation is shown in the following table no.3.

Table 3. Dependence of slope deformations on the degree of seismic excitation [2] (Mironov, 1973)

Degree of seismic excitation	Particle velocity cm/s	Possible consequences
6	2.7-5.5	Cracks in wet rocks up to 10 cm wide; isolated cases of sliding and rockfall from bench slopes
7	5.5-11.0	Minor cracks on dry slopes; numerous cracks on water-saturated surfaces; occasional sliding and rockfall from benches
8	11.0-22.0	Large number of cracks on bench slopes and in loose deposits; possible sliding and detachment of smaller rock fragments
9	22.0-42.0	Crack widths on bench slopes and in weak rocks reach up to 10 cm; possible sliding of isolated rock masses
10	42.0-75.0	In loose and highly saturated rocks, crack widths reach several decimeters; sliding in weak zones; possible rockfalls on steep bench sections along bedding planes
11	75.0-150.0	Formation of numerous cracks and fissures; vertical displacement of rock masses along bedding planes; rolling, sliding, and rockfall from bench slopes
12	>150 cm/s	Loss of integrity of hard rock masses in blocks and bench slopes; significant rockfall and large-scale sliding of slope sections

By knowing the dynamic limit values of the resistance of the rock mass under conditions of deep crack and fissure formation, it is possible to determine the critical particle velocity at which corresponding stresses are generated. The critical velocity is determined based on an appropriate analytical relationship that correlates the particle velocity with the dynamic strength characteristics and acoustic properties of the rock mass.

$$v_{kr} = \frac{2k_d \cdot \sigma_{pst}}{\gamma \cdot C}, cm/s$$

Where is:

K_d – coefficient of dynamic resitance,

Σ_{pst}- static stress limit in the rock mass (dN/cm^2),

γ- bulk density of the medium (g/cm^3)

The critical velocity represents the threshold value of the parameter (PPV) at which dynamic stress exceeds the elastic limit of the rock mass and transitions into the domain of plastic damage. Its determination enables a direct correlation between the parameters of the seismic wave and the degree of deformation of the bench slope,

ASSESSMENT OF THE EFFECT OF BLASTING ON BENCH SLOPES

The quantitative assessment of the influence of blasting on the stability of slopes in open pit mines can be carried out based on the intensity of seismic vibrations induced by blasting, under conditions that ensure the stability of working bench slopes.

Table 4. [3]

Degree of seismic excitation	5	6	7	8	9	10	11	12
Speed of oscilation	1.7-2.7	2.7=5.5	5.5-11	11-22	22-42	42-75	75-150	>150

The particle velocity at the surface of the slope mass is taken as the criterion for intensity. Based on equation (1), a graph of the intensity zone can be constructed as a function of explosive consumption, for rocks with a given bulk density and velocity of sound propagation in air.

CURRENT RESEARCH

Traditionally, seismometers and accelerometers have been widely used for monitoring seismic effects induced by blasting operations. Although these instruments provide reliable and valuable data regarding the characteristics of blasting events, they often offer limited insight into the broader risks associated with dynamic seismic wave propagation. Furthermore, conventional monitoring systems can be relatively expensive and require significant investment for installation, calibration, and maintenance.

In recent years, increasing attention has been directed toward the development and application of alternative technologies for seismic monitoring. One promising approach involves the use of audio records [4] (Skibic -Brzozowska, 2023) where advanced audio recording devices are capable of detecting frequencies below 20 Hz, which overlap with the frequency range of seismic waves generated by blasting activities, as well as natural seismic events that can extend below 1 Hz.

At the Faculty of Natural and technical sciences at University Goce Delcev in Stip, within the Department of surface mining and soil and rock mechanics, the geotechnology laboratory has developed a high-precision seismic data acquisition (DAQ) system for real time monitoring, processing and visualization [5] (Panov, Pekevski, & Popovski, 2023). The system is designed as a mobile, autonomous, and portable station, enabling seismic data collection at any location.

Through the analysis of seismic data obtained using audio recording systems, the research aims to improve existing monitoring practices, enhance safety, and contribute to the optimization of operational costs in mining processes [6] (Panov & Bikov, 2024).

Particular emphasis is placed on our prototype system, developed using the SBC Raspberry Pi 4, the high-precision ADS1263 AD HAT with an ultra-low-noise 32-bit analogue-to-digital (A/D) converter, and the EG-4.5-II geophone. The input range is ±2.5V, with the ability to amplify via a PGA, and sampling is done at 100 Hz [7] (Bikov, Panov, & Popovski, 2024).



Figure 2. Raspberry Pi 4, HAT ADS1263, and EG-4.5-II geophone [7] (Bikov, Panov, & Popovski, 2024)

Although the seismic data acquisition system has been successfully developed and implemented, the research is currently in the field testing and validation phase. The prototype has been deployed at several surface mines, where continuous seismic data acquisition is being carried out to evaluate its functionality, accuracy, and reliability under real mining conditions. Due to the ongoing stage of the research, a sufficient amount of experimental data has not yet been collected to perform a comprehensive quantitative analysis or to establish a direct comparison with conventional seismic monitoring methods. Nevertheless, the preliminary tests indicate that the system operates reliably and demonstrates significant potential for acquiring high-quality seismic records, providing a solid foundation for further research. The next phase of the study will focus on processing and analyzing the collected data, comparing the results with measurements obtained using standard seismological instruments, and evaluating the feasibility of the proposed system for practical application in monitoring blasting operations.

CONCLUSION

Based on the conducted analysis, it can be concluded that explosive blasting represents a significant source of induced seismicity that directly affects the stability of slopes in surface mines. The generated seismic waves cause dynamic stresses within the rock mass, which may lead to the formation of cracks, deformations, sliding, and rockfalls.

The intensity of these effects is directly dependent on the explosive charge, the distance from the blasting site, and the geomechanical characteristics of the rock mass. The application of empirical models, particularly the Sadowski relationship, enables reliable estimation of peak particle velocity (PPV) as a key parameter for risk assessment.

The analysis has shown that there are critical PPV values at which the rock mass transitions from elastic to plastic behavior, resulting in permanent damage and reduced slope stability. Therefore, defining these threshold values is essential for safe design and execution of blasting operations.

Furthermore, modern monitoring methods, especially the use of audio-based DAQ systems, represent an innovative and cost-effective solution for continuous seismic monitoring. These systems provide high precision, mobility, and real-time data analysis, significantly improving risk control and management.

By integrating conventional and modern monitoring approaches, a more efficient assessment of the dynamic effects of blasting can be achieved, contributing to improved safety, optimization of operational parameters, and sustainable management of surface mining operations.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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RESEARCH OF PROCEDURAL MODALITIES OF INVESTIGATING SAFETY INCIDENTS IN THE BUSINESS SYSTEM

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ABSTRACT

The goal of occupational safety is to protect employees from unfavorable working conditions in the working environment, i.e. from the consequences of the realization of the present dangers and harmful factors in the working environment, which are manifested in the form of injuries at work and occupational diseases. This is achieved by designing preventive measures for occupational safety in order to reduce to the smallest possible measure the risks for safety and health at work and by designing corrective measures for protection after the realization of incident situations. The choice and effectiveness of designing corrective measures in the field of occupational safety depends on the way of investigating incident situations and determining the cause, i.e. factors that led to the realization of such events.

This paper presents the research conducted in business entities of the region on the perception of the need to investigate incidents in the field of occupational safety, operational procedures for investigating such events, as well as possible consequences for the business system. Also, the factors that are the most common causes of incident events in the field of occupational safety were identified in order to improve the investigation procedures of these incidents through the design of corrective measures.

The improvement of the occupational safety system in the business system should go in the direction of building an adequate information system that will enable the monitoring of all relevant factors important for the occupational safety system. This approach should ensure a more efficient investigation of incidents in the field of occupational safety, identification of the causes of their occurrence, and the design of preventive and corrective measures. In conditions of accelerated development and use of information technologies and artificial intelligence in many areas, they also find their place in the field of occupational safety. The implementation of these technologies in occupational safety systems should contribute to the implementation and development of sustainable occupational safety systems, and within them new modalities of investigation of incident situations.

Keywords: occupational safety, incident situation, investigation.

INTRODUSTION

Occupational safety is a multidisciplinary and interdisciplinary scientific and professional field concerned with the study of the adverse effects of work and work processes on the safety and health of workers and, accordingly, with the design of appropriate protective measures. The implementation of occupational safety within a business system is achieved through the establishment and application of an occupational safety management system. Such a system constitutes an integral part of every business organization. Its functioning is ensured through the execution of processes and activities aimed at protecting workers in the workplace and the working environment. Occupational safety measures are designed to reduce the likelihood of risks arising from the presence of hazards and harmful factors in the working environment. The primary responsibility of the employer is to plan and organize the occupational safety system within the framework of business processes. This obligation is also regulated by occupational safety legislation. In all countries of the region, occupational safety regulations require employers to establish and maintain an effective occupational safety system. National legislative frameworks in the region are largely aligned with European legal standards, particularly those established by the general framework Directive 89/391/EEC, which lays down the fundamental principles for the introduction of measures aimed at improving the safety and health of workers at work [1]. The need for effective occupational safety management within business systems/organizations has led to the development of standards and best practice guidelines that provide recommendations for the protection of human resources through the enhancement of occupational safety and health. Standardization in the field of occupational safety management is primarily based on the implementation of the ISO 45001 standard. The ISO 45001 standard requires organizations that implement it to establish, apply, and maintain processes that include reporting, investigation, and corrective actions for the purpose of identifying, managing, and addressing incidents and nonconformities [2]. Processes related to incident response and the management of their consequences involve the implementation of appropriate measures and the effective control of resulting outcomes. Furthermore, the standard requires organizations to investigate incidents, determine their root causes, prevent their recurrence, implement corrective actions, and review risk assessments where necessary. It also emphasizes the involvement of all relevant stakeholders in these processes to ensure continuous improvement of the occupational safety management system.

In certain situations, despite the implementation of occupational safety measures, incident situations may still occur in the working environment. An incident is defined as an occurrence arising out of or in the course of work that could lead, or does lead, to injury or impairment of health [2]. The occurrence of incident situations, in order to fulfill the preventive role of occupational safety and reduce the likelihood of recurrence, requires a thorough investigation of such events. Incident investigation is a cause-and-effect activity because it is conducted after the occurrence of an undesirable event, which is subsequently analyzed and explained [3]. Furthermore, the investigation of occupational safety incidents is carried out with the objective of mitigating and remedying the consequences resulting from their occurrence. The consequences of

an accident or incident situation may manifest in various forms, including worker injuries, interruption of production and technological processes, and damage to material assets and natural resources [4].

The preventive role of the occupational safety system implies that the injury itself is of secondary importance, while the primary objective is to identify its causes in order to undertake appropriate preventive and corrective actions. The causes of occupational injuries are generally classified into two groups, although this classification is relative due to the complex interactions among these factors:

- causes in which the so-called subjective factor (human factor) predominates, relating to the characteristics and behavior of the worker;
- objective causes related to the level and duration of exposure to hazards and harmful factors, i.e., factors associated with the working environment, workplace conditions, and social environment [5].

Identifying the actual causes of incident situations or occupational injuries is often challenging because some factors that appear to be significant may not be the true causes. Instead, the underlying causes are frequently hidden due to insufficient expertise, lack of thorough analysis, subjective judgment by investigators, or because the injured worker and other individuals involved in the incident failed to provide relevant and accurate information. The procedure for investigating the hidden causes of occupational incidents and accidents involves the analysis of four key elements within the working environment – organization, workplace, human factors, and safety measures – as illustrated in Figure 1.

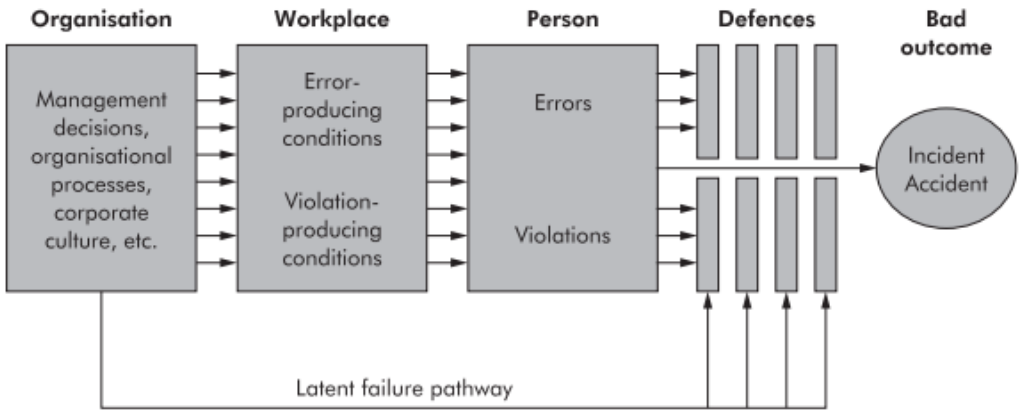

Figure 1. Reason's model of incident/accident stages [6].

Ultimately, the investigation of occupational safety incidents, through the development and implementation of preventive and corrective safety measures, should contribute to improvements in occupational safety management. In this context, procedures for investigating all incidents are of great importance, as they facilitate the clear identification of the root causes of hazardous events that may result in adverse consequences for workers, equipment, or the working environment [7]. An incident investigation procedure represents an established set of rules for conducting investigations through the application of specific methods aimed at determining the root causes of the occurrence of a harmful event. The procedure for investigating a harmful event should be presented in a format that is suitable both for occupational safety professionals and for all individuals involved in the investigation process [8].

At the current stage of information technology development and its increasingly widespread application across various fields, these technologies are also finding significant applications in the

field of occupational safety, particularly in the investigation of safety incidents. Artificial intelligence and natural language processing (NLP) systems show immense potential in processing and interpreting large datasets for risk analysis [9]. These technologies are key to automatically extracting critical factors from unstructured occupational accident reports, enabling the creation of structured datasets and faster identification of causal relationships [9]. By processing vast amounts of historical safety data, AI can discern patterns and correlations, predicting possible incidents and failure points before they occur [10]. This proactive approach allows for the implementation of preventative measures, reducing the likelihood of accidents and incidents [10].

METHODOLOGY SECTION

The objective of this research was to determine the existence of standardized operational procedures used in the investigation of occupational safety incidents. Furthermore, the research sought to examine whether the investigation of incident situations leads to changes in the management of occupational safety consequences and to identify the dominant factors contributing to the occurrence of incident situations in the field of occupational safety.

Hypothesis: Occupational safety incident situations generate consequences for the business system/organization and for the occupational safety management system.

The material used in this research consists of data collected through an online survey conducted among business systems, i.e., companies operating in the region. The survey gathered responses from 70 business entities from regional countries, excluding Slovenia: Croatia (5), Bosnia and Herzegovina (48), Serbia (14), Montenegro (2), and North Macedonia (1). The research was conducted during 2025.

In this research, the following variables were used: independent variables (*Business system/company/organization profile and Investigation of occupational safety incidents*) and the dependent variable (*Consequences of incident situations for the business system/company/organization*).

The measurement scale for the independent variable *Business system/company/organization profile* was composed of the following individual variables:

1. Number of employees
2. Business activity/industry sector
3. Ownership type
4. Job position.

The measurement scale for the independent variable *Investigation of occupational safety incidents* was composed of the following individual variables:

1. Operational procedures for incident investigation
2. Manifestations of incident occurrence
3. Occurrence of severe consequences resulting from incidents situations (serious or fatal occupational injuries)
4. Causal factors contributing to incident occurrence.

The measurement scale for the dependent variable *Consequences of incident situations for the business system/company/organization* was composed of the following individual variables:

1. Negative impact on organizational occupational safety objectives
2. Costs associated with mitigating the consequences of occupational incidents/accidents (direct and indirect costs)
3. Damage to the organization's reputation among employees
4. Damage to the organization's reputation among external stakeholders and customers.

Respondents evaluated the individual dependent variables using a five-point Likert scale, where the minimum score was 1 (Strongly Disagree) and the maximum score was 5 (Strongly Agree).

Microsoft Excel and the SPSS software package were used for statistical data processing and analysis. Descriptive and analytical statistical methods were applied using standard statistical indicators, including frequency, percentage, sum, arithmetic mean, standard deviation, median, Spearman's rank correlation coefficient, and the nonparametric Mann–Whitney U test.

RESULTS AND DISCUSION

The sample structure, in terms of frequencies for the independent variable *Businnes system/company/organization profile*, is presented as follows:

1. *Number of employees* (Up to 50 – 16%, From 50 to 200 – 17%, From 200 to 500 – 24%, From 500 to 1000 – 13%, and Over 1000 – 30%).
2. *Business activity/industry sector* (Production – 83%, Non-productive – 17%). Among companies engaged in production activities, the most represented sectors in the sample were: Energy (supply of electricity, gas, water, etc.) – 26%, Mining – 17%, and Other production activities – 14%. Among non-productive activities, the most represented sector was Health and social care – 9%.
3. *Ownership type* (State-owned – 24%, Private – 44%, Mixed ownership – 27%, and Other – 5%).
4. *Job position* (Member of the management board – 17%, Head of the occupational safety sector/departments/service – 40%, Occupational safety professionals – 29%, Employee knowledgeable in occupational safety – 10%, and Other – 4%).

The individual variables and the frequency distribution of the measurement scale for the independent variable *Investigation of occupational safety incidents* are presented in Figures 2–5.

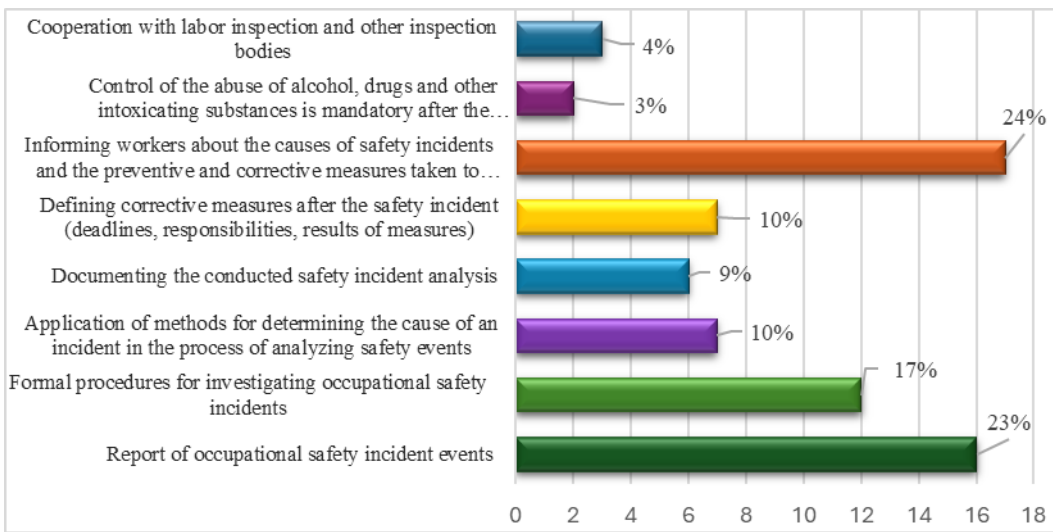

Figure 2. Operational procedures for incident investigation applied by the surveyed business systems/organizations

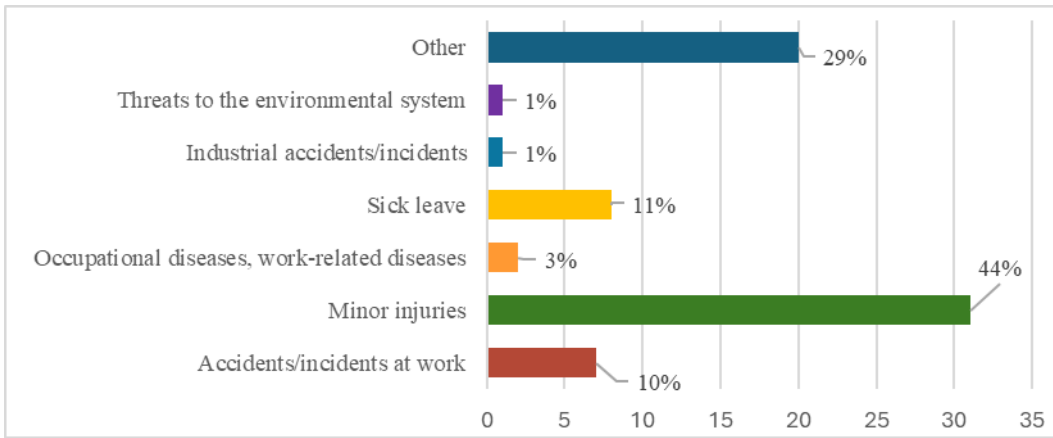

Figure 3. Manifestations of incident occurrence in the surveyed business systems/organizations

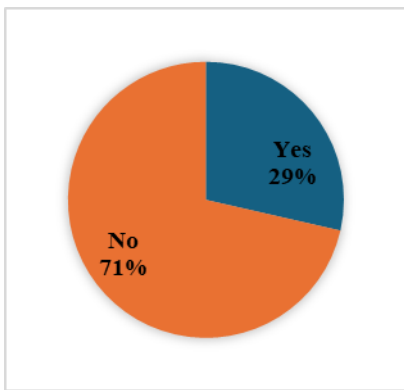

Figure 4. Occurrence of severe consequences resulting from incident situations (serious or fatal occupational injuries)

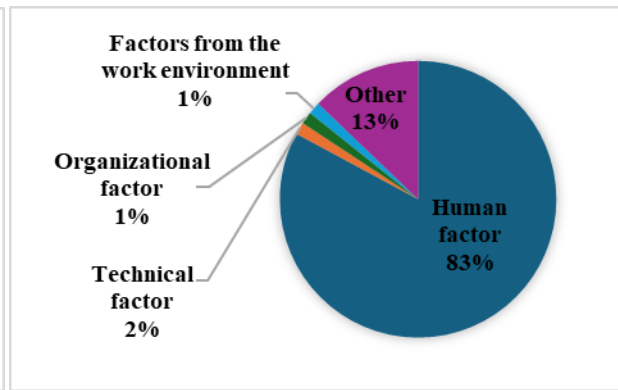

Figure 5. Causal factors contributing to incident occurrence

According to the presented results, various modalities and procedural approaches to the investigation of safety incidents, i.e., occupational safety incidents, are applied within the surveyed business systems/organizations. The most frequently implemented approaches are *Informing workers about the causes of safety incidents and the preventive and corrective measures taken to prevent similar events in the future* (24%), *Report of occupational safety incident events* (23%), and *Formal procedures for investigating occupational safety incidents* (17%), while other approaches are represented to a lesser extent.

The most common manifestation of occupational safety incidents in the surveyed business systems/organizations is minor occupational injuries, accounting for 44% of all reported cases. Furthermore, 71% of the surveyed business system/organizations reported that no severe consequences of safety breaches had occurred in the form of serious or fatal occupational injuries.

The research findings also identified the most significant causal factors contributing to the occurrence of incident situations. The human factor was identified as the dominant cause, accounting for 83% of all cases. Based on these findings, it can be concluded that the design of preventive and corrective occupational safety measures should primarily focus on addressing

human-related factors in order to reduce the occurrence of incident situations and improve overall workplace safety. The obtained results are also supported by findings reported in the literature regarding the dominant role of the human factor as a cause of occupational safety incidents. It is generally accepted that 80–90% of accidents are attributable to human error [11]. Human errors represent a dominant contributing factor in complex and high-risk systems [12]. A systematic review of the literature confirms that human errors and violations of established procedures are central factors contributing to industrial accidents [13].

The process of investigating incident situations and identifying the most significant causal factors, with particular emphasis on the human factor, increasingly involves the application of information technologies, including artificial intelligence, machine learning, and related technologies. The identification of root causes is of particular importance in high-risk industries, as it provides the basis for developing appropriate preventive and corrective measures aimed at addressing the identified causes of incident occurrence. In high-risk industries, artificial intelligence has been used to identify factors contributing to incident situations, with a particular focus on mapping human errors and unsafe behaviors [14]. By utilizing advanced machine learning algorithms, such systems can effectively analyze environmental conditions and personnel behavior in the period preceding an accident, thereby providing objective insights independent of investigator bias [14].

Table 1 presents the descriptive analysis (descriptive indicators: arithmetic mean and standard deviation) of the individual variables comprising the measurement scale of the dependent variable *Consequences of incident situations for the business system/company/organization*.

Table 1. Descriptive analysis of the individual variables comprising the measurement scale of the dependent variable *Consequences of incident situations for the business system/company/organization.*

Variables	Arithmetic mean	Standard deviation
Negative impact on organizational occupational safety objectives	3.84	1.05
Costs associated with mitigating the consequences of occupational incidents/accidents (direct and indirect costs)	3.90	0.99
Damage to the organization's reputation among employees	4.06	0.98
Damage to the organization's reputation among external stakeholders and customers	4.03	1.07
Total	3.96	1.02

The research results indicate that, according to the respondents/business systems/organizations, incident situations do have consequences, and these consequences were rated relatively highly (overall mean score = 3.96). However, the consequences for the organization are slightly more valued those for the occupational safety system within the organization, with the variable *Negative impact on organizational occupational safety objectives* receiving the lowest rating.

Correlation analysis was applied to determine the relationships between the variables, while the correlation coefficient was used to assess the strength and direction of these relationships. The correlations among the individual variables of the measurement scale *Investigation of occupational safety incidents* are presented in Table 2**.**

According to Spearman's interpretation of correlation coefficients, values ranging from 0.2 to 0.4 indicate a weak positive correlation, values from 0.4 to 0.7 indicate a moderate to significant positive correlation, and values from 0.7 to 1.0 indicate a high or very high positive correlation [15], [16].

Table 2. Correlation matrix of the variables comprising the measurement scale *Investigation of occupational safety incidents.*

Correlations			Investigation of occupational safety incidents
Spearman's rho	Operational procedures for incident investigation	Correlation Coefficient	.282*
		Sig. (2-tailed)	.018
		N	70
	Manifestations of incident occurrence	Correlation Coefficient	.554**
		Sig. (2-tailed)	.000
		N	70
	Occurrence of severe consequences resulting from incidents situations (serious or fatal occupational injuries)	Correlation Coefficient	.433**
		Sig. (2-tailed)	.000
		N	70
	Causal factors contributing to incident occurrence	Correlation Coefficient	.626**
		Sig. (2-tailed)	.000
		N	70
	Investigation of occupational safety incidents	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	70

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

The variables comprising the measurement scale *Investigation of occupational safety incidents* exhibited significant positive correlations (level of significance < 0,01), with the exception of the variable *Operational procedures for incident investigation*, which demonstrated a weak positive correlation (level of significance < 0,05). The strongest correlation was identified for the variable *Causal factors contributing to incident occurrence*, suggesting that the respondents/business systems/organizations consider the identification of causal factors to be the most influential component of the incident investigation process.

The correlations among the individual variables of the measurement scale *Consequences of incident situations for the business system/company/organization* are presented in Table 3.

All variables comprising the measurement scale *Consequences of incident situations for the business system/company/organization* exhibited high to very high positive correlations (level of significance < 0,01). Respondents/business systems/organizations who, on the scale *Negative impact on organizational occupational safety objectives*, give higher marks, to a statistically significantly greater extent, at the level of significance < 0.01, evaluate better the *Costs associated with mitigating the consequences of occupational incidents/accidents (direct and indirect costs)*, better assess *Damage to the organization's reputation among employees* and *Damage to the organization's reputation among external stakeholders and customers*, and better evaluate the *Consequences of incident situations for the business system/company/organization*. The strongest correlation was found on the variable *Damage to the organization's reputation among external stakeholders and customer*, followed by the variable *Negative impact on organizational occupational safety objectives*, which leads to the conclusion that the respondents/business systems/organizations believe that the consequences of incident situations for the business system/company/organization are most influenced by these two variables, i.e. the realization of incident situations creates consequences for the organization as a whole, but also affects the occupational safety system that has been established.

Table 3. Correlation matrix of the variables comprising the measurement scale *Consequences of incident situations for the business system/company/organization.*

Correlations			1	2	3	4	***Consequences of incident situations for the business system/company/organization***
Spearman's rho	1. *Negative impact on organizational occupational safety objectives*	Correlation Coefficient	1.000	.745**	.733**	.742**	.907**
		Sig. (2-tailed)	.	.000	.000	.000	.000
		N	70	70	70	70	70
	2. *Costs associated with mitigating the consequences of occupational incidents/accidents (direct and indirect costs)*	Correlation Coefficient	.745**	1.000	.693**	.758**	.890**
		Sig. (2-tailed)	.000	.	.000	.000	.000
		N	70	70	70	70	70
	3. *Damage to the organization's reputation among employees*	Correlation Coefficient	.733**	.693**	1.000	.820**	.878**
		Sig. (2-tailed)	.000	.000	.	.000	.000
		N	70	70	70	70	70
	4. *Damage to the organization's reputation among external stakeholders and customers*	Correlation Coefficient	.742**	.758**	.820**	1.000	.912**
		Sig. (2-tailed)	.000	.000	.000	.	.000
		N	70	70	70	70	70
	5. *Consequences of incident situations for the business system/company/organization*	Correlation Coefficient	.907**	.890**	.878**	.912**	1.000
		Sig. (2-tailed)	.000	.000	.000	.000	.
		N	70	70	70	70	70

**. Correlation is significant at the 0.01 level (2-tailed).

In order to determine whether the selection of an operational procedure influences the overall incident investigation process, i.e., whether statistically significant differences exist among the selected procedures, the nonparametric Mann–Whitney U test was applied. For the purposes of the analysis, all procedures were classified into two independent groups: 1. group (*Formal procedures for investigating occupational safety incidents; Application of methods for determining the cause of an incident in the process of analyzing safety events; Defining corrective measures after the safety incident (deadlines, responsibilities, results of measures); Informing workers about the causes of safety incidents and the preventive and corrective measures taken to prevent similar events in the future*) and 2. group (*Report of occupational safety incidents events*; *Documenting the conducted safety incident analysis*; *Control of the abuse of alcohol, drugs and other intoxicating substances is mandatory after the occurrence of an safety incident, Cooperation with labor inspection and other inspection bodies.*

The results of the Mann–Whitney U test (Table 4) indicate that there is a statistically significant difference between first and second groups procedures used in the investigation of incident situations.

The Mann–Whitney U test confirmed a significant difference between procedures 1. group ($Md = 6$, $n = 44$) and 2. group procedures ($Md = 7$, $n = 26$), $U = 384.500$, $z = -2.345$, $p = 0.019$, $r = 0.28$. The identified statistical difference indicates a moderate effect size (Pallant, 2009; Cohen, 1988).

The statistically significantly higher rank observed for 2. group investigation procedures suggests that business organizations more valued on incident reporting and documentation procedures, control of alcohol and substance abuse in connection with incident occurrences, and cooperation with inspection and regulatory authorities during the incident investigation process.

Table 4. Mann–Whitney U Test results for the variable *Investigation of occupational safety incidents*: Operational procedures for incident investigation.

Ranks				
	Operational procedures for incident investigation	**N**	**Mean Rank**	**Sum of Ranks**
Investigation of occupational safety incidents	1.group	44	31.24	1374.50
	2. group	26	42.71	1110.50
	Total	70		

Test Statistics[a]	
	Investigation of occupational safety incidents
Mann-Whitney U	384.500
Wilcoxon W	1374.500
Z	-2.345
Asymp. Sig. (2-tailed)	.019
a.Grouping Variable: Operational procedures for incident investigation	

CONCLUSION

The incident investigation process should be organized in such a way that it enables the rapid identification of the root causes of incident occurrences, i.e., harmful events. The investigation of incidents and the implementation of corrective actions are aimed at improving safety and preventing the recurrence of events that may have adverse consequences for the system, employees, and the environment.

Furthermore, it is necessary to select an appropriate incident investigation modality that is best suited to the business system/organization implementing it, both from the perspective of operational and procedural requirements and in terms of its effectiveness in preventing or mitigating adverse consequences.

The research findings confirmed that incident situations generate consequences both for the business system/organization as a whole and for the occupational safety management system, thereby confirming the initial research hypothesis. Furthermore, the selection of specific modalities, procedures, and approaches used in the investigation of occupational safety incidents influences both the effectiveness of the investigation process and the quality of the outcomes obtained.

In the current era of rapid development in information technologies and artificial intelligence, new opportunities are emerging for their application in the field of occupational safety, particularly in the investigation of safety-related incident situations. The research results indicate that the accurate identification of the causes of incident occurrence is a key factor in the proper development of appropriate and effective protective measures within the occupational safety management system.

The application of these technologies provides opportunities for the introduction of electronic record-keeping procedures, the processing and analysis of large volumes of data, the reduction of investigator subjectivity, and the precise identification of the most significant causes of incident situations based on available data. Ultimately, these capabilities contribute to the establishment and continuous improvement of sustainable occupational safety management systems.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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SOXHLET DEFATTING AND ITS EFFECT ON THE ANTIOXIDANT CAPACITY OF COLD-PRESSED OILSEED CAKES

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ABSTRACT

Cold pressing of oilseeds such as poppy, pumpkin, and sesame yields high-quality edible oils and generates nutritionally rich oilseed cakes that retain a certain proportion of residual oil. This study aimed to quantify the residual oil content in cold-pressed poppy, sesame, and pumpkin seed cakes and to evaluate the effect of its complete removal by Soxhlet extraction on their antioxidant capacity. The results showed that the highest proportion of residual oil remained in pumpkin seed cake, while the lowest was found in sesame cake. In terms of antioxidant properties, poppy seed cake exhibited the highest antioxidant capacity, whereas sesame cake showed the lowest. Following Soxhlet defatting, antioxidant capacity increased in all samples. The most pronounced enhancement was recorded in poppy seed cake, while the smallest increase was observed in pumpkin seed cake. These findings indicate that removing residual oil improves antioxidant capacity; however, this effect is not directly proportional to the amount of oil removed. Although pumpkin seed cake had the highest residual oil content and underwent the greatest oil extraction, it showed the smallest change in antioxidant activity. This suggests that factors other than residual oil content, such as the composition of phenolic compounds, play a significant role in determining the antioxidant potential of defatted oilseed cakes. Overall, Soxhlet defatting can be considered a useful step in enhancing the functional properties of oilseed cakes, supporting their potential application as value-added ingredients in food and nutraceutical formulations.

Keywords: pumpkin seed, sesame, poppy seed, DPPH, ABTS

INTRODUSTION

Cold pressing is a widely used technology for producing edible vegetable oils because it preserves thermolabile bioactive compounds and avoids the use of organic solvents during extraction. In addition to high-quality oils, this process generates substantial amounts of oilseed

cakes, which remain rich in proteins, dietary fibers, minerals, phenolic compounds, and residual oils. Nowadays, there is a growing demand for cold-pressed plant oils, which are produced with relatively simple mechanical devices that can be used locally on the farm or by rural cooperatives. Cold-pressed oils are anticipated to reach the highest growth rate in the next few years [1], [2]. Cold-press processing lies below 50 °C, as opposed to 50–100 °C typically reached during expelling, retaining most of the bioactive and nutritional value of oils [3].

Oilseed by-products generated after cold pressing have attracted increasing attention as sustainable raw materials for the development of value-added functional ingredients. In contrast to solvent extraction, cold pressing preserves a substantial proportion of naturally occurring bioactive compounds while minimizing chemical processing, resulting in press cakes with high nutritional and functional potential [4], [5]. Among various oilseeds, sesame (*Sesamum indicum L.*), pumpkin (*Cucurbita pepo L.*), and poppy (*Papaver somniferum L.*) seeds represent particularly valuable sources of proteins, dietary fiber, and phytochemicals with well-documented antioxidant properties.

Cold-pressed cakes obtained from these seeds contain considerable amounts of high-quality proteins, typically ranging from approximately 20 % to more than 60 %, depending on the botanical origin and processing conditions. Pumpkin seed cake generally exhibits the highest protein content, frequently exceeding 50 %, making it an attractive ingredient for protein enrichment of functional foods [4]. Besides proteins, these by-products provide significant quantities of insoluble and soluble dietary fiber, residual lipids, minerals, and numerous antioxidant constituents, including phenolic acids, flavonoids, lignans, tocopherols, and other secondary metabolites that contribute to their biological activity [4], [6]. Consequently, cold-pressed oilseed cakes are increasingly recognized not merely as industrial residues but as valuable ingredients within the framework of sustainable food systems and circular bioeconomy strategies [7].

Unlike solvent-extracted meals, cold-pressed cakes retain a relatively high proportion of residual oil because mechanical pressing does not completely disrupt the oil-bearing cellular structures. Depending on the seed type and processing parameters, a substantial fraction of lipids remains entrapped within the plant matrix, thereby increasing the caloric value of the material while simultaneously affecting its physicochemical properties [4]. The presence of residual oil may also influence the extraction of hydrophilic phytochemicals by limiting solvent penetration, reducing matrix wettability, and restricting the diffusion of polar compounds into aqueous extraction media. Furthermore, hydrophobic interactions between lipids and phenolic constituents may decrease the overall recovery of antioxidant molecules during water-based extraction procedures [8].

To overcome these limitations, a defatting step is frequently introduced prior to the extraction of bioactive compounds. Soxhlet extraction using non-polar solvents such as hexane remains one of the most widely employed laboratory methods for efficient lipid removal from plant materials. Elimination of residual oil not only improves solvent accessibility to the intracellular matrix but may also increase the release of protein-bound and cell wall-associated phenolic compounds by disrupting hydrophobic interactions and enhancing mass transfer [9], [10]. As a result, defatted oilseed cakes often exhibit improved extraction yields of phenolics and enhanced antioxidant activity in aqueous extracts compared with their non-defatted counterparts. Nevertheless, the magnitude of this effect depends on the specific botanical source, extraction conditions, and the chemical composition of the plant matrix, highlighting the need for systematic evaluation of defatting as a pretreatment strategy for different cold-pressed oilseed cakes. Therefore, the aim of this study was to determine the residual oil content in cold-pressed sesame, pumpkin, and poppy seed cakes and to evaluate the effect of Soxhlet defatting on antioxidant activity measured by DPPH and ABTS radical scavenging assays.

METHODOLOGY SECTION

Materials

Cold-pressed sesame, pumpkin, and poppy seed cakes obtained after industrial oil pressing from Linum Ltd., Serbia, were used in this study. 2,2-difenil-1-pikrilhidrazil (DPPH), 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), and all other chemicals used in this study were purchased from Sigma-Aldrich Chemie GmbH and were of analytical grade.

Sample Preparation

Oilseed cakes were ground in a ball mill MM400-Retsch (Verder Scientific, German) and sieved through a sieve with a pore size of 0.6 mm in order to obtain homogeneous samples suitable for analysis.

Soxhlet Extraction of Residual Oil

Residual oil was extracted using hexane in a Behr E4 (Labor-Technik, German) Soxhlet apparatus at 80°C until complete defatting was achieved. The residual oil content was calculated gravimetrically.

Determination of Antioxidant Activity

Antioxidant activity was evaluated using DPPH and ABTS radical scavenging assays in aqueous extracts prepared before and after Soxhlet defatting.

DPPH free radicals scavenging activity assay

The oilseed cake powder was taken in a dilution of 1 % (w/v) and mixed with 0.1 mM–ethanolic DPPH free radical, in a ratio 1 : 18. Mixtures were homogenized and left in the dark for 30 min. The absorbance was measured at 517 nm using a UV-visible spectrophotometer (Ultrospec 3300 pro, Amerischam Bioscienc). For making control, ethanol was used instead of the sample. The antioxidant activity was expressed as a percentage of DPPH activity calculated as:

$$DPPH\ capacity\ (\%) = \frac{Absorbance\ of\ control - Absorbance\ of\ sample}{Absorbance\ of\ control} \times 100 \quad (1)$$

ABTS free radical scavenging activity assay

The ability of the probiotic powder to scavenge ABTS radical was tested according to Re et al. [11].ABTS radical cation was produced in the reaction between ABTS (7 mM) and potassium persulfate (2.45 mM final concentration). The reaction mixture was kept in the dark at room temperature for 16 h before use. Further, ABTS solution was diluted with 5 mM phosphate-buffered saline (pH 7.4) until the absorbance of 0.700 (± 0.010) was reached. Diluted ABTS solution was mixed with samples in a ratio 99 : 1; absorbance was measured at 734 nm after 5 min. The antioxidant activity was calculated as follows:

$$ABTS\ capacity\ (\%) = \frac{Absorbance\ of\ blank - Absorbance\ of\ sample}{Absorbance\ of\ blank} \times 100 \quad (2)$$

Statistical analysis

All experiments were performed in triplicate, and the results are presented as means with standard deviations. The Tukey test was used to determine significant differences between samples ($p < 0.05$). Data analysis was conducted using Microsoft Excel (Microsoft Office 2013 Edition, USA) and OriginPro 8 (Origin Lab Co., Northampton, USA).

RESULTS AND DISCUSSION

Residual Oil Content in Cold-Pressed Oilseed Cakes

The residual oil content varied considerably among the investigated oilseed cakes, as shown in Table 1. Pumpkin seed cake contained the highest amount of residual oil (28.8 %), followed by poppy seed cake (20.9 %), while sesame cake showed the lowest residual oil content (12.12 %).

Table 1. The residual oil content

	Sesame seed cake	Pumpkin seed cake	Poppy seed cake
Residual oil, %	12.12±0.22	28.8±0.41	20.9±0.35

The relatively high residual oil content confirms that cold pressing, although environmentally friendly and suitable for preserving oil quality, is less efficient at recovering lipids than solvent extraction methods. Significant quantities of oil therefore remain trapped within the cake matrix, potentially affecting the extractability of hydrophilic bioactive compounds.

Changes in Radical Scavenging Activity

The antioxidant capacity measured by both DPPH and ABTS assays increased markedly in sesame and poppy seed cakes after extraction (Figure 1). In sesame cake, DPPH radical scavenging activity increased from 5.4 % to 14.2 %, while ABTS activity rose from 6.1 % to 14.6 %. In poppy seed cake, even more pronounced increases were observed, with DPPH activity rising from 16.4 % to 25.4 % and ABTS activity increasing from 18.9 % to 46.7 %. These results indicate that the removal of residual oil enhanced the extractability and accessibility of hydrophilic antioxidant compounds, particularly phenolic constituents associated with the protein–polysaccharide matrix.

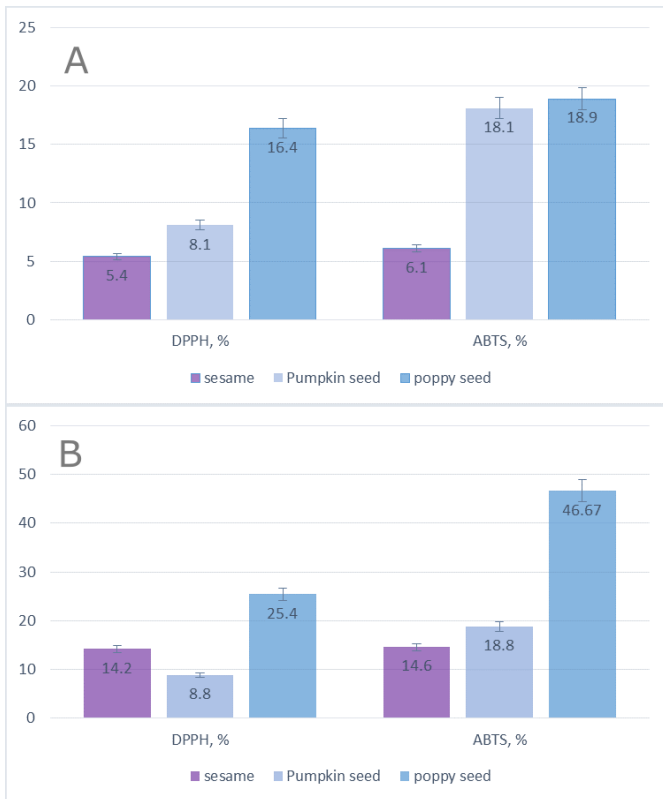

Figure 1. Antioxidant capacity of oilseed cake before (A), and after (B) defatting

Previous studies have shown that phenolic compounds in oilseeds are often bound to cell wall polysaccharides or proteins and may be partially masked by residual lipids, which hinder solvent penetration and reduce extraction efficiency [8], [12]. Removal of lipids improves matrix porosity and facilitates the release of phenolic acids, lignans, and flavonoids into polar extraction solvents used for antioxidant assays [8], [12]. In addition, non-lipid components such as proteins and peptides may contribute to radical scavenging activity through hydrogen atom donation, metal chelation, and electron transfer mechanisms [13].

Sesame seeds are especially rich in lignans such as sesamin, sesamolin, and sesamol, compounds recognized for their potent antioxidant activity and ability to protect against oxidative deterioration [14]. Although some lignans are lipophilic, their oxidative transformation products and associated phenolics can become more readily extractable after oil removal, explaining the significant increase in antioxidant activity observed in the defatted sesame cake.

Poppy seeds contain a variety of phenolic acids, including p-coumaric, ferulic, and caffeic acids, as well as tocopherols and other antioxidants [15]. The dramatic enhancement in ABTS scavenging activity after extraction suggests that many of these phenolics are concentrated within the solid matrix and become substantially more available once the oil fraction is removed. The larger increase in ABTS compared with DPPH may reflect the greater sensitivity of the ABTS assay to both hydrophilic and moderately lipophilic antioxidants. In contrast to sesame and poppy seed cakes, pumpkin seed cake exhibited an increase in DPPH activity (from 8.1 % to 8.8 %) and ABTS activity (from 18.1 % to 18.8 %). Pumpkin seed oil is known to contain high concentrations of tocopherols, carotenoids, phytosterols, and squalene, which exhibit strong antioxidant properties [16]. Since these compounds are predominantly lipophilic, they are largely removed during Soxhlet extraction with hexane.

CONCLUSION

The present study demonstrated that residual oil content differs substantially among cold-pressed sesame, pumpkin, and poppy seed cakes, with pumpkin seed cake retaining the highest amount of oil and sesame cake the lowest. Defatting significantly enhanced the measured antioxidant capacity of sesame and poppy seed cakes, as evidenced by increased DPPH and ABTS radical scavenging activities, indicating improved accessibility and extractability of hydrophilic antioxidant compounds following lipid removal. These findings suggest that residual oil may limit the extraction efficiency of phenolic constituents by reducing solvent penetration and restricting the release of matrix-bound bioactive compounds. In contrast, only marginal changes in antioxidant activity were observed in pumpkin seed cake after defatting, most likely due to the removal of lipophilic antioxidants naturally present in pumpkin seed oil. Overall, the results demonstrate that the effect of defatting on antioxidant potential is strongly dependent on the chemical composition of the oilseed matrix and the distribution of antioxidant compounds between the lipid and non-lipid fractions. Defatting therefore represents an important pretreatment for maximizing the recovery of hydrophilic antioxidants from sesame and poppy seed cakes, while its benefits appear limited for pumpkin seed cake. These findings provide valuable guidance for the valorization of cold-pressed oilseed by-products as sustainable sources of natural antioxidants and functional food ingredients.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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EFFECT OF FLAXSEED–BASED HYDROGEL COMPOSITION ON MECHANICAL PROPERTIES OF EXTRUDED MICROSPHERS

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ABSTRACT

Immobilization of probiotics within hydrogels is a promising approach for enhancing probiotic protection and stability. Mechanical properties and structural integrity of hydrogels play a crucial role in maintaining particle functionality during processing and application. In this study, the mechanical properties of hydrogels based on flaxseed cake, alginate, and pectin were investigated, together with the effect of fermentation on their strength. Probiotics were immobilized by the extrusion technique, producing seven types of spherical particles with an average diameter of approximately 2.8 mm. Results showed that the addition of pectin to alginate improved the mechanical properties of hydrogels more than the addition of flaxseed cake or flaxseed mucilage, while the optimal composition was achieved with a flaxseed mucilage to alginate ratio of 35:100. Increasing alginate concentration in flaxseed mucilage reduced hydrogel firmness from 0.525 to 0.120 N. Fermentation affected particle strength differently depending on hydrogel composition, indicating a strong influence of fermentation on hydrogel structure and intermolecular interactions among components. These findings highlight the importance of formulation design and fermentation in tailoring hydrogel properties for probiotic immobilization and suggest significant potential for developing stable, functional delivery systems.

Keywords: encapsulation, alginate, pectin, probiotic, flaxseed cake.

INTRODUSTION

Functional foods enriched with probiotic microorganisms have attracted increasing scientific and industrial interest owing to their potential to promote gastrointestinal health and reduce the

risk of various chronic diseases. Nevertheless, the successful application of probiotics in food systems largely depends on maintaining an adequate number of viable cells throughout processing, storage, and gastrointestinal transit. Environmental stresses such as oxygen exposure, low pH, bile salts, temperature fluctuations, and osmotic stress may substantially reduce probiotic viability, thereby limiting their health-promoting effects [1], [2], [3]. Consequently, considerable efforts have been devoted to developing delivery systems capable of preserving probiotic functionality until consumption.

Hydrogel-based encapsulation has become one of the most effective approaches for protecting probiotic cells because hydrogels provide a hydrated three-dimensional polymer network that acts as a physical barrier against adverse environmental conditions while allowing the diffusion of nutrients and metabolites. Among the available encapsulation methods, extrusion is particularly advantageous due to its simplicity, low production cost, high encapsulation efficiency, and the absence of harsh processing conditions that could compromise bacterial viability [4], [5], [6], [7]. However, the protective performance of hydrogel carriers depends not only on encapsulation efficiency but also on their structural integrity and mechanical stability.

The mechanical properties of hydrogel carriers have emerged as key quality attributes influencing their technological performance. Mechanical strength determines the ability of hydrogel particles to resist deformation, abrasion, and rupture during manufacturing, drying, storage, transportation, and incorporation into food matrices. Furthermore, mechanically stable carriers are more likely to maintain their structural integrity under gastrointestinal conditions, thereby ensuring controlled probiotic release at the desired site of action [2]. Therefore, optimizing the mechanical behavior of hydrogel particles is essential for the development of reliable probiotic delivery systems.

Sodium alginate remains the most widely investigated biopolymer for probiotic encapsulation due to its excellent biocompatibility, biodegradability, non-toxicity, and ability to rapidly form hydrogels through ionic crosslinking with calcium ions under mild conditions. Alginate beads generally exhibit high encapsulation efficiency and favorable biocompatibility; however, their relatively porous structure and moderate mechanical strength may compromise long-term stability and protection of probiotic cells [8]. For this reason, numerous studies have focused on combining alginate with complementary natural polymers or functional fillers capable of reinforcing the hydrogel network and modifying its functional and mechanical characteristics [7], [8].

Pectin is one of the most extensively studied polysaccharides for improving alginate-based hydrogels because of its gel-forming ability, compatibility with alginate, and potential prebiotic activity. The incorporation of pectin has been reported to increase gel compactness, reduce pore size, and enhance the mechanical resistance of composite hydrogels through additional intermolecular interactions within the polymer matrix [8]. Besides conventional hydrocolloids, increasing attention has recently been directed toward plant-derived agro-industrial by-products as sustainable ingredients for designing multifunctional encapsulation systems.

Partially defatted flaxseed powder, obtained as a by-product of cold-pressed flaxseed oil production, is rich in dietary fiber, proteins, residual flaxseed mucilage, lignans, and other bioactive compounds. Owing to its high water-binding capacity and complex biochemical composition, this material may influence hydrogel formation, water retention, network architecture, and the mechanical behavior of composite particles. In addition to improving structural properties, partially defatted flaxseed powder may serve as a source of fermentable substrates that support probiotic survival, thus providing both technological and nutritional advantages. The valorization of this by-product is also consistent with current strategies promoting sustainability and circular bioeconomy in food production [9], [10].

Therefore, the present study aimed to develop composite alginate-based hydrogel carriers containing pectin and partially defatted flaxseed powder and to evaluate the influence of these additives on the physicochemical and mechanical properties of the beads. Particular emphasis was placed on understanding how modifications of the hydrogel matrix affect particle strength.

METHODOLOGY SECTION

Materials

Cold-pressed flaxseed cake obtained after industrial oil pressing from Linum Ltd., Serbia, was used in this study. Alginate and pectin from citrus (Sigma Aldrich, St. Louis, MO, USA) were used for carrier composition.

Carrier material pretreatment

Flaxseed cake was ground in a ball mill and sieved through a sieve with a pore size of 0.6 mm. The flaxseed powder obtained in this way was dissolved in distilled water and pasteurized at 60 °C for 60 min, as well as pectin from citrus, flaxseed mucilage and alginate. Flaxseed mucilage was obtained by adding 1 % grounded flaxseed cake to distilled water and incubating at 75 °C for 1 h. After incubation, the mixture was centrifuged at 4.000 rpm for 4 min, and the supernatant was collected and used for further analysis.

Encapsulation method

Seven carriers, with average diameter about 2.8 mm, were obtained using extrusion method described by Krunic and Rakin [7]: AP- 1.0 % alginate and 0.67 % of pectin, AL- 1.0 % of alginate and 2.5 % of flaxseed, APL- 1.0 % alginate, 0.67 % of pectin, and 2.5 % of flaxseed and ALL- 0.6 % of alginate and 2.5 % of flaxseed, 1AL - 1.0 % alginate and 0.18 % flaxseed mucilage, 0.75AL – 0.75 % alginate and 0.18 % flaxseed mucilage and 0.5AL – 0.5 % alginate and 0.18 % flaxseed mucilage. All samples have encapsulated probiotics in a concentration of about 7 log CFU/g.

Determination of the hydrogel beads mechanical properties

Mechanical properties of carriers were analysed 5 days after preparation and for some samples after 4.5 h of coconut milk (Alpro, Belgium) fermentation at 37 °C with 10 % (w/v) carrier with probiotic addition. The tests were performed using a Universal Testing Machine, AG-Xplus (Shimadzu, Japan), equipped with a 100 N force load cell.

Statistical analysis

All experiments were performed in triplicate, and the results are presented as means with standard deviations. The Tukey test was used to determine significant differences between samples ($p < 0.05$). Data analysis was conducted using Microsoft Excel (Microsoft Office 2013 Edition, USA) and OriginPro 8 (Origin Lab Co., Northampton, USA).

RESULTS AND DISCUSSION

Alginate-flaxseed mucilage beads

Based on the presented texture/compression data for particles formulated with 0.5 % flaxseed mucilage and increasing alginate concentrations (0.5–1.0 %), a clear effect of alginate concentration on mechanical behavior can be observed (Figure 1).

The particles containing 0.5 % alginate exhibited the highest resistance to deformation, showing the greatest average maximum force (0.525 N) and maximum stress (0.144 N/mm²), indicating superior mechanical strength and a more rigid structure. Their force-strain profiles also revealed steeper curves and higher rupture forces, suggesting a stronger, more elastic gel network that can withstand compression before failure.

Increasing alginate concentration to 0.75 % led to a pronounced reduction in mechanical strength, with the maximum force decreasing to 0.134 N and the stress to 0.032 N/mm². A similar trend was observed for 1.0 % alginate, where particles showed the lowest strength parameters (0.120 N and 0.029 N/mm², respectively). The much flatter force-strain curves for these formulations indicate softer and less resistant particles. Literature shows that the incorporation of flaxseed mucilage into sodium alginate matrices may alter the mechanical behavior of hydrogel particles by modifying the polymer network density and elasticity [12], [13]. Similar effects of

flaxseed mucilage on structural-mechanical properties, including reduced hardness and increased elasticity, were reported by Sungatullina et al. [12]. Furthermore, alginate–flaxseed gum composite hydrogels were shown to possess enhanced network stability and tunable mechanical characteristics depending on composition and crosslinking conditions [13].

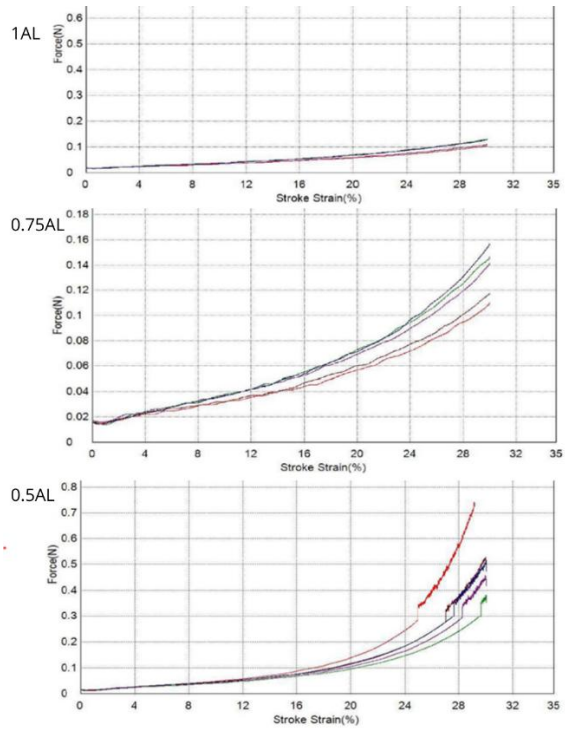

Figure 1. Graphics of the mechanical properties of carriers 1AL, 0.75AL and 0.5AL

Interestingly, the expected strengthening effect with increasing alginate concentration was not observed. Instead, excessive alginate appeared to weaken the structure, likely due to the formation of a denser but more brittle or less homogeneous network, possibly limiting effective intermolecular interactions between alginate and flaxseed mucilage. In contrast, the 0.5 % alginate formulation may represent a more optimal polymer ratio, promoting balanced chain entanglement and crosslinking, resulting in enhanced elasticity and compressive strength. This correlates with the literature data showing the complex interaction of alginate with other carbohydrates and proteins [8]

Overall, the results suggest that 0.5 % flaxseed mucilage combined with 0.5 % alginate provides the most mechanically robust particles, while higher alginate levels reduce firmness and elasticity, highlighting the importance of polymer ratio optimization for tailoring bead mechanical properties.

Beads with a combination of flaxseed cake, alginate and pectin from citrus

Non-fermented beads

Based on the mechanical characterization, distinct differences in particle strength and elasticity were observed among the four formulations between alginate, pectin and flaxseed cake (AP, APL, AL, ALL). The sample AP exhibited the highest mechanical resistance, with a corrected maximum force of 0.622 N and maximum stress of 0.090 N/mm², substantially higher

than all other samples (Figure 2). This indicates a highly cohesive and elastic network able to withstand compression before rupture.

Sample ALL showed the second highest strength (0.279 N, 0.067 N/mm²), but was markedly weaker than AP, suggesting a less rigid yet still mechanically stable structure. Sample AL exhibited intermediate behaviour (0.345 N, 0.058 N/mm²), while sample APL had the lowest compressive strength (0.188 N, 0.033 N/mm²), indicating the softest and least resistant matrix among the tested formulations. A trend similar to that observed for the alginate-flaxseed mucilage system was also evident in the alginate-flaxseed cake formulations. Specifically, particles containing the same concentration of flaxseed cake but a lower alginate concentration exhibited enhanced mechanical properties. Similar behaviour has been observed for alginate combined with chitosan, whey proteins, and whey protein hydrolysates, where those components contribute to strengthening the polymer network and improving the mechanical properties of the hydrogel beads [2], [6], [8].

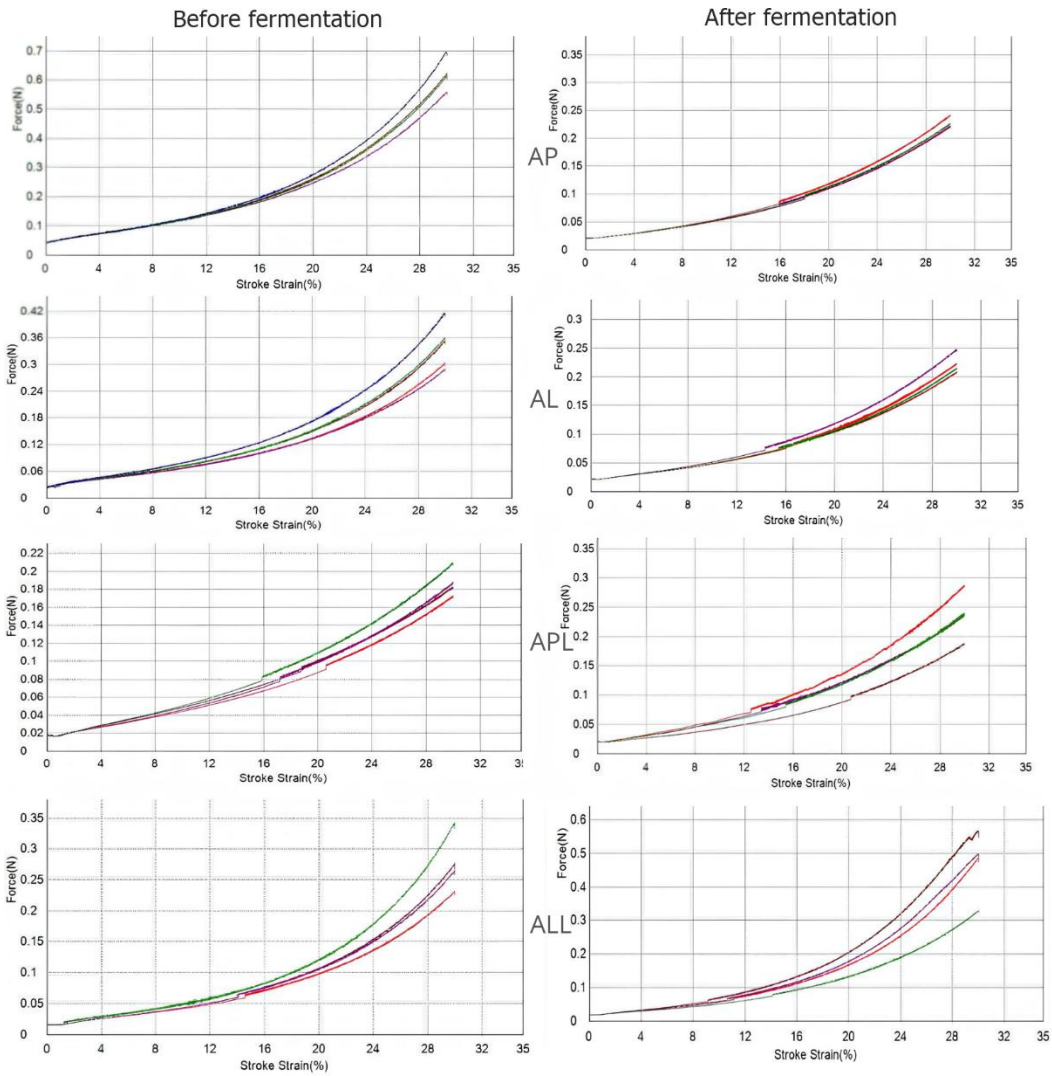

Figure 2. Graphics of the mechanical properties of carriers AP, AL, APL, ALL, before and after fermentation of coconut milk

The much steeper force-strain profile of AP suggests a denser or better integrated polymer network, whereas the gradual reduction in force from AL to APL points to lower structural cohesion. These findings suggest that alginate exhibits greater compatibility with pectin, resulting in stronger intermolecular interactions than with flaxseed cake. However, the simultaneous incorporation of both components appears to disrupt network formation, leading to a weaker polymer matrix.

Beads after fermentation of coconut milk (fermented samples AP, AL, APL and ALL were APF, ALF, APLF and ALLF)

Fermentation altered the mechanical properties considerably and modified the ranking of formulations. Among fermented samples, ALLF displayed the highest mechanical strength (0.470 N, 0.063 N/mm²), substantially outperforming all other fermented formulations (Figure 2). Its higher rupture force and steeper compression curve suggest fermentation reinforced the structure in this formulation, likely through enhanced polymer interactions or matrix densification.

ALF and APLF showed intermediate strength, with ALF (0.224 N) and APLF (0.238 N) having comparable force values, although ALF exhibited slightly higher stress values, indicating marginally greater resistance. APF showed the lowest mechanical strength (0.229 N, 0.028 N/mm²), representing a dramatic decrease compared with non-fermented AP.

The strength ranking after fermentation can be summarized as: ALLF >> APLF ≈ APF ≈ ALF (force) and ALLF > ALF > APLF > APF (stress).

A notable observation is the pronounced weakening of alginate-pectin beads after fermentation (from 0.622 to 0.229 N; ~63% reduction), suggesting fermentation substantially disrupted its initially strong gel network. In contrast, ALL benefited from fermentation, showing the strongest post-fermentation structure, indicating greater matrix tolerance or even structural reinforcement under fermentation conditions.

Fermentation generally reduced elasticity and compressive strength in samples AP, AL and APL, particularly in sample AP, likely due to partial polymer degradation, rearrangement of intermolecular associations, or increased porosity within the matrix. However, sample ALL exhibited the opposite trend, suggesting formulation-dependent responses to fermentation. Similar observations have been reported for alginate-based particles containing whey proteins, whey protein hydrolysate, or chitosan. However, the effect of fermentation varied among these particle formulations. The greatest improvement was observed in beads containing alginate and whey proteins, followed by those containing alginate and whey protein hydrolysate. In contrast, alginate-chitosan particles exhibited the smallest increase in mechanical properties during fermentation, which was even lower than that observed for alginate beads [2], [6], [8].

These results indicate that fermentation does not uniformly weaken particles; rather, its impact strongly depends on the original polymer composition and network organization, with some systems becoming softer while others may develop enhanced rigidity. This highlights the importance of formulation optimization when designing fermented biopolymer particles with tailored mechanical performance.

CONCLUSION

Among all seven formulations, AP showed the highest mechanical resistance, indicating the strongest and most cohesive network. The 0.5 % alginate beads with flaxseed mucilage ranked among the mechanically strongest systems overall and were considerably stronger than AL, APL and ALL as well as the particles containing flaxseed mucilage and higher alginate concentrations. This supports the observation that 0.5 % alginate represents an optimal mucilage-alginate balance, promoting effective chain entanglement and elastic recovery.

A marked reduction in the strength of flaxseed mucilage beads occurred when the alginate concentration increased to 0.75 % and 1.0 %, with maximum forces lower than those of all four samples, AP, AL, APL, and ALL. This suggests that excessive alginate weakened the matrix more

severely than the compositional differences that account for the lower strength of samples AL, APL, and ALL compared to AP.

Based on maximum force, the overall strength ranking can be summarized as: AP > 0.5AL > AL > ALL > APL > 0.75AL > 1AL, while stress values indicate somewhat different rigidity behavior: 0.5AL > AP > ALL > AL > APL > 0.75AL > 1AL. This distinction suggests that AP is highly load-bearing and elastic, whereas the 0.5% alginate particles are comparatively stiffer and more resistant per unit area.

Overall, two mechanically favorable systems emerged: AP and the 0.5AL, although likely due to different structural mechanisms. In contrast, increasing alginate above 0.5% led to the weakest systems, emphasizing that polymer concentration alone does not guarantee reinforcement; rather, mechanical performance depends on achieving an optimal balance between polymer content, crosslinking density, and network homogeneity. Fermentation generally reduced elasticity and compressive strength in samples AP, AL and APL, compared to sample ALL which exhibited the opposite trend, suggesting formulation-dependent responses to fermentation.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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INFLUENCE OF SELECTED PLANT ADDITIVES ON THE FATTY ACID PROFILE OF TRADITIONAL JANJ CHEESE

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ABSTRACT

Janj cheese is a traditional dairy product produced from raw cow's milk in the mountainous Janj region of Bosnia and Herzegovina, where cattle are mainly fed on natural mountain pastures. This study investigated the effect of adding selected plant additives (oregano, basil, parsley, rosemary, and chives) at a concentration of 0.50% on the fatty acid composition of Janj cheese. Six cheese samples were produced, including one control sample without additives and five experimental samples with plant additions. Fatty acid composition was determined by gas chromatography with flame ionization detection (GC–FID), and data were analyzed using one-way ANOVA at $p<0.05$. The results showed that saturated fatty acids (SFA) were dominant in all samples (59.34–61.48%), with palmitic (C16:0), stearic (C18:0), and myristic acid (C14:0) as the most abundant. Monounsaturated fatty acids (MUFA) ranged from 33.39% to 34.86%, with oleic acid (C18:1) as the major component. Polyunsaturated fatty acids (PUFA) ranged from 4.81% to 6.52%, with linoleic (C18:2) and α-linolenic acid (C18:3 n-3) as the major components. α-Linolenic acid was markedly higher in most treated samples compared to the control, indicating a potential nutritional benefit of plant enrichment. Lipid quality indices (atherogenic index (AI), thrombogenic index (TI), h/H ratio, and desirable fatty acids (DFA)) showed slight modifications

in treated samples, indicating subtle changes in lipid nutritional quality. These findings suggest that the addition of plant additives at 0.50% can slightly modify the fatty acid profile of Janj cheese, particularly contributing to an increase in the n-3 PUFA fraction.

Keywords: Janj cheese, plant additives, fatty acids, lipid quality indices.

INTRODUCTION

Traditional food products are recognized as an important component of cultural heritage, reflecting specific production practices adapted to local environmental conditions. In addition to their nutritional importance, traditional foods contribute to the preservation of regional identity, biodiversity, and traditional knowledge transmitted through generations. They are closely associated with local customs, geographical origin, and sustainable food production systems, which further increases their cultural and economic significance [1], [2].

Dairy products occupy an important place in the human diet due to their high nutritional value and richness in essential nutrients, including proteins, fats, calcium, vitamins, and trace elements. Milk and dairy products are recognized as one of the most important dietary sources of highly bioavailable calcium and high-quality proteins, which are essential for bone health, muscle function, and overall metabolic processes [3], [4]. In addition to their nutritional importance, dairy products contain numerous bioactive compounds that may positively influence human health, including bioactive peptides, conjugated linoleic acid, and beneficial fatty acids [3], [5]. The transformation of milk into cheese is considered an efficient method for preserving these nutrients through fermentation and ripening processes, which additionally contribute to the development of characteristic texture, flavor, and aroma [6]. During cheese ripening, complex biochemical and microbiological changes occur, resulting in improved digestibility and the formation of compounds associated with the sensory and functional quality of cheese [7].

Milk fat is composed of a large number of fatty acids, and more than 400 different fatty acids have been identified in milk fat [8]. The diversity of fatty acids contributes to the high biological value of milk fat because the human organism can selectively utilize the required fatty acids, although many cannot be synthesized endogenously. Fatty acids differ in chain length and degree of saturation, ranging from short-chain to long-chain fatty acids with varying numbers of double bonds [9]. Milk fat contains saturated and branched-chain fatty acids, monounsaturated fatty acids (MUFA), and polyunsaturated fatty acids (PUFA). A typical milk fat composition includes approximately 62% saturated fatty acids, 29% monounsaturated fatty acids, and 4% polyunsaturated fatty acids [10]. Although diets rich in saturated fatty acids have traditionally been associated with an increased risk of cardiovascular diseases, unsaturated fatty acids, particularly cis-monounsaturated and n-3 polyunsaturated fatty acids, are considered beneficial due to their protective effects on cardiovascular health [11]. In addition, polyunsaturated fatty acids play important physiological and functional roles in the human body [12]. The fatty acid composition of milk and dairy products may also be modified during processing and storage through physical and chemical reactions such as oxidation and the formation of trans fatty acids [13].

Cheese is a significant source of readily digestible fats, containing a wide range of saturated (SFA), monounsaturated (MUFA), and polyunsaturated fatty acids (PUFA) [14], [15]. Although dairy fats are often associated with a high proportion of SFAs, research indicates that cheeses also contain bioactive components such as short-chain fatty acids and natural trans isomers, primarily vaccenic acid (VA) and conjugated linoleic acids (CLA) [5], [16]. These fatty acids have been shown to possess a variety of health-promoting properties, including anticarcinogenic, antiatherogenic, antioxidant, and anti-inflammatory effects [12], [17]. The fatty acid profile of cheese is not identical to that of the raw milk, as it is influenced by technological processes, microbial activity, and lipolytic changes during ripening [18], [19].

The composition of fatty acids in dairy products depends on numerous factors, including the breed of animals, stage of lactation, season, and diet [20], [19]. Studies have shown that grazing on mountainous pastures with specific plant cover significantly improves the lipid profile, increasing the proportion of unsaturated fatty acids, particularly PUFAs, compared to conventional feeding

systems [21]. In addition to dietary factors, modern food technology explores strategies to enhance nutritional quality through the direct addition of functional ingredients. For example, cheese fortification with walnut paste significantly increases the content of omega-3 fatty acids while reducing the proportion of saturated fatty acids [22].

The use of aromatic and medicinal plants in traditional cheese production serves a dual purpose: improving sensory characteristics by forming specific aromas and acting as a natural preservative [23], [24], [25]. Plant species such as oregano, basil, parsley, and rosemary are rich in volatile compounds that contribute to the unique taste and aroma of the product [23], [24]. In addition, certain plant species contain notable amounts of polyunsaturated fatty acids, particularly alpha-linolenic acid (C18:3 n-3), which may contribute to modifications in the fatty acid profile of enriched dairy products [22]. In Southeastern Europe, traditional brined cheeses are the most commonly consumed type of cheese and are often named after the regions where they are produced [16].

Among the traditional cheeses of Bosnia and Herzegovina, Janj cheese stands out due to its distinctive sensory characteristics and traditional artisanal production. Originating from the mountainous area surrounding the Janj River in Bosnia and Herzegovina (Šipovo municipality, Republika Srpska), this cheese is traditionally produced from cow's milk, either raw or mildly heat-treated, without the use of commercial starter cultures. Such production practices enable the development of indigenous microflora, which contributes significantly to the characteristic flavor and overall sensory profile of the cheese [24], [25].

Given that the fatty acid profile directly influences the nutritional value and lipid quality indices of cheese, understanding the effect of plant additives on this profile is of considerable scientific and practical interest. The aim of this study was to investigate the effect of adding oregano, basil, parsley, rosemary, and chives on the fatty acid composition of traditional Janj cheese.

MATERIALS AND METHODS

Sample preparation and experimental design

The production of Janj cheese samples was carried out in a rural household in Lipovača (Šipovo municipality), a region recognized for its long-standing tradition of artisanal dairy processing.

For this study, six cheese samples were produced, including a control sample (without additives) and five samples enriched with different plant additives: oregano (*Origanum vulgare*), basil (*Ocimum basilicum*), parsley (*Petroselinum crispum*), rosemary (*Salvia rosmarinus*), and chives (*Allium schoenoprasum*). The plant additives were incorporated at a concentration of 0.50%.

After evening milking, the milk was filtered and allowed to rest at room temperature for 14 h. Milk readiness for coagulation was assessed empirically by heating a 100 mL milk sample until visible curd and whey separation occurred. After confirming readiness, the milk was heated to 38 °C and rennet (0.2% of total milk volume) was added. The mixture was left undisturbed at this temperature for 20 min to allow curd formation.

Following coagulation, the temperature was increased to 50 °C. The curd was gently stirred for 10 min to facilitate cutting and manually pressed against the vessel walls for an additional 10 min to expel whey, which reached 48 °C during this step. The resulting cheese mass was divided into 500 g portions and flattened to a thickness of approximately 1 cm. Salt was evenly applied at 1.5%, together with the respective concentrations of plant additives.

Although Janj cheese is traditionally formed into braids, the process was slightly modified in this study by shaping the cheese into rolls to better incorporate the plant additives. The finished cheese rolls were placed on an inclined surface for 30 min to allow final whey drainage. Finally, the samples were wrapped in plastic foil and stored at +4 °C until laboratory analysis.

Table 1. Concentration of plant additives used in Janj cheese production

Plants	Sample	Concentration (%)
-	1.1	-
Oregano (*Origanum vulgare*)	1.2	0.50
Basil (*Ocimum basilicum*)	1.3	0.50
Parsley (*Petroselinum crispum*)	1.4	0.50
Rosemary (*Salvia rosmarinus*)	1.5	0.50
Chives (*Allium schoenoprasum*)	1.6	0.50

Fatty acid analysis

Fatty acid methyl esters (FAMEs) were prepared from the cheese samples through direct esterification using a saturated solution of potassium hydroxide (KOH) in methanol. The fatty acid composition was determined using a Clarus 680 gas chromatograph (Perkin Elmer) equipped with a flame ionization detector (FID) and an Elite-wax L capillary column (60 m length, 0.32 mm internal diameter, 0.5 μm film thickness). A Sigma Aldrich Supelco 37-component FAME MIX was utilized as the analytical standard. The injector and detector temperatures were maintained at 250 °C, with a sample injection volume of 1 μL. The oven temperature program began at 60 °C for 2 minutes, increased to 200 °C at a rate of 10 °C/min, and then reached 240 °C at a rate of 5 °C/min, with a final hold time of 30 minutes. The total analysis duration was 54 minutes. Nitrogen served as the carrier gas at a flow rate of 1.5 mL/min, while hydrogen and air were used for the FID. Fatty acid content is expressed as a weight percentage of the total identified fatty acids (g/100 g of total fatty acids).

Based on the obtained fatty acid profiles, key indices were calculated to evaluate the nutritional quality and the impact of the lipid fraction on human health. The Atherogenicity Index (AI) and the Thrombogenicity Index (TI) were determined using the following equation [16], [17]:

$$AI=[\sum C12:0+(4\times C14:0)+C16:0]/\sum UFA$$

$$TI=(C14:0 + C16:0 + C18:0)/[(0.5\times\Sigma MUFA) + (0.5 \times\Sigma n\text{-}6\ PUFA) + (3\times\Sigma n\text{-}3\ PUFA) + (n\text{-}3/n\text{-}6)]$$

Additionally, the ratio of hypocholesterolemic to hypercholesterolemic fatty acids (h/H) was calculated according to the formula:

$$h/H= (cis\text{-}C18:1 + \Sigma PUFA)/(C12:0 + C14:0 + C16:0)$$

Furthermore, the proportion of desirable fatty acids (DFA), representing the sum of all unsaturated fatty acids and stearic acid, was calculated to assess the nutritional impact of plant additives [22], [14], [18]:

$$DFA=\sum MUFA+\sum PUFA+C18:0$$

Statistical analysis

Statistical processing of the experimental data was conducted using the Microsoft Excel 2013 software package and the IBM SPSS Statistics 22.0 computer program for Windows (Armonk, NY, United States). All analyses were performed in triplicate and results are presented as mean values ± standard deviation (SD) based on three randomly selected samples. The significance of differences between arithmetic means was determined using one-way analysis of variance (ANOVA) followed by Tukey HSD post-hoc tests for multiple comparisons. Statistical significance was defined at a 95% confidence level ($p < 0.05$).

RESULTS AND DISCUSSION

Analysis of the lipid profile of Janj cheese samples enriched with selected plant additives confirmed the characteristic predominance of saturated fatty acids (SFA), which accounted for more than 59% of total fatty acids in all analyzed samples (Table 4). Among SFAs, palmitic acid (C16:0), stearic acid (C18:0), and myristic acid (C14:0) were the most abundant, which is consistent with the fatty acid profiles previously reported for traditional brined cheeses from the Balkan region [14], [21]. The proportion of total SFA ranged from 59.34% in the oregano-treated sample (1.2) to 61.48% in the rosemary-treated sample (1.5), while the control sample contained 59.39% SFA. Slight increases in SFA content observed in samples containing parsley, rosemary, and chives were primarily associated with higher proportions of palmitic and stearic acids.

Despite the dominance of saturated fatty acids, all samples contained notable levels of unsaturated fatty acids (UFA), ranging from 38.53% to 40.66% (Table 4). Monounsaturated fatty acids (MUFA) represented the largest fraction of UFA, with oleic acid (C18:1) identified as the predominant component. The highest MUFA content was observed in basil-treated cheese (1.3; 34.86%), followed by oregano-treated cheese (1.2; 34.79%), whereas rosemary-treated cheese (1.5) showed the lowest value (33.39%). These findings are in agreement with previous studies indicating that traditional cheeses produced from raw milk and pasture-fed animals are naturally rich in oleic acid and other nutritionally relevant MUFAs [19].

The addition of plant additives influenced the polyunsaturated fatty acid (PUFA) fraction, particularly the content of α-linolenic acid (C18:3 n-3). While the control sample (1.1) contained only 0.13% α-linolenic acid, markedly higher values were detected in samples enriched with basil (1.3), parsley (1.4), rosemary (1.5), and chives (1.6), reaching values above 1.20% (Table 3). This increase contributed to a marked reduction in the n-6/n-3 ratio. The control sample exhibited relatively high n-6/n-3 ratio of 39.75, whereas samples enriched with parsley, rosemary, and chives showed considerably lower values ranging from 2.43 to 2.72. The oregano-treated sample (1.2) exhibited a lower n-6/n-3 ratio than the control (15.31 vs. 39.75), although its improvement was less pronounced compared to the other plant-treated samples, likely due to the lower n-3 fatty acid content of oregano. Contemporary nutritional recommendations emphasize the importance of maintaining a lower n-6/n-3 ratio in order to reduce inflammatory and cardiovascular risks. Excessive amounts of n-6 polyunsaturated fatty acids (PUFA) and a very high n-6/n-3 ratio promote the pathogenesis of many diseases, including cardiovascular disease, cancer, and inflammatory and autoimmune diseases, whereas increased levels of n-3 PUFA (a low n-6/n-3 ratio) exert suppressive effects [12]. Therefore, the observed reduction in this ratio suggests that the incorporation of selected herbs may positively influence the nutritional quality of Janj cheese.

The PUFA/SFA ratio ranged from 0.08 to 0.11, while the UFA/SFA ratio varied between 0.63 and 0.68 (Table 4). Although these values remain below the ratios generally recommended for a more favorable lipid profile, they are comparable to those reported for many traditional full-fat cheeses produced from cow's milk [17], [18]. The relatively low PUFA/MUFA ratio observed in all samples additionally confirms the predominance of monounsaturated fatty acids within the unsaturated lipid fraction.

Lipid quality indices provided additional insight into the nutritional characteristics of the analyzed cheeses. The atherogenicity index (AI) ranged from 1.51 to 1.65, while the thrombogenicity index (TI) varied from 2.05 to 2.32 (Table 4). The lowest AI and TI values were observed in oregano-treated cheese (1.2) and basil-treated cheese (1.3), indicating a slightly more favorable lipid profile compared to the control and other treated samples. These values were lower than those reported for commercial cow's milk cheeses, where AI reaches up to 3.06 and TI up to 3.87 [17]. Furthermore, the obtained values are comparable to those reported for traditional Mediterranean and Balkan cheeses produced under pasture-based systems, such as Greek Tsalafouti (AI: 1.65–2.99; TI: 1.99–3.06) [18] and Kupres cheese (AI: 1.55–1.76) [16]. The ratio of hypocholesterolemic to hypercholesterolemic fatty acids (h/H) ranged from 0.88 to 0.97, with the highest value observed in the oregano-treated sample. This range suggests an improvement in the balance of nutritionally desirable fatty acids, as the values for Janj cheese are comparatively

higher than the average reported for Tsalafouti cheese (0.695) and considerably above the levels for commercial cow's milk cheeses, which range from 0.43 to 0.49 [17], [18].

The proportion of desirable fatty acids (DFA), representing the sum of unsaturated fatty acids and stearic acid, exceeded 51% in all analyzed samples and reached the highest value in oregano-treated cheese (53.32%). These values are notably higher than those reported for commercial cow's milk cheeses (38.14–40.89%) [17] and various traditional white brined cow's milk cheeses from the Balkan region (34.45–46.34%) [16]. Furthermore, the DFA content in Janj cheese exceeds the values calculated for traditional Tsalafouti cheese, which range from approximately 35.6% to 49.7% [18]. These results indicate that the addition of selected plant additives may contribute to a modest improvement in the nutritional quality of Janj cheese without causing substantial alterations in its traditional lipid composition.

Overall, the obtained results suggest that the incorporation of aromatic and medicinal plants at a concentration of 0.50% may contribute to subtle but nutritionally relevant modifications in the fatty acid profile of Janj cheese, particularly through the enhancement of the n-3 PUFA fraction and improvement of the n-6/n-3 ratio. Such findings support the potential application of plant additives in the production of traditional dairy products while preserving their characteristic composition and regional identity.

Table 2. Content of saturated fatty acids in Janj cheese samples

Fatty acid	1.1	1.2	1.3	1.4	1.5	1.6
C4:0	$2.06^{b} \pm 0.04$	$1.61^{a} \pm 0.38$	$2.20^{b} \pm 0.02$	$2.22^{b} \pm 0.01$	$2.24^{b} \pm 0.06$	$2.22^{b} \pm 0.01$
C6:0	$1.19^{ab} \pm 0.04$	$1.08^{a} \pm 0.15$	$1.29^{b} \pm 0.02$	$1.29^{b} \pm 0.01$	$1.30^{b} \pm 0.02$	$1.29^{b} \pm 0.01$
C8:0	$0.71^{b} \pm 0.01$	$0.68^{a} \pm 0.01$	$0.75^{b} \pm 0.00$	$0.76^{b} \pm 0.00$	$0.76^{b} \pm 0.02$	$0.75^{b} \pm 0.00$
C10:0	$1.37^{a} \pm 0.05$	$1.45^{a} \pm 0.04$	$1.56^{b} \pm 0.00$	$1.58^{b} \pm 0.02$	$1.57^{b} \pm 0.03$	$1.56^{b} \pm 0.02$
C11:0	0.00 ± 0.00	0.00 ± 0.00	0.02 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
C12:0	$1.84^{ab} \pm 0.05$	$1.80^{a} \pm 0.03$	$1.88^{bc} \pm 0.00$	$1.92^{c} \pm 0.01$	$1.91^{bc} \pm 0.04$	$1.88^{bc} \pm 0.03$
C13:0	$0.11^{b} \pm 0.00$	$0.11^{b} \pm 0.01$	$0.08^{a} \pm 0.00$	$0.08^{a} \pm 0.00$	$0.08^{a} \pm 0.00$	$0.08^{a} \pm 0.01$
C14:0	$8.08^{ab} \pm 0.16$	$8.03^{a} \pm 0.02$	$8.14^{abc} \pm 0.02$	$8.23^{bc} \pm 0.05$	$8.31^{c} \pm 0.08$	$8.27^{c} \pm 0.13$
C15:0	$1.74^{ab} \pm 0.04$	$1.73^{a} \pm 0.00$	$1.76^{abc} \pm 0.00$	$1.77^{bcd} \pm 0.02$	$1.81^{d} \pm 0.01$	$1.80^{cd} \pm 0.02$
C16:0	$27.53^{a} \pm 0.78$	$27.61^{a} \pm 0.14$	$27.69^{a} \pm 0.01$	$27.99^{ab} \pm 0.28$	$28.53^{b} \pm 0.22$	$28.47^{b} \pm 0.33$
C17:0	$1.45^{c} \pm 0.07$	$1.33^{b} \pm 0.01$	$1.24^{a} \pm 0.03$	$1.24^{a} \pm 0.04$	$1.28^{ab} \pm 0.02$	$1.24^{a} \pm 0.05$
C18:0	$12.44^{a} \pm 0.53$	$12.66^{ab} \pm 0.05$	$12.63^{a} \pm 0.00$	$12.78^{abc} \pm 0.19$	$13.14^{c} \pm 0.09$	$13.12^{bc} \pm 0.14$
C20:0	0.42 ± 0.05	0.45 ± 0.00	0.43 ± 0.01	0.44 ± 0.01	0.45 ± 0.01	0.45 ± 0.01
C21:0	$0.14^{b} \pm 0.09$	$0.09^{b} \pm 0.00$	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
C22:0	$0.03^{a} \pm 0.01$	$0.20^{ab} \pm 0.01$	$0.16^{ab} \pm 0.01$	$0.25^{b} \pm 0.22$	$0.10^{ab} \pm 0.01$	$0.16^{ab} \pm 0.07$
C23:0	0.00 ± 0.00	$0.19^{bc} \pm 0.01$	$0.15^{b} \pm 0.03$	$0.20^{c} \pm 0.04$	0.00 ± 0.00	0.00 ± 0.00
C24:0	$0.28^{b} \pm 0.02$	$0.32^{b} \pm 0.01$	$0.36^{bc} \pm 0.00$	$0.47^{c} \pm 0.14$	$0.00^{a} \pm 0.00$	$0.00^{a} \pm 0.00$

[a-c] Statistically significant differences ($p < 0.05$) are indicated by different lowercase letters within rows

Table 3. Content of unsaturated fatty acids in Janj cheese samples

Fatty acid	1.1	1.2	1.3	1.4	1.5	1.6
C14:1	$0.64^{b} \pm 0.09$	$0.55^{a} \pm 0.00$	$0.56^{a} \pm 0.01$	$0.57^{a} \pm 0.02$	$0.60^{ab} \pm 0.01$	$0.65^{b} \pm 0.03$
C15:1	0.50 ± 0.02	0.51 ± 0.01	0.51 ± 0.01	0.51 ± 0.00	0.52 ± 0.00	0.52 ± 0.01
C16:1	$0.99^{ab} \pm 0.12$	$1.99^{b} \pm 0.00$	$2.00^{b} \pm 0.02$	$0.05^{a} \pm 0.00$	$0.06^{a} \pm 0.01$	$0.06^{a} \pm 0.02$
C17:1	$0.75^{d} \pm 0.05$	$0.69^{c} \pm 0.04$	$0.61^{a} \pm 0.00$	$0.63^{ab} \pm 0.01$	$0.66^{abc} \pm 0.01$	$0.67^{bc} \pm 0.01$
C18:1	$29.19^{a} \pm 1.94$	$30.55^{ab} \pm 0.31$	$30.72^{ab} \pm 0.05$	$31.15^{b} \pm 0.40$	$31.02^{ab} \pm 0.34$	$31.14^{b} \pm 1.22$
C20:1	$1.33^{b} \pm 0.49$	$0.39^{a} \pm 0.07$	$0.31^{a} \pm 0.01$	$0.28^{a} \pm 0.05$	$0.28^{a} \pm 0.04$	$0.47^{a} \pm 0.25$
C22:1	$0.69^{b} \pm 0.06$	$0.11^{a} \pm 0.03$	$0.15^{a} \pm 0.03$	$0.27^{a} \pm 0.20$	$0.25^{a} \pm 0.00$	$0.30^{a} \pm 0.14$
C18:2 c+t	$1.30^{a} \pm 0.23$	$2.25^{ab} \pm 0.04$	$2.82^{b} \pm 0.03$	$2.85^{b} \pm 0.07$	$2.54^{ab} \pm 0.33$	$1.69^{ab} \pm 0.87$
C18:3 n-6	$0.36^{c} \pm 0.03$	$0.32^{bc} \pm 0.01$	$0.24^{a} \pm 0.01$	$0.30^{b} \pm 0.06$	$0.27^{ab} \pm 0.01$	$0.26^{ab} \pm 0.01$
C18:3 n-3	$0.13^{a} \pm 0.05$	$0.09^{a} \pm 0.01$	$1.20^{b} \pm 0.00$	$1.24^{bc} \pm 0.01$	$1.28^{d} \pm 0.01$	$1.27^{cd} \pm 0.01$
C20:2	$4.28^{c} \pm 2.04$	$2.60^{b} \pm 0.00$	$0.31^{a} \pm 0.01$	$0.54^{a} \pm 0.03$	$0.95^{ab} \pm 0.11$	$1.53^{ab} \pm 0.52$
C20:3 n-6	0.28 ± 0.18	0.19 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
C20:3 n-3	0.00 ± 0.00	0.07 ± 0.01	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
C20:4	0.14 ± 0.08	0.15 ± 0.01	0.08 ± 0.01	0.17 ± 0.10	0.00 ± 0.00	0.00 ± 0.00
C20:5	$0.03^{a} \pm 0.01$	$0.20^{ab} \pm 0.01$	$0.16^{ab} \pm 0.01$	$0.25^{b} \pm 0.22$	$0.10^{ab} \pm 0.01$	$0.16^{ab} \pm 0.07$

[a-c] Statistically significant differences ($p < 0.05$) are indicated by different lowercase letters within rows

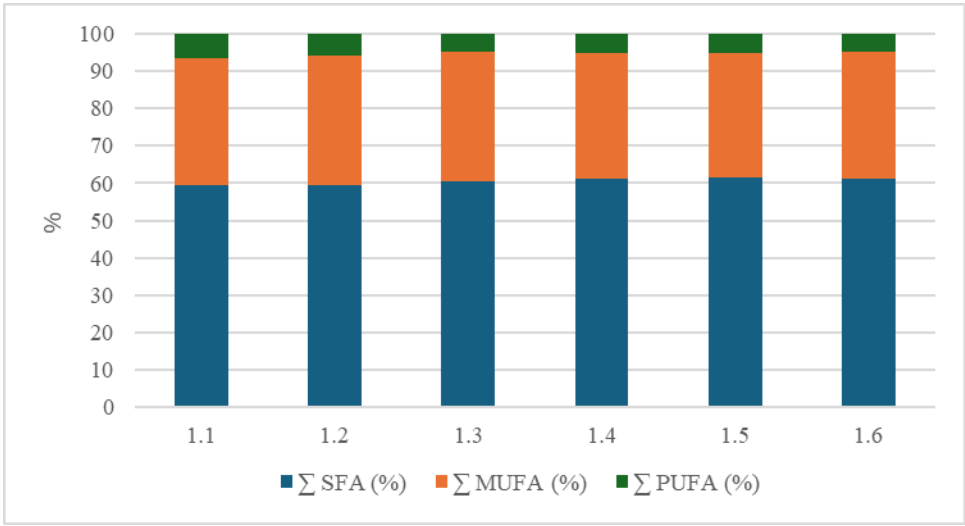

Figure 1. Distribution of fatty acids in Janj cheese samples

Table 4. Fatty acid profile and lipid quality indices of Janj cheese samples

Parameter / Sample	1.1	1.2	1.3	1.4	1.5	1.6
∑ SFA (%)	59.39	59.34	60.34	61.22	61.48	61.29
∑ UFA (%)	40.61	40.66	39.67	38.81	38.53	38.72
∑ MUFA (%)	34.09	34.79	34.86	33.46	33.39	33.81
∑ PUFA (%)	6.52	5.87	4.81	5.35	5.14	4.91
UFA/SFA	0.68	0.68	0.66	0.63	0.63	0.63
PUFA/MUFA	0.19	0.17	0.14	0.16	0.15	0.15
PUFA/SFA	0.11	0.10	0.08	0.09	0.08	0.08
n-6/n-3	39.75	15.31	2.54	2.59	2.72	2.43
DFA (%)	53.05	53.32	52.30	51.59	51.67	51.84
AI	1.52	1.51	1.57	1.62	1.65	1.64
TI	2.32	2.27	2.05	2.08	2.17	2.14
h/H	0.95	0.97	0.94	0.96	0.93	0.93

CONCLUSION

The results of this study indicate that the addition of selected plant additives can modify the fatty acid composition of traditional Janj cheese. Although all samples retained the typical fatty acid profile of ruminant milk cheeses, characterized by a predominance of saturated fatty acids, the addition of plant additives, particularly basil, parsley, rosemary, and chives, contributed to modifications in the polyunsaturated fatty acid fraction, especially n-3 fatty acids, as well as to a more favorable n-6/n-3 ratio. Improvements in the fatty acid profile were also reflected in lipid quality indices, with slightly lower atherogenicity and thrombogenicity indices and favorable h/H ratios observed in several enriched samples compared to the control. These findings suggest that the incorporation of plant additives may represent a simple and sustainable approach for enhancing certain nutritional aspects of Janj cheese while preserving its traditional production technology and authentic characteristics.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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PHYSICOCHEMICAL AND SENSORY CHARACTERIZATION OF HONEY AND ITS ADULTERANTS

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ABSTRACT

The honey market in Bosnia and Herzegovina faces significant challenges regarding product authenticity and quality control. The lack of a well-regulated inspection system, combined with limited consumer awareness, creates favorable conditions for the distribution of adulterated products. In this study, 25 honey samples were examined: 10 honey samples within their declared shelf life, 7 samples older than three years, 3 commercially available samples suspected of adulteration, and 5 laboratory-prepared adulterants consisting of inverted sugar syrups with varying proportions of honey and tartaric acid. Physicochemical analysis included determination of sugar content, ash content, water content, total acidity, hydroxymethylfurfural (HMF) concentration, and electrical conductivity, conducted in accordance with applicable regulations. Sensory evaluation was performed using descriptive testing methods by trained assessors. Only four of the ten samples within shelf life were in accordance with all chemical parameters, while the remaining six exhibited elevated HMF values, excessive moisture, or increased acidity. All samples older than three years showed markedly elevated HMF content (174–1478 mg/kg). Two of the three suspected commercial samples were confirmed as adulterated by chemical analysis, and none passed sensory evaluation. All laboratory adulterants failed chemical testing, while sensory evaluation identified them as adulterated in only 55% of cases. Overall, two-thirds of declared honey samples were sensorily accepted, while fewer than half were chemically correct. The findings demonstrate that current prescribed analytical methods are insufficient to guarantee honey authenticity, and the introduction of additional detection methods along with stricter market surveillance is strongly recommended.

Keywords: honey, adulteration, quality control, physicochemical analysis, sensory evaluation.

INTRODUCTION

Honey has been a foodstuff of particular importance to human nutrition since antiquity, with its use dating back at least 10,000 years, as evidenced by a cave painting depicting honey gathering discovered in the Cueva de la Araña, Valencia, Spain. Throughout history, honey has been used not only as a food but also for medicinal purposes in the treatment of wounds and various ailments, in the mummification process in ancient Egypt, and even as a means of tax payment in the Roman Empire, while China is regarded as the cradle of organised beekeeping [1].

Honey consists essentially of different sugars (up to 80%), predominantly fructose and glucose, and water (approximately 17%), together with minor constituents such as organic acids, minerals, vitamins, enzymes, pigments, volatile oils, and aromatic substances. Carbohydrates are primarily responsible for determining key physicochemical properties such as viscosity, granulation, and hygroscopicity. Organic acids are present in the smallest quantities (approximately 0.5%) and include lactic, citric, butyric, propionic, formic, acetic, tartaric, succinic, oxalic, gluconic, and malic acids. In addition, honey mineral content ranges from 0.04% to 0.2%, consisting of macro- and microelements [2]. Honey has a low water activity and an acidic pH, and creates an inhospitable environment for microorganisms [3].

Its consistency may range from fluid to viscous, or from partly to entirely crystallised. Owing to its botanical origin, taste and aroma vary considerably, and color ranges from almost colorless to dark brown [4]. Honey is readily digestible, rapidly and almost completely metabolized, and represents a natural source of energy (approximately 1270–1320 kJ per 100 g), owing primarily to its high content of readily absorbable monosaccharides, glucose and fructose [5].

Honey quality is traditionally assessed based on a range of physicochemical parameters (Table 1), as defined by the applicable national regulation on honey and other bee products [6]. These parameters serve not only to assess overall quality but also as indicators of botanical and geographical origin, storage conditions, thermal treatment, and potential adulteration [7].

Table 1. Quality requirements for honey according to the current national regulation

Quality parameter	Honey type	Regulatory limit
Reducing sugars (glucose + fructose)	Blossom honey	≥ 60 g/100 g
	Honeydew honey and blends	≥ 45 g/100 g
Sucrose content	General requirement	≤ 5 g/100 g
	Honeydew, acacia, and lavender honey	≤ 10 g/100 g
Moisture content	All honey types	≤ 20 g/100 g
Electrical conductivity	Blossom honey (except those listed below) and blends Exceptions include linden, heather, and honeydew honey.	≤ 0.8 mS/cm
	Honeydew honey, chestnut honey, and their blends	> 0.8 mS/cm
Free acidity	All honey types	≤ 50 meq/kg
Hydroxymethylfurfural (HMF)	All honey types	≤ 40 mg/kg

Sensory analysis encompasses the evaluation of color, viscosity, crystallisation, odor, aroma, and taste, and is used to confirm botanical origin, verify the absence of sensory defects, and understand consumer preferences. Sensory evaluation can reveal defects such as fermentation, foreign odors (e.g., smoke), metallic taste, or inconsistency with the declared botanical origin, defects that standard physicochemical analyses cannot always detect [8].

Honey, as a high-value food product, is highly susceptible to adulteration through the addition of inexpensive commercial sugar syrups such as high-fructose corn syrup, glucose syrup, invert sugar syrup, cane sugar syrup, and rice or wheat syrups, or indirect feeding of bees with syrups during the production period, premature extraction of immature honey, mislabelling of geographical origin, or thermal treatment aimed at removing natural crystallisation. Such adulteration alters the chemical composition of honey, reduces its bioactive compounds, and consequently diminishes its nutritional quality, authenticity, and commercial value [9], [10]. Although advanced analytical techniques (spectroscopic, chromatographic, isotopic) provide high specificity and reliability in confirming adulteration, basic physicochemical parameters (moisture,

pH, electrical conductivity, HMF) remain a valuable and accessible tool for preliminary screening of honey authenticity [11].

The present study was motivated by the widespread occurrence of adulterated products marketed and labelled as honey. Considering the above, this study aimed to compare the physicochemical composition with the sensory properties of both honey and its adulterants to define reliable indicators for the detection of adulteration.

MATERIALS AND METHODS

A total of 25 samples were examined, divided into four groups: 10 honey samples within their declared shelf life, 7 samples older than three years, 3 commercially available samples suspected of adulteration, and 5 laboratory-prepared adulterants consisting of inverted sugar syrups with varying proportions of honey and tartaric acid (Table 2).

Table 2. Honey samples

Sample	Notes	Sample
N1	Declared honey, within shelf life	Acacia honey
N2		Meadow honey
N3		Meadow honey
N4		Oak honeydew
N5		Fructose honey
N6		Sage honey
N7		Heather honey
N8		Buckwheat honey
N9		Chestnut honey
N10		Oak honeydew
O1	Honey >3 years old	Acacia honey
O2		Meadow honey
O3		Meadow honey
O4		Honeydew
O5		Linden honey
O6		Honey with fruit
O7		Acacia honey, with honeycomb
SA1	No label; purchased at open market	suspected of adulteration
SA2		suspected of adulteration
SA3		suspected of adulteration
LA1	Lab-prepared adulterant	Inverted sucrose, 1 g tartaric acid
LA2		Inverted sucrose + 1 g tartaric acid + 7.5% acacia honey
LA3		Inverted sucrose + 1 g tartaric acid + 20% acacia honey
LA4		Inverted sucrose+1g tartaric acid+40% acacia honey; incubated 15 days at 35°C
LA5		Inverted sucrose + 2 g tartaric acid

Physicochemical analysis included determination of sugar content (total sugar content, TSC; reducing sugar content, RSC; and sucrose content, SC), ash content, moisture, total acidity (TA), hydroxymethylfurfural (HMF) concentration, and electrical conductivity (EC), conducted in

accordance with the applicable regulation on methods for the control of honey and other bee products [12]. Results are expressed as mean values ± standard deviation (SD) of three replicates.

Sensory evaluation was performed using descriptive testing methods by trained assessors. The evaluation was based on the color, consistency, odor, aroma, and taste of honey to distinguish genuine from adulterated honey.

Statistical analysis was performed using one-way ANOVA followed by Tukey's HSD post-hoc test, using IBM SPSS Statistics 22.0, with statistical significance set at $p < 0.05$.

RESULTS AND DISCUSSION

The results of the physicochemical analysis of the analyzed honey samples are presented in Table 3. Statistically significant differences were observed between samples ($p < 0.05$).

The total sugar content (TSC) ranged widely, from 58.5% (O4) to 77.9% (N6 and LA1), with the majority of genuine honey samples clustering above 65%. Reducing sugar content ranged from 22.5% to 74.2%. All commercial and suspicious market samples contained more than 60 g/100 g reducing sugars, complying with the regulatory requirements for blossom honey. In contrast, laboratory-prepared adulterated samples LA2 (22.5%) and LA3 (39.2%) were well below the minimum permitted value, clearly indicating the addition of sucrose-based sweeteners. Sucrose content showed the greatest variability, ranging from 0.1% (O5) to 49.7% (LA2).

Table 3. Physicochemical characteristics of the analyzed honey samples

	TSC (%)	RSC (%)	SC (%)	EC (mS/cm)	Ash (%)	moisture (%)	TA (mmol/kg)	HMF (mg/kg)
N1	74.4^{jk}±0.7	72.0^{l}±0.7	2.3^{cde}±0.2	0.14^{a}±0.03	0.10^{a}±0.01	15.8^{a}	11.1^{b}±0.3	6.9^{abc}±0.7
N2	70.6^{gh}±0.7	70.0^{j}±0.4	0.6^{ab}±0.1	0.34^{a}±0.05	0.20^{a}±0.07	21.0^{a}	48.5^{q}±05	11.2^{bcd}±0.4
N3	72.4^{i}±0.6	69.7^{j}±0.5	2.5^{cdef}±0.1	0.27^{a}±0.04	0.09^{a}±0.04	19.0^{a}	32.3^{l}±0.4	18.0^{d}±0.3
N4	65.8^{d}±0.5	63.4^{g}±0.4	2.2^{cde}±0.1	0.26^{a}±0.03	0.15^{a}±0.06	23.0^{a}	37.7^{n}±0.4	4.5^{abc}±0.3
N5	68.3^{ef}±0.5	60.7^{e}±0.3	7.3^{i}±0.2	O.04^{a}±0.00	0.01^{a}±0.00	19.6^{a}	3.7^{a}±0.1	247.2^{j}±3.6
N6	77.9^{m}±0.7	70.4^{jk}±0.9	7.1^{i}±0.4	0.49^{a}±0.16	0.34^{a}±0.16	18.4^{a}	40.6^{p}±0.2	2.6^{ab}±0.2
N7	69.8^{fg}±0.3	67.3^{i}±0.8	2.4^{cde}±0.1	0.53^{a}±0.13	0.38^{a}±0.13	17.4^{a}	17.0^{fg}±0.1	2.5^{ab}±0.2
N8	70.4^{g}±0.5	67.9^{i}±0.3	2.4^{cde}±0.1	0.40^{a}±0.14	0.28^{a}±0.14	18.2^{a}	56.1^{r}±0.2	56.0^{e}±0.5
N9	73.0^{ij}±0.4	70.1^{j}±0.5	2.8^{defg}±0.1	0.73^{a}±0.16	0.43^{a}±0.16	17.0^{a}	26.7^{k}±0.1	1.9^{a}±0.1
N10	63.1^{c}±0.5	61.3^{ef}±0.3	1.7^{bcd}±0.2	15.98^{b}±1.54	13.55^{b}±0.85	17.4^{b}	99.9^{s}±0.6	17.5^{d}±0.2
O1	67.6^{e}±1.1	67.1^{i}±0.8	0.5^{ab}±0.1	0.14^{a}±0.02	0.03^{a}±0.01	18.0^{a}	16.1^{ef}±0.7	455.7^{l}±8.0
O2	70.4^{g}±1.0	67.1^{i}±0.7	3.1^{efg}±0.3	0.22^{a}±0.04	0.06^{a}±0.01	17.2^{a}	35.7^{m}±1.0	1405.9^{o}±9.7
O3	69.5^{fg}±0.9	65.5^{h}±0.7	3.8^{fgh}±0.2	0.26^{a}±0.05	0.07^{a}±0.02	18.2^{a}	38.7^{no}±0.8	1478.3^{p}±6.4
O4	58.5^{a}±0.6	55.2^{d}±0.5	3.1^{efg}±0.1	0.74^{a}±0.13	0.57^{a}±0.18	16.4^{a}	39.2^{o}±0.6	174.9^{g}±4.5
O5	74.3^{jk}±0.5	74.2^{m}±0.4	0.1^{a}±0.0	0.49^{a}±0.10	0.35^{a}±0.15	18.8^{a}	14.8^{d}±0.3	0^{a}
O6	60.7^{b}±0.5	31.3^{b}±0.3	27.9^{k}±0.6	0.12^{a}±0.02	0.07^{a}±0.02	17.8^{a}	23.1^{i}±0.9	263.9^{k}±5.8
O7	73.3^{ij}±0.6	68.2^{i}±0.4	4.9^{b}±0.2	0.12^{a}±0.02	0.02^{a}±0.00	18.4^{a}	15.7^{de}±0.5	188.1^{h}±4.1
SA1	72.2^{i}±0.7	70.7^{jk}±0.5	1.5^{bc}±0.6	0.18^{a}±0.05	0.07^{a}±0.01	18.6^{a}	21.7^{h}±0.3	51.4^{e}±1.4
SA2	72.5^{i}±0.7	70.8^{jkl}±0.4	1.6^{bcd}±0.2	0.10^{a}±0.04	0.1^{a}±0.03	19.6^{a}	12.1^{bc}±0.1	13.4^{cd}±0.6
SA3	73.6^{ij}±0.5	69.8^{j}±0.4	3.8^{fgh}±0.2	0.14^{a}±0.04	0^{a}	17.2^{a}	27.2^{k}±0.5	1083.2^{n}±7.6
LA1	77.9^{m}±0.8	61.8^{ef}±0.6	15.4^{j}±0.3	0.11^{a}±0.03	0^{a}	17.8^{a}	12.1^{bc}±0.3	110.2^{f}±1.9
LA2	72.1^{hi}±0.9	22.5^{a}±0.5	49.7^{m}±0.3	0.07^{a}±0.01	0^{a}	18.4^{a}	12.4^{c}±0.2	0^{a}
LA3	75.8^{kl}±1.1	39.2^{c}±0.7	36.5^{l}±0.4	0.10^{a}±0.01	0^{a}	17.0^{a}	16.9^{fg}±0.2	4.5^{abc}±0.1
LA4	70.6^{gh}±0.7	62.3^{fg}±0.5	8.4^{i}±0.2	0.11^{a}±0.02	0^{a}	17.2^{a}	17.6^{g}±0.1	202.1^{i}±4.5
LA5	76.1^{l}±0.8	71.5^{kl}±0.4	4.6^{b}±0.4	0.19^{a}±0.03	0^{a}	19.2^{a}	25.1^{j}±0.5	523.1^{m}±5.8

$^{a-s}$ Mean values with different letters in the same column differ significantly ($p < 0.05$).

Most authentic commercial samples met the maximum permitted value of 5 g/100 g; however, elevated sucrose concentrations were observed in N5, N6, O6, and all laboratory-prepared adulterated samples, particularly LA2 (49.7%) and LA3 (36.5%). Such values are inconsistent with the composition of mature natural honey and strongly suggest adulteration with commercial sugars. Previous studies have reported that nectar-derived honey is typically characterized by a TSC value above 60%, while increased sucrose levels are considered indicative of premature harvesting or possible adulteration [13], [14].

Electrical conductivity in samples ranged from 0.04 to 0.74 mS/cm (samples N5 and O4, respectively), whereas sample N10 exhibited a markedly elevated value (15.98 mS/cm), which statistically distinguished it from all other samples. A similar pattern was observed for ash content, with samples N1–N9 containing 0.01–0.43% ash, whereas sample N10 exhibited a markedly higher value of 13.55%. Notably, ash was undetectable (0%) in most laboratory adulterants (LA2–LA5, SA3), consistent with the expected dilution of mineral content when sucrose/inverted syrup replaces the natural honey matrix. The electrical conductivity of honey results from the presence of mineral salts and organic acids and is directly related to botanical origin, allowing certain honey types to be distinguished on this basis. Similar results for electrical conductivity were reported by some authors [3]. The absence of ash content in all adulterated samples was consistent with the fact that added sugar syrups alter the mineral and elemental composition of honey [2].

Moisture values were relatively homogeneous across the dataset (15.8–23.0%), without a clear separation between genuine and adulterated groups. Most samples complied with the regulatory limit of 20%, whereas N2 (21.0%) and N4 (23.0%) exceeded the maximum permitted value, indicating an increased risk of fermentation and reduced storage stability. The significant increase in honey moisture content was possibly attributable to intensified metabolic reactions occurring at elevated storage temperatures [15]. Elevated moisture can adversely affect honey quality during storage, as it creates favorable conditions for microbial activity, including fermentation [13].

Free acidity ranged from 3.7 to 99.9 mmol/kg (N5 and N10, respectively). Most samples complied with the regulatory limit of 50 mmol/kg, samples N8 (56.1 mmol/kg) and N10 (99.9 mmol/kg) exceeded the permitted value, indicating possible fermentation or deterioration during storage. Higher acidity reflects a greater concentration of organic acids derived from specific nectar sources as well as enzymatic activity during honey maturation, and is influenced by botanical origin and regional environmental conditions [14].

The greatest differences were observed for HMF content, which ranged from non-detectable (samples O5 and LA2) to 1478.3 mg/kg (sample O3). While HMF concentrations in fresh commercial samples were generally below the regulatory limit of 40 mg/kg, aged samples (O1–O7) showed substantially higher values, reaching more than 1400 mg/kg. Similarly, laboratory-prepared adulterated samples and suspicious market samples showed markedly elevated HMF concentrations, especially LA5 (523.1 mg/kg) and SA3 (1083.2 mg/kg). These findings indicate that HMF content was markedly affected by prolonged storage, thermal processing, and sugar syrup adulteration. Freshly harvested honey contains negligible or very low HMF concentrations (≤15 mg/kg), whereas elevated HMF levels are associated with prolonged storage, excessive heating, or adulteration with invert sugar syrups [14-17]. Sugar composition, particularly sucrose and reducing sugar content, is among the most sensitive indicators of honey adulteration [2], [18], [19]. The addition of sugar syrups alters the carbohydrate profile and often increases HMF, while certain adulterants may also affect moisture, pH, and electrical conductivity [17], [19]. Consequently, the combined evaluation of HMF and sugar composition provides a more reliable basis for detecting adulteration than either parameter alone.

Most samples within their shelf life were satisfactory according to the RSC, SC, moisture, and EC requirements. N1, N7, and N9 were fully compliant across all six parameters and can be regarded as reference-quality honey. However, several regulatory breaches were identified: N2 and N4 exceeded the 20 g/100 g moisture limit. N8 exceeded both the acidity and HMF limits, while N10 greatly exceeded the acidity limit (99.9 meq/kg) and showed an EC value and ash content that indicated an atypical, non-blossom origin rather than a simple quality defect.

For honey samples older than three years (O1–O7), HMF was the parameter most frequently and most substantially exceeded., with O1–O3 exceeding the 40 mg/kg limit by more than tenfold (455.7–1478.3 mg/kg) as a direct consequence of prolonged storage, while all other quality parameters (RSC, SC, moisture, EC, acidity) remained within regulatory limits for these three samples. O5 was the only sample in this group fully compliant with all parameters, including non-detectable HMF, representing the best-preserved profile despite its age.

Among samples suspected of adulteration (SA1–SA3), SA2 was fully compliant with all regulated parameters. SA1 showed only a marginal HMF exceedance (51.4 vs. 40 mg/kg), while SA3 grossly exceeded the HMF limit (1083.2 mg/kg), providing strong chemical grounds for rejecting this sample despite other quality parameters all falling within permitted ranges.

Laboratory-prepared adulterants (LA1–LA5) best illustrate the limitations of relying on any single regulatory parameter. LA2 and LA3 had RSC well below the 45–60 g/100 g range and SC far above the 5–10 g/100 g range, yet their HMF values were negligible (0 and 4.5 mg/kg). Samples LA4 and LA5 showed RSC and SC values within or close to the permitted range, but both highly exceeded the HMF limit. LA1 was the only sample showing both sugar-related limits and HMF higher than allowed.

Sensory evaluation of samples within their shelf life classified seven of the ten samples as authentic honey, while three samples were not accepted. Sample N2 exhibited a pronounced sour taste, likely resulting from elevated moisture content that induced fermentation. Sample N3 was suspected of containing added table sugar (sucrose) and exhibited an inadequate, heterogeneous consistency. Sample N4 was rejected owing to an atypical odor and taste, with a white foam layer several millimetres thick observed on its surface, characteristic of fermentation.

Sensory evaluation revealed that samples O1–O6 were not accepted for consumption owing to pronounced changes in odor, taste, and consistency resulting from prolonged storage. In contrast, sample O7 was assessed as authentic honey and was fully accepted by the assessors. Notably, the presence of a piece of comb within the honey likely further influenced the perceived authenticity of the sample, even though physicochemical analysis revealed an elevated HMF content. This sample remained entirely homogeneous and in a liquid state after several years of storage, with no visible crystallisation, which was in agreement with the typical characteristics of acacia honey, including a higher fructose-to-glucose ratio, slower crystallisation, and lower acidity and HMF values [20].

Sensory analysis revealed that the physicochemical results were not always consistent with assessors' perception. For sample SA1, assessors were uncertain whether the sample constituted honey based on taste, odor, and aroma, whereas color and consistency were assessed by all evaluators as characteristic of honey. In contrast, sample SA2 was rated as the sensorially poorest sample, particularly with respect to taste and consistency, despite fully meeting the requirements prescribed by the regulation according to the physicochemical analysis. Sample SA3 was accepted as natural honey.

Sensory evaluation of the laboratory-prepared adulterants showed that sample LA1 had less acceptable color, odor, and aroma, while taste and consistency were rated as relatively acceptable. Samples LA2 and LA3 were satisfactory in terms of color, consistency, and odor, but their taste and aroma were rated as atypical. Sample LA4 was particularly noteworthy, as the assessors expressed no suspicion of adulteration: consistency, color, taste, odor, and aroma were all rated as characteristic of natural honey, despite physicochemical results indicating substantial deviations. Sample LA5 was not accepted by the assessors concerning taste, odor, and aroma. The addition of a small proportion of natural honey to laboratory-prepared adulterated samples may hinder the sensory detection of quality deviations, which was consistent with previous findings showing that low levels of adulteration are more difficult to identify, particularly in acacia honey [9]. This confirms that sensory evaluation alone is insufficient for the reliable detection of honey adulteration and should always be interpreted together with physicochemical indicators, as conventional analytical approaches generally provide only a preliminary assessment of honey authenticity [9], [21], [22]. A similar pattern was reported by Bodor et al. [9], who found that trained assessors were able to distinguish authentic and adulterated acacia honey samples based on

only four sensory attributes, whereas eight sensory attributes differed significantly in linden honey. These findings indicate the limited sensitivity of human sensory perception, particularly at low levels of syrup adulteration. More broadly, honey authentication remains a challenging analytical task because no single method can reliably detect all forms of adulteration [21], [23], [24].

Therefore, recent studies recommend combining routine physicochemical analyses with advanced instrumental techniques and chemometric approaches to improve the reliability of honey authentication [2], [14], [22]. Physicochemical parameters remain essential because they are standardized indicators of honey maturity, stability, and quality; however, they are also influenced by thermal processing, storage conditions, and the addition of sugar syrups [2].

Although sensory analysis is valuable for identifying some adulterated samples, it is more commonly used to differentiate botanical origin and assess overall sensory quality than to provide definitive evidence of adulteration [9], [20]. Consequently, discrepancies between sensory and physicochemical evaluations, as observed in the present study, should be regarded as an expected outcome rather than a contradiction, reflecting the complementary nature and inherent limitations of these two approaches [18], [20].

Electronic nose and electronic tongue technologies have demonstrated high classification accuracy, with misclassifications occurring primarily in samples containing approximately 10% added sugar syrup [9]. Rapid spectroscopic techniques, including portable FT-IR spectroscopy, UV-Vis spectroscopy combined with chemometric analysis, and ion mobility spectrometry (IMS), are increasingly being proposed as practical tools for market surveillance because they enable the rapid discrimination of authentic and adulterated honey samples while requiring less complex analytical procedures [10], [25], [26].

CONCLUSION

The findings of this study demonstrate that the combined application of physicochemical and sensory analyses provides a reliable approach for assessing honey quality and authenticity. Physicochemical analysis revealed significant differences between honey within shelf life, aged honey, suspected of adulteration, and laboratory-prepared adulterated samples. HMF, sucrose, reducing sugar, and moisture content emerged as the most sensitive indicators of deviation. Elevated HMF values were observed in both long-term stored samples and certain laboratory-prepared adulterants, indicating that HMF reflects thermal treatment and honey ageing but, on its own, is not a reliable indicator of adulteration. The laboratory-prepared adulterants confirmed that sugar syrup addition significantly modified the chemical composition of honey, most notably through elevated sucrose levels and reduced reducing sugar content.

Sensory analysis enabled the recognition of most samples with pronounced deviations, but was not sufficient to reliably distinguish all adulterated samples from authentic ones. Certain adulterated samples were sensorially assessed as natural honey, while some samples that met the prescribed physicochemical criteria received poor sensory scores. These results indicate that visual appearance, the presence of honeycomb, or particular consistency characteristics may influence the assessors' subjective evaluations. At the same time, samples with pronounced physicochemical deviations generally exhibited sensory changes that were readily detectable.

It can therefore be concluded that neither physicochemical nor sensory analysis alone is sufficient for the reliable assessment of honey authenticity. Their combined application can substantially increase the reliability of identifying non-authentic and substandard samples, which is of particular importance for consumer protection and for combating honey adulteration.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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NATURAL SCIENCES
PRIRODNE NAUKE

ENHANCEMENT OF IONIZATION RATES FORMULAS IN TUNNELING AND BARRIER-SUPPRESSION REGIMES

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ABSTRACT

The precise modelling of laser–target interactions in the regimes of tunneling and barrier-suppression ionizations is important, as these mechanisms dominate in the strong-field regime. In this study, we examine the dynamics of the transition from tunneling to barrier-suppression ionization by applying an empirically adapted formula. Within an enhanced analytical framework, the shift between these two ionization regimes is characterized more clearly. The proposed model preserves the computational efficiency of analytical approaches by improving their physical consistency. While it is generally accepted that the ionization rate depends on the intensity of the applied laser field, our findings indicate that it is also influenced by the initial momentum of the outgoing electron, as well as by the laser frequency. We further demonstrate that, in addition to long-range Coulomb interactions, these effects play a significant role in the strong-field ionization domain, providing a basis for exploring new mechanisms in intense laser–matter interactions.

Keywords: strong-field ionization, laser intensity, initial momentum, Coulomb interactions

INTRODUCTION

The continuous development of laser technology, along with experimental and theoretical advancements, has greatly enhanced our understanding of light-matter interactions. The newfound availability of laser pulses with high intensity and short duration has opened avenues for studying atomic and molecular dynamics on their natural time scales. The electronic configuration of atoms and molecules can be significantly altered by intense laser fields, leading to nonlinear dynamics that lie beyond the scope of perturbation theory [1], [2], [3]. Laser-induced ionization is one of the

fundamental processes in modern strong-field physics and has been the subject of extensive theoretical and experimental investigations over the past several decades [4]. Depending on the intensity of the applied laser field and its frequency, different ionization mechanisms can dominate. The multiphoton ionization regime (MPI) is characterized by the absorption of several photons whose cumulative energy is sufficient to overcome the ionization potential of the target. As the laser intensity increases, the electric field of the laser significantly distorts the Coulomb potential experienced by the bound electron, leading to the tunneling ionization regime (TI). In this process, the electron escapes by quantum-mechanical tunneling through the field-lowered potential barrier, even when the photon energy alone is insufficient to overcome the binding energy [5], [6], [7], [8]. For even stronger laser fields, the Coulomb barrier can be suppressed below the energy level of the bound electron, enabling direct electron escape without tunneling. This mechanism, known as barrier-suppression ionization (BSI) represents the extreme limit of strong-field ionization [9], [10], [11].

The distinction between multiphoton and tunneling ionization regimes is commonly characterized by the Keldysh parameter γ, which provides a measure of the relative importance of photon absorption and tunneling dynamics [5]. In atomic units ($e = \hbar = m_e = 1$, used throughout this paper), parameter γ can be calculated as $\gamma = \frac{\omega\sqrt{2I_p}}{F}$, where ω is laser frequency, I_p is ionization potential and F is the laser electric field strength. For $\gamma < 1$ TI is dominant process, whereas for $\gamma > 1$ leading target ionization is through the MPI mechanism. For $\gamma \sim 1$ there is intermediate regime in which both processes can occur [10].

Understanding electron dynamics in intense laser fields requires accurate modelling of tunneling and barrier-suppression ionization expressions. Such modeling seems to be the first step toward understanding almost all strong-field phenomena When an electron exits the parent atom, its initial momentum distribution and the residual ionic core's influence are all factors that must be considered. These initial conditions have a significant impact on the electron motion caused by the laser field, which in turn impacts the observable features of numerous nonlinear processes. During the tunneling regime, the electron emerges from the Coulomb barrier distorted by lasers with quantum-mechanical characteristics that convey information about both the atomic structure and ionization dynamics. The behavior of ionization rates, photoelectron spectra, and angular distributions however differs in the barrier-suppression regime, where the potential barrier is lowered to allow electrons to escape directly. Therefore, the accurate representation of ionization rates and electron emission characteristics across various laser parameters requires knowledge of the transition between the TI and the BSI regimes. Also, high-order harmonic generation and laser-induced electron diffraction are largely dependent on the conditions prevailing during the ionization step, which also determine the recollision dynamics of the ionized electron with its parent ion [2], [3], [12]. Hence, it is essential to have an in-depth understanding of the dynamics of ionization for both interpretations on experimental measurements and attosecond techniques for studying ultrafast electronic motion on its natural timescale [2].

In this paper, we enhance the analytical description of laser-induced ionization in intense laser fields, combining a modified semi-empirical ionization model with an improved treatment of strong-field electron dynamics. Our approach incorporates physical effects that become significant in the TI and the BSI regimes. The paper is organized as follows: in the next section, we concisely describe the modifications to the ionization rate formulae that account for the non-zero initial momentum of the outgoing electron, the laser frequency and the long-range Coulomb interaction. We then present and discuss our results, followed by a brief conclusion.

ANALYTICAL FRAMEWORK

The theoretical approach developed in this work is based on a modified analytical description of strong-field ionization that extends the semi-empirical ionization model proposed by Tong and Lin [13]. While the original formulation provides an accurate representation of ionization rates for atoms exposed to intense laser fields, it does not explicitly account for the influence of the initial momentum of the outgoing electron, the laser frequency or the continuous dependence on the

ionization regime characterized by the Keldysh parameter γ. To overcome these limitations, new analytical expressions are obtained that incorporate these effects within a unified framework.

The derivation begins with the Tong and Lin ionization formula, which serves as the reference expression for the field-dependent ionization rate in this work [13]. Their work extends the well-known analytical expression for the TI rate to the BSI regime, while maintaining the relative simplicity of the approach:

$$W_{BSI}^{TL}(F) = W_{TI}(F) \times W_{corr}^{TL}(F) \qquad (1)$$

$$W_{corr}^{TL}(F) = \exp\left[-\alpha \frac{Z_c^2}{I_p} \frac{F}{k^3}\right] \qquad (2)$$

Term $W_{TI}(F)$ represents formula for the tunneling ionization rate in intense laser fields based on the Ammosov–Delone–Krainov (ADK) theory [6], [7], [8]. The ADK model assumes a quasistatic electric field, making it valid when the laser field varies slowly compared to the electron tunneling time.

$W_{corr}^{TL}(F)$ is an empirical correction factor expressed in terms of scaled field strength F and scaled ionization energy I_p, with an empirical parameter α, Z_c is the charge seen by the active electron and $k = \sqrt{2I_p}$. Numerical values for empirical parameter α and Z_c are listed in [13], for specific atoms and atomic ions.

The original Tong and Lin formulation is first generalized by introducing the non-zero initial momentum of the outgoing photoelectron, (p), as an explicit variable rather than assuming electron emission with vanishing momentum at the tunnel exit [14]. This modification allows the ionization rate to depend directly on the initial momentum distribution, thereby providing a more realistic description of the electron immediately after ionization. The resulting analytical expression preserves the simplicity of the original model while extending its applicability to realistic situations in which the finite photoelectron momentum acquired during the ionization process cannot be neglected. A second extension concerns the explicit inclusion of laser frequency ω and the Keldysh parameter γ. Consequently, the analytical expression remains valid across the various laser frequency and naturally reproduce the corresponding limiting behaviors through Keldysh parameter γ. Also, we assumed that the angular momentum and magnetic quantum numbers of the valence electrons are zero (l=0, m = 0) in pre-exponential part of $W_{TI}(F)$. Taking all abovementioned into account, the new ionization rate formula is therefore expressed as a function of the laser field strength, the initial photoelectron momentum and laser frequency:

$$W_{BSI}^{TLp}(F,\omega,p) = \frac{C_l^2}{2(2I_p)^{\frac{Zc}{\sqrt{2I_p}}-1}} \left(\frac{2Z^3}{Fn^{*3}}\right)^{\frac{2Zc}{\sqrt{2I_p}}-1} \times \exp\left[-\alpha \frac{Z_c^2}{I_p} \frac{F}{(\sqrt{2I_p})^3}\right] \times \exp\left[-\frac{2Z^3}{3Fn^{*3}} - -\frac{p^2\gamma^3}{3\omega}\right] \qquad (3)$$

In above equation, n^* is effective principal quantum number, Z is charge state of atoms and C_l is coefficient that measures the amplitude of the electron wavefunction in the tunnelling region [13]. Through previous definition of parameter γ, the effects of the laser frequency and the atomic ionization potential are simultaneously incorporated into the improved analytical model. According to the well-established procedure described in [15] it is convenient to use the parabolic coordinates to express initial photoelectron momentum as:

$$p = \frac{1}{2}\left(\sqrt{F\eta - 1} - \frac{1}{\eta\sqrt{F\eta - 1}}\right) \qquad (4)$$

where η is the parabolic coordinate that satisfies the following condition $\eta > 1/F$ [16].

With the parameters p, ω and γ introduced above, we further explore their influence on the ionization rate profile. The dependence of the ionization rate on p describes the momentum-

resolved features of the ionization process, while the dependence on frequency allows the investigation of ionization over a wide range of laser wavelengths. The dependence on γ parameter allows us to verify the corresponding ionization regime. Together, they provide a more complete analytical description of strong-field ionization than the original Tong and Lin formulation.

It is known that Coulomb correction models upgrade the common TI and BSI frameworks by incorporating the long-range Coulomb interaction between the escaping electron and the parent ion [7], [8], [9]. Consequently, despite the increase in laser field intensity, the contribution of the atomic potential remains non-negligible. The inclusion of Coulomb corrections alters the imaginary part of the action, thereby influencing the resulting total ionization rate [7], [8]. Thus, we have upgraded the $\mathrm{W}_{\mathrm{BSI}}^{\mathrm{TLp}}(F,\omega,p)$ formula by incorporating a more general form of the Coulomb interaction [17]:

$$C_{corr}=\left[\frac{(1-\varepsilon)F}{2\frac{Z}{n^{*2}}^{3}}\right]^{-2n^{*}} \qquad (5)$$

The derivation details are given in [17], while parameter ε represents the degree of polarization of the laser field. Therefore, modified ionization rate $\mathrm{W}_{\mathrm{BSI}_{\mathrm{mod}}}^{\mathrm{TL}}(F,\omega,p)$ is expressed as:

$$\mathrm{W}_{\mathrm{BSI}_{\mathrm{mod}}}^{\mathrm{TL}}(F,\omega,p)=\frac{C_l^2}{2(2I_p)^{\frac{Zc}{\sqrt{2I_p}}-1}}\left[\frac{(1-\varepsilon)F}{2\frac{Z}{n^{*2}}^{3}}\right]^{-2n^{*}}\times\exp\left[-\alpha\frac{Z_c^2}{I_p}\frac{F}{(\sqrt{2I_p})^3}\right]\times\exp\left[-\frac{2Z^3}{3Fn^{*2}}-\frac{p^2\gamma^2}{3\omega}\right] \qquad (6)$$

The resulting analytical model preserves the computational efficiency characteristic of semi-analytical approaches while improving their physical consistency. In particular, the derived expression in Eq. (3) accounts for improvements arising from non-zero initial electron momentum and the continuous evolution between the TI and BSI ionization regimes, enabling more accurate predictions of ionization rates and electron dynamics over a broad range of laser parameters. In addition, the influence of the generalized long-range Coulomb potential, given in Eq. (5), on the ionization dynamics is taken into account through Eq. (6).

This framework provides a convenient basis for comparison with numerical simulations and experimental measurements, while maintaining the transparency of an analytical formulation. In the next section, we will compare ionization rates $\mathrm{W}_{\mathrm{BSI}}^{\mathrm{TLp}}(F,\omega,p)$ and $\mathrm{W}_{\mathrm{BSI}_{\mathrm{mod}}}^{\mathrm{TL}}(F,\omega,p)$ for representative atoms, following avaliable numerical data for α, C_l, Z_c in [13], [18].

RESULTS

This section presents the results obtained from the application of the ionization rate formulas given in Eqs. (3) and (6), considering the case of a linearly polarized laser field ($\varepsilon = 0$). Linear polarization represents one of the most extensively studied configurations in strong-field atomic physics because of its relative simplicity and its direct relevance to a wide range of experimental investigations [9], [19], [20].

The analysis focuses on the dependence of the ionization rate on the laser parameters, such as the electric field strength, laser intensity, and frequency, as well as on the atomic properties of the target species (I_p, C_l, α). The predictions obtained from Eqs. (3) and (6) are compared over a broad range of field parameters to evaluate the consistency of the proposed analytical model and to identify the conditions under which their results converge or significantly differ.

Helium and argon atoms are chosen as representative noble gas atoms because they are among the most widely used noble gases in experimental research. Helium is characterized by its simple electronic structure and high ionization potential $I_p^{\mathrm{He}} = 24.59\ \mathrm{eV} = 0.904\ \mathrm{a.u.}$, making it an ideal model system for studying fundamental atomic interactions and collision processes. Argon, in contrast, has a more complex electronic configuration, lower ionization potential,

$I_p^{\mathrm{Ar}} = 15.76\ \mathrm{eV} = 0.579\ \mathrm{a.u.}$ and is widely employed in plasma physics, gas discharge experiments, laser technologies, and spectroscopy due to its favorable physical and chemical properties. Consequently, these two noble gas atoms serve as representative benchmark systems for both experimental and theoretical investigations in atomic and molecular physics [20], [21], [22], [23].

Our study is based on the Ti: sapphire laser system with following parameters: wavelength $\lambda_1 = 800\ \mathrm{nm}$ and frequency $\omega_1 = 0.05696\ \mathrm{a.u.}$,wavelength $\lambda_2 = 1000\ \mathrm{nm}$ and frequency $\omega_2 = 0.0456\ \mathrm{a.u.}$ Since the laser field is linearly polarized, its strength is given by:

$$F_{\mathrm{lin}} = \frac{27.5}{5.1\times10^{9}}\sqrt{I},$$

where I is the intensity of the laser field being used.

As an initial step, the values of the γ parameter for two laser frequences (ω_1, ω_2) are shown for each atom individually (Fig. 1a and Fig. 1b) to verify that the system remains within the TI and the BSI regime ($\gamma < 1$).

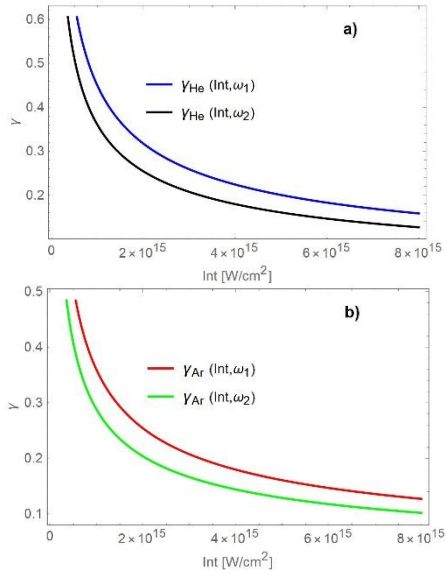

Figure 1. γ parameter for: a) helium atoms, b) argon atoms, for both atoms the intensity is in the range 10^{14} – $8\times10^{15}\ \mathrm{W/cm^2}$

Next, we investigate the influence of the non-zero initial momentum of the outgoing electron and the laser frequency (wavelength) on the ionization rate $\mathrm{W}_{\mathrm{BSI}}^{\mathrm{TLp}}(F,\omega,p)$. The role of the initial momentum is analyzed for different values of the parameter η, allowing us to assess its contribution to the ionization dynamics. The results obtained for helium atoms are presented in Fig. 2, while the corresponding results for argon atoms are shown in Fig. 3.

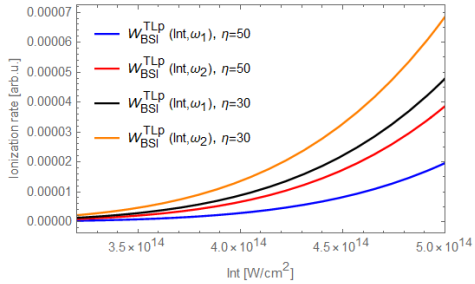

Figure 2. Comparison of the W_{BSI}^{TLp} ionization rates for He atoms, for different η values. The central wavelengths of the laser are $\lambda_1 = 800\ nm$ and $\lambda_2 = 1000\ nm$, $C_l = 2.67, \alpha = 7$ and intensity range is 3.2 x10^{14} - 5x10^{14} W/cm^2

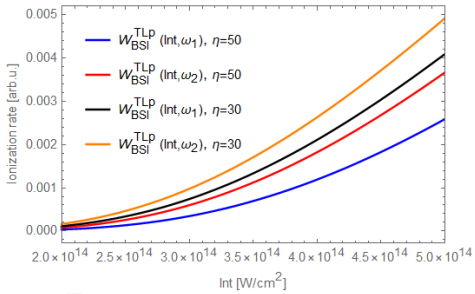

Figure 3. Comparison of the W_{BSI}^{TLp} ionization rates for Ar atoms, for different η values. The central wavelengths of the laser are $\lambda_1 = 800\ nm$ and $\lambda_2 = 1000\ nm$, $C_l = 2.19, \alpha = 9$ and intensity range is 2x10^{14}-5x10^{14} W/cm^2

As a final assessment, the ionization rates $W_{BSI}^{TLp}(F, \omega, p)$ and $W_{BSI_{mod}}^{TL}(F, \omega, p)$ for helium and argon atoms are evaluated to emphasize the influence of the long-range Coulomb potential on the ionization dynamics, see Figs. 4 and 5.

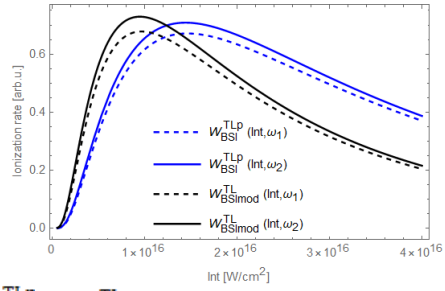

Figure 4. Comparison of the $W_{BSI}^{TLp}$and W_{BSImod}^{TL} ionization rates for He atoms, $\eta = 30, C_l = 2.67, \alpha = 7$. The central wavelengths of the laser are $\lambda_1 = 800\ nm$ and $\lambda_2 = 1000\ nm$, and intensity range is 10^{14} - 10^{16} W/cm^2

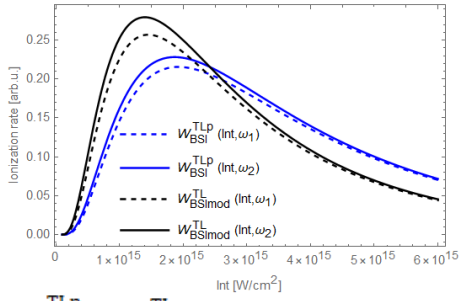

Figure 5. Comparison of the the W_{BSI}^{TLp} and W_{BSImod}^{TL} ionization rates for Ar atoms, $\eta = 30, C_l = 2.19, \alpha = 9$. The central wavelengths of the laser are $\lambda_1 = 800\ nm$ and $\lambda_2 = 1000\ nm$, and intensity range is 10^{14}-10^{16} W/cm^2

The obtained results are presented to assess the validity and accuracy of the analytical model and the proposed analytical expressions. A comprehensive discussion of the results is presented in the subsequent section.

DISCUSSION

The following analysis examines the dependence of the enhanced ionization rates on key laser parameters, including the electric field strength, laser intensity, and frequency, as well as on the intrinsic properties of the target atoms (helium and argon), such as the ionization potential I_p and empirical parameter α. The predictions of Eqs. (3) and (6) are systematically compared over a broad range of field parameters to appraise the consistency of the analytical model and to determine the domains in which these predictions exhibit agreement or significant variance.

The γ parameter values shown in Fig. 1 indicate that the system remains predominantly within the TI and BSI regimes over the investigated parameter range for both atoms. This observation supports the applicability of the employed analytical models and provides the basis for further comparison of the ionization rates. Also, the influence of the non-zero initial momentum of the outgoing electron Eq. (4). and laser frequency on ionization rate is revealed (Fig. 2 and Fig. 3). As the laser intensity increases, the stronger laser field significantly modifies the electron dynamics, resulting in an increased probability of electron excitation and subsequent ionization. This behavior is characteristic of strong-field ionization processes, where the nonlinear interaction between the laser field and the atomic potential plays a dominant role [5], [12]. The variations of parabolic coordinate η and hence the inclusion of the non-zero initial momentum of the outgoing electron, introduce an additional modulation of the ionization response by altering the effective interaction conditions between the laser field and the target system. For specific values of parabolic coordinate η, the ionization rate exhibits a stronger enhancement, indicating that the system parameters can either promote or suppress the electron emission, depending on the degree of coupling to the external field. Furthermore, the influence of the laser frequency becomes significant even at the beginning of the investigated intensity range ~4 x10^{14} $\mathrm{W/cm^2}$. A suitable choice of laser frequency enhances energy transfer from the laser field to the electron, facilitating more efficient population of continuum states and increasing the likelihood of strong-field ionization [24]. Even moderate changes in laser frequency can substantially modify the ionization dynamics for both atoms, see Fig. 2 (orange line) and Fig. 3 (orange line). The combined effect of increasing laser intensity, varying coordinate η, and tuning the laser frequency reveals a significant interplay between laser field strength and system-dependent parameters in the TI and BSI regimes for helium and argon atoms [21], [23].

Additional comparative analyses of the ionization rates $\mathrm{W}_{\mathrm{BSI}}^{\mathrm{TLp}}(F,\omega,p)$ and $\mathrm{W}_{\mathrm{BSI}_{\mathrm{mod}}}^{\mathrm{TL}}(F,\omega,p)$ demonstrate the importance of the long-range Coulomb interaction, as shown in Figs. 4 and 5. The observed increase in the ionization rate can be attributed to the modification of the electron's tunneling pathway by the Coulomb potential. For case of $\mathrm{W}_{\mathrm{BSI}_{\mathrm{mod}}}^{\mathrm{TL}}(F,\omega,p)$, the effective potential barrier experienced by the electron is further reduced, resulting in a higher barrier-suppression ionization rate for both atoms. Consequently, the electron can escape more efficiently from the bound state, which leads to an enhanced ionization rate, see Fig. 4 (solid black line for helium atoms) and Fig. 5 (solid blue line for argon atoms). Previous experimental studies have verified the important role of the Coulomb interaction in strong-field ionization, both in the TI and BSI regimes [25], [26]. In particular, the long-range Coulomb potential has been shown to significantly influence measured photoelectron dynamics [26], while Coulomb-barrier-suppression models have been shown to reproduce experimentally observed enhanced ionization rates in the strong-field regime [25]. Moreover, the ionization rate $\mathrm{W}_{\mathrm{BSI}_{\mathrm{mod}}}^{\mathrm{TL}}(F,\omega,p)$ for argon is more sensitive to C_{corr}, Eq. (5), because argon enters the tunneling ionization regime at relatively lower laser intensities, see Fig. 4. In contrast, helium, owing to its higher ionization potential, is less sensitive to the influence of C_{corr} and requires stronger laser fields for comparable tunneling rates. Since helium enters the TI and BSI regimes at higher laser intensities, the effect of the long-range Coulomb

interaction on the ionization dynamics remains relatively weak, see Fig. 5. Our results show that the use of $W^{TL}_{BSI_{mod}}(F, \omega, p)$ improves the ionization rate predictions by approximately 10% for helium atoms and by nearly 25% for argon atoms. These quantitative differences demonstrate the magnitude of the improvement and highlight the enhanced accuracy of the proposed approach across the considered strong-field ionization regimes. These behaviors are consistent with the physical picture of strong-field ionization, in which the combined effects of the external laser field and the residual Coulomb potential determine the shape of the effective barrier and strongly influence electron dynamics and the ionization rate [15], [26], [27].

The results presented in this section demonstrate the validity and applicability of the analytical ionization rate models considered for linearly polarized laser fields. They also establish a reference framework for extending the analysis to other polarization states, where additional effects associated with electron dynamics and laser-field geometry become increasingly important.

CONCLUSION

The transition from the TI regime to the BSI regime has been systematically analyzed within an enhanced analytical framework that provides a more comprehensive description of strong-field ionization dynamics. The obtained results demonstrate that the ionization rate is influenced not only by the laser intensity but also by the initial momentum of the outgoing photoelectron and the laser frequency, highlighting the multidimensional nature of the ionization process, which is of particular importance in contemporary experiments. Furthermore, the analysis confirms that the long-range Coulomb interaction remains significant even in the BSI regime and cannot be neglected when accurately describing electron dynamics. While the strong laser field modifies the atomic potential and facilitates electron release, the residual Coulomb interaction governs important aspects of the electron motion after barrier suppression. Incorporating this contribution into the analytical model therefore improves the description of the ionization dynamics and provides more accurate ionization rate predictions across different parameters. These results help us better understand the connection between the TI and BSI regimes and provide a more reliable theoretical basis for modelling strong-field phenomena. Besides their essential importance, the results present novel avenues for investigating unexplored strong-field ionization mechanisms and improving our understanding of ultrafast laser-matter interactions.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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POST-COLLISION MOLECULAR DYNAMICS OF ELECTRON-IMPACT IONIZED MOLECULAR CATIONS

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ABSTRACT

Within the ATMOLCOL project, experimental studies of electron–molecule collisions increasingly rely on theoretical models that can clarify the molecular mechanisms leading to fragmentation. This work contributes by developing a computational approach to simulate the fragmentation of molecular cations originating from their ground-state electronic configurations. The primary electron–molecule scattering event is not modeled explicitly; instead, the focus is placed on post-collision nuclear dynamics under internal energy conditions relevant to experiments. Molecular dynamics simulations are employed to analyze dissociation pathways, identify transition structures, and estimate activation energies. Particular attention is given to numerical stability and to verifying that the observed fragmentation channels are not artifacts of limited trajectory sampling or insufficient exploration of the potential energy surface. At this stage, the methodology is tested on the N_2^+ molecular cation as a benchmark diatomic system. Despite its simplicity, N_2^+ provides a well-controlled reference for studying bond cleavage, monitoring energy conservation during dynamical propagation, and validating the robustness of the approach. This benchmark assessment is a necessary step before extending the model to larger polyatomic systems, where energy redistribution and competing fragmentation pathways become more complex. Overall, the study represents a methodological contribution toward a quantitative description of radiation-induced molecular fragmentation within the ATMOLCOL framework.

Keywords: electron–molecule collisions, fragmentation pathways, short-time processes.

INTRODUCTION

Low-energy electron–molecule collisions play a central role in a wide range of physical and chemical environments, including cold plasmas, planetary and interstellar media, atmospheric

processes, and radiation-driven chemistry [1-5]. In many of these systems, electron impact leads not only to electronic excitation or ionization, but also to molecular fragmentation, dissociation, and energy redistribution among nuclear degrees of freedom [6, 7]. A reliable theoretical interpretation of such processes therefore requires a consistent description of the post-collision nuclear dynamics following the initial electron–molecule interaction [8, 9].

Within the ATMOLCOL framework, electron–molecule collisions are typically treated as a two-step process. In the first step, the electronic interaction between the incident electron and the target molecule leads to excitation, attachment, or ionization, often described using quantum scattering methods. In the second step, the system evolves on one or more potential energy surfaces, during which nuclear motion governs bond stretching, vibrational excitation, and eventual fragmentation. While the electronic dynamics are frequently well captured by state-of-the-art scattering calculations, the subsequent nuclear motion is often treated using simplified or implicit models, despite its crucial role in determining observable fragment distributions.

Fragmentation observables, such as kinetic energy release, angular distributions, and branching ratios between different dissociation channels, are inherently sensitive to the time-dependent nuclear dynamics after the collision. In particular, energy deposited during the electron impact is redistributed among vibrational modes on ultrafast time scales [10], and even small inaccuracies in the description of this redistribution can lead to significant deviations in predicted fragment yields [11]. This makes post-collision nuclear dynamics a key ingredient for connecting microscopic collision mechanisms to experimentally accessible observables.

Classical and semiclassical molecular dynamics approaches provide a natural and computationally efficient framework for modeling nuclear motion following electron impact, especially when the focus lies on qualitative trends, methodological validation, or large-scale simulations involving many trajectories. In this context, it is essential to establish robust and numerically stable integration schemes that accurately conserve energy and preserve the phase-space structure of the system over long propagation times. Such validation is particularly important before extending the approach to more complex, multidimensional molecular systems relevant for ATMOLCOL applications.

In this work, we present a methodological study of post-collision nuclear dynamics. Post-collision nuclear motion is modeled classically on a one-dimensional Morse potential, with the impact of the electron incorporated through the initial internal energy. The equations of motion are integrated using the Velocity Verlet algorithm over 5000 time steps to ensure numerical stability and energy conservation. Simulations are performed using a modular in-house code optimized for efficient trajectory propagation and energy monitoring. Computations are carried out on a high-performance workstation equipped with modern multi-core processors and dedicated graphical processing units (GPUs), enabling scalable extension to multidimensional and ensemble-based simulations.

The present study is intended as a foundational step toward incorporating impact-induced nuclear dynamics into the ATMOLCOL framework, providing a controlled environment for testing integration schemes and analyzing their suitability for modeling fragmentation processes in electron–molecule collisions.

THEORETICAL MODEL

The post-collision nuclear dynamics is described within a classical framework, where the motion of the nuclei evolves on an effective potential energy surface corresponding to the electronically perturbed molecular state. Such approach is commonly adopted when the primary electron-molecule interaction is treated separately and the focus lies on the subsequent redistribution of energy among nuclear degrees of freedom. In this regime, classical and semiclassical trajectory methods have proven to be effective tools for capturing vibrational motion, bond stretching and dissociation dynamics, provided that the underlying potential energy surface accurately represents the relevant anharmonic features of molecular binding [12-14]. For a controlled methodological study, we consider a one-dimensional diatomic model represented by

the Morse potential, which captures essential features of molecular binding and anharmonicity while remaining numerically transparent.

The interaction potential is given by

$$V(x) = D\left[1 - e^{-a(x-x_0)}\right]^2$$

where D is the dissociation energy, a determines the curvature of the potential well, and x, x_0 denotes the equilibrium internuclear separation. Although simplified, the Morse potential provides a realistic description of bond stretching and dissociation and is therefore well suited for benchmarking molecular dynamics schemes intended for fragmentation studies [15]. Recent work has further demonstrated that simple analytical potentials can serve as reliable effective models when validated against ab initio potential energy surfaces, particularly in methodological and benchmarking contexts [16].

The nuclear motion is governed by Newton's equation of motion,

$$m\frac{d^2x}{dt^2} = -\frac{dV(x)}{dt}$$

where m m is the reduced mass of the diatomic system. The force acting on the nuclei is obtained analytically from the derivative of the Morse potential, allowing for stable and efficient numerical propagation. Such classical trajectory approaches have been shown to reproduce key aspects of vibrational energy redistribution and bond dynamics following electronic excitation and ionization, especially when the emphasis lies on qualitative trends and numerical stability rather than fully quantum-resolved distribution [13, 17]

In the present work, the primary electron–molecule collision is not treated explicitly. Instead, its effect is incorporated through the choice of initial conditions and internal energy, consistent with the post-collision regime probed in electron-impact experiments. This separation allows us to focus on validating the nuclear dynamics model and its suitability for describing fragmentation processes within the ATMOLCOL framework.

NUMERICAL METHOD

The time evolution of the nuclear motion is obtained by numerically integrating Newton's equation of motion using the Velocity Verlet algorithm, a standard integration scheme in molecular dynamics simulations. This algorithm is particularly well suited for conservative systems, as it is time reversible and symplectic, ensuring good long-term stability and accurate energy conservation [18]. Early formulations of Verlet-type integration were introduced to preserve Hamiltonian structure of the equations of motion, laying the foundation for modern molecular dynamics integrators [19].

For a given position x_i_and velocity v_i at time t_i, the position at the next time step is updated according to

$$x_{i+1} = x_i + v_i\Delta t + \frac{1}{2}a_i\Delta t^2$$

where $a_i = \frac{F(x_i)}{m}$ is the acceleration derived from the Morse force. The velocity is then updated using

$$v_{i+1} = v_i + \frac{1}{2}(a_i + a_{i+1})\Delta t$$

where a_{i+1} is evaluated at the new position x_{i+1}. These update rules ensure that energy drift remains bounded over long simulations and that phase-space structure is preserved, properties that have been emphasized in recent assessments of classical MD schemes [20].

The simulations are performed in reduced units, where the reduced mass is set to m =1.0 and a fixed time step Δt=0.01 is given in corresponding dimensionless time units. The trajectories are propagated for N=5000 time steps, corresponding to a total simulation time sufficient to assess the stability of bound motion and energy conservation. Initial conditions are chosen such that the system remains within the Morse potential well, allowing for controlled analysis of oscillatory dynamics.

The numerical implementation explicitly stores the time evolution of position, velocity, potential energy, and total mechanical energy. This enables a direct assessment of numerical accuracy through monitoring of energy conservation and phase-space structure, which is essential before extending the approach to impact-induced fragmentation scenarios.

RESULTS

As a first validation step, the numerical scheme is applied to a diatomic benchmark system representing the nuclear motion of the N^{2+} molecular cation. Diatomic systems provide a controlled testing ground for post-collision nuclear dynamics, as they allow direct monitoring of bond stretching, energy redistribution, and phase-space structure without the additional complexity of multidimensional mode coupling present in larger molecules [21]. Classical trajectory studies have similarly employed diatomic benchmarks to assess numerical stability and vibrational energy flow [22], while recent work on N_2^+ dissociative processes highlights the relevance of accurate post-collision to experimentally observable fragmentation [23]. This makes them particularly suitable for methodological studies aimed at validating integration schemes prior to extension to polyatomic targets relevant for ATMOLCOL.

The nuclear motion is propagated on a Morse potential surface, shown in Fig. 1, which models the effective potential energy surface of the electronically perturbed molecular ion. For the chosen initial conditions, the system remains in a bound dynamical regime, executing anharmonic oscillatory motion around the equilibrium position. This regime is representative of post-collision situations in which the energy deposited by electron impact is insufficient to induce immediate dissociation but leads to significant vibrational excitation. The anharmonic shape of the potential allows for a realistic description of bond stretching and provides a suitable benchmark for post-collision nuclear dynamics.

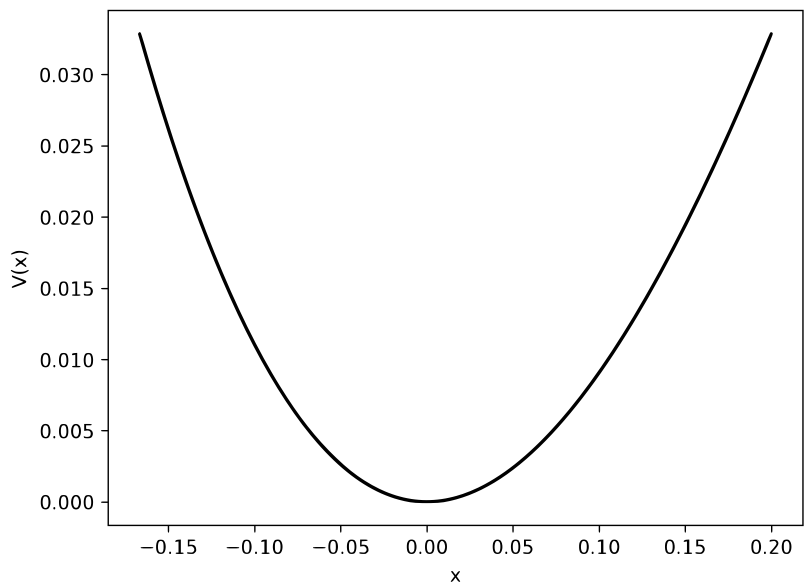

Figure 1. Morse potential V(x) used to model the effective potential energy surface of the diatomic molecular cation.

The time evolution of the total mechanical energy is shown in Fig. 2. The energy remains nearly constant throughout the simulation, with small oscillations around a mean value and no systematic drift. The apparent oscillations are of numerical origin and remain at the 10^{-6} level relative to the mean energy. The absence of systematic drift indicates stable numerical propagation using the Velocity Verlet integration scheme. To quantify the numerical stability, the deviation of the total energy from its mean value is plotted in Fig. 3, demonstrating that fluctuations remain well below the 10^{-4} level over the full propagation time. This confirms that the chosen time step and integration scheme are adequate for describing post-collision nuclear dynamics on the relevant time scales.

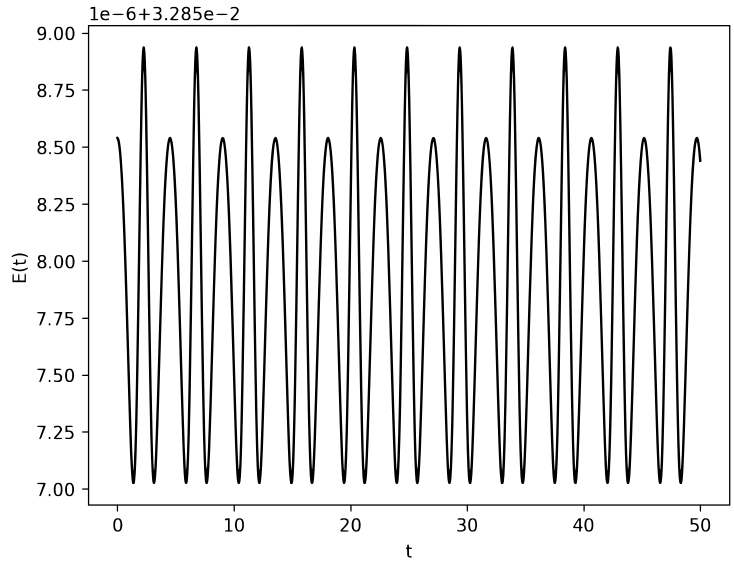

Figure 2. Time evolution of the total mechanical energy E(t) for bound nuclear motion on the Morse potential.

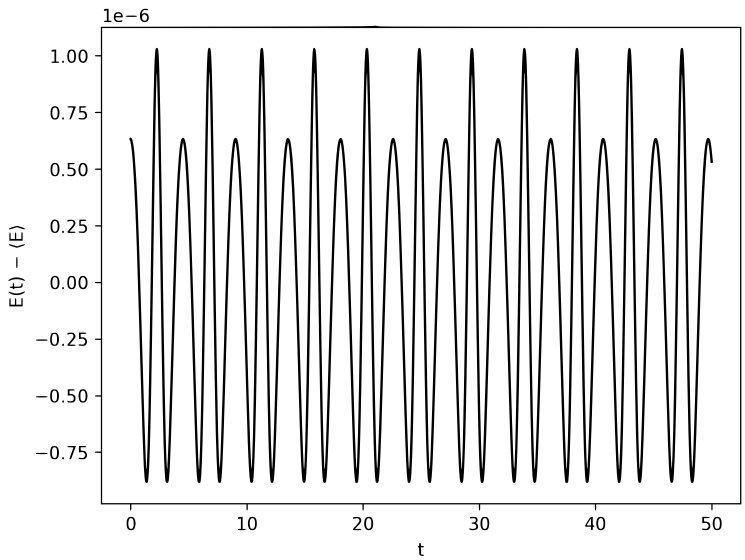

Figure 3. Deviation of the total mechanical energy from its mean value, E(t)−⟨E⟩ over the full simulation time.

Further insight into the dynamical behavior is obtained from the phase-space trajectory (x,v), shown in Fig. 4. The closed, regular orbit indicates stable bound motion and preserves the expected phase-space structure of an anharmonic oscillator. The absence of distortion or secular spreading in phase space further validates the symplectic character of the Velocity Verlet integrator and its suitability for extended molecular dynamics simulations.

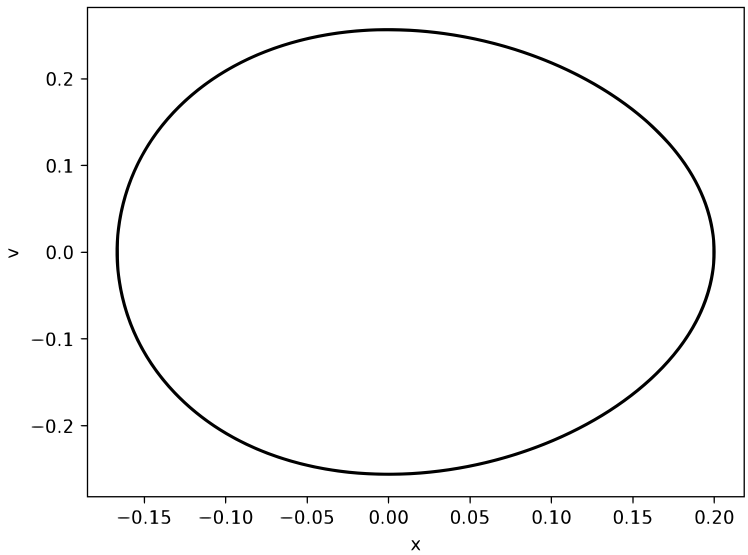

Figure 4. Phase-space trajectory (x,v) corresponding to bound nuclear motion in the Morse potential.

DISCUSSION

The results presented above demonstrate that the adopted molecular dynamics scheme provides a stable and physically consistent description of post-collision nuclear motion on an effective potential energy surface. Although the primary electron–molecule interaction is not treated explicitly, the present approach captures the essential features of the nuclear dynamics that follow electronic excitation or ionization, which are directly relevant for the interpretation of fragmentation phenomena investigated within the ATMOLCOL project.

In electron–molecule collisions, the energy transferred during the impact is rapidly redistributed among nuclear degrees of freedom, governing whether the system remains bound, undergoes vibrational excitation, or proceeds toward dissociation. The bound dynamical regime analyzed here corresponds to post-collision conditions below the effective dissociation threshold, where nuclear motion remains confined but highly sensitive to the amount of deposited internal energy. Accurate modeling of this regime is a prerequisite for understanding the transition to fragmentation at higher excitation energies.

The excellent energy conservation and preserved phase-space structure observed in the present simulations confirm that the Velocity Verlet integrator is well suited for describing such post-collision nuclear dynamics over extended propagation times, in agreement with recent benchmark studies emphasizing numerical stability in molecular dynamics simulations [24]. This is particularly important for impact-induced processes, where small numerical artifacts may accumulate and lead to artificial dissociation or unphysical energy drift, thereby compromising the interpretation of experimental observables.

While the present study is restricted to a one-dimensional diatomic benchmark, it establishes a controlled reference framework for extending the approach to more complex molecular systems.

In polyatomic targets, additional degrees of freedom will introduce energy redistribution among vibrational modes and competing fragmentation pathways. The validated numerical stability demonstrated here provides confidence that such effects can be explored systematically by extending the model to multidimensional potential energy surfaces and ensemble-based simulations.

Within the ATMOLCOL framework, the present methodology offers a practical route for coupling electronic scattering calculations with post-collision nuclear dynamics. By providing a transparent and numerically robust description of nuclear motion following electron impact, the approach represents a foundational step toward quantitative modeling of electron-induced molecular fragmentation.

CONCLUSION

In this work, a classical molecular dynamics framework has been developed and validated for the description of post-collision nuclear dynamics relevant to electron–molecule interactions within the ATMOLCOL project. By focusing on the nuclear motion following electronic excitation or ionization, the present approach addresses a key component required for the interpretation of fragmentation processes induced by electron impact.

Using a diatomic benchmark system modeled by a Morse potential, we have demonstrated that the Velocity Verlet integration scheme provides stable numerical propagation with excellent energy conservation and preservation of phase-space structure. These properties are essential for reliable simulations of post-collision dynamics, where small numerical inaccuracies may otherwise lead to artificial dissociation or unphysical energy redistribution.

Although the present study is restricted to bound nuclear motion in a one-dimensional model, it establishes a controlled methodological reference for future extensions. In particular, the framework can be naturally generalized to higher-dimensional systems and polyatomic molecules, where multiple vibrational degrees of freedom and competing fragmentation pathways play a dominant role. The validated numerical stability achieved here provides confidence that such extensions can be pursued without compromising physical consistency.

Within the ATMOLCOL framework, the present results represent a foundational step toward coupling electronic scattering calculations with post-collision nuclear dynamics. The approach offers a transparent and computationally efficient route for modeling post-collision molecular dynamics following electron impact, and paves the way for future studies addressing dissociative regimes, threshold behavior, and complex molecular targets.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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ENERGY-DEPENDENT FRAGMENTATION DYNAMICS OF ELECTRON-IMPACT IONIZED MOLECULAR CATIONS

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ABSTRACT

Fragmentation of molecular cations formed by electron-impact ionization is governed primarily by the redistribution of internal energy deposited during the collision event. A detailed understanding of how this energy drives the transition from bound vibrational motion to irreversible bond cleavage is essential for interpreting energy-resolved fragmentation measurements. In this work, we analyze the dependence of dissociation behavior on internal energy using a controlled diatomic benchmark system. Electron-impact ionization is represented through controlled initialization of internal energy on the molecular cation potential energy surface, followed by classical propagation of the nuclear motion. The study focuses on identifying effective dissociation thresholds, characterizing near-threshold dynamical regimes, and examining the scaling of fragmentation times with increasing internal energy. Ensemble simulations are employed to determine dissociation probability as a function of deposited energy and to analyze the redistribution between kinetic and potential energy during bond stretching. The results provide a physically transparent description of energy-driven molecular breakup and offer a reference for interpreting energy-dependent fragmentation phenomena investigated within the ATMOLCOL project.

Keywords: energy redistribution, dissociation threshold, electron-impact ionization, molecular dynamics, fragmentation dynamics.

INTRODUCTION

Fragmentation of molecular ions produced by electron-impact ionization is primarily governed by the redistribution of internal energy deposited during the collision event. Once ionization occurs, the excess energy introduced into the molecular system is redistributed among the internal degrees of freedom and may eventually drive the system from bound vibrational motion toward irreversible bond cleavage. Understanding how this energy redistribution translates

into observable fragmentation behaviour is essential for interpreting energy-resolved measurements in electron–molecule collision experiments. Studies of low-energy electron interactions with molecules have demonstrated that such processes play an important role in a wide range of environments, including plasmas, atmospheric chemistry, and radiation-induced molecular processes [1,2].

In many experiments the final fragments produced after the collision can be detected with high accuracy, while the intermediate nuclear dynamics that lead from ionization to dissociation remain inaccessible to direct observation. Consequently, theoretical and computational approaches are required in order to connect the measured fragment distributions with the underlying molecular motion. In particular, the characterization of energy thresholds separating bound and dissociative regimes is crucial for understanding the onset of fragmentation and the dependence of dissociation rates on the internal energy of the system

Near the dissociation threshold, molecular systems often exhibit complex dynamical behaviour. Instead of immediate bond rupture, the nuclear motion may remain temporarily confined within the potential well, undergoing extended vibrational motion before escaping toward dissociation. Such near-threshold dynamics lead to broad distributions of dissociation times and introduce strong sensitivity to the amount of internal energy deposited during the ionization event. Similar behaviour has been discussed in studies of molecular dissociation dynamics where the competition between vibrational trapping and bond rupture produces distinct dynamical regimes near the dissociation limit [3].

Because of the intrinsic complexity of polyatomic molecular systems, simplified benchmark models are often used to gain insight into the fundamental mechanisms governing energy-driven fragmentation. Diatomic molecular ions provide particularly useful reference systems in this context. Despite their structural simplicity, they retain the essential ingredients required to describe bond stretching, anharmonic vibrational motion, and dissociation processes. The Morse potential has long been used as an effective model potential to describe the anharmonic behaviour of diatomic bonds and their dissociation properties [4,5].

In the present work we investigate how internal energy influences the dissociation dynamics of an ionized diatomic molecule using classical molecular dynamics simulations on an effective potential energy surface. Electron-impact ionization is represented through controlled initialization of internal energy in the molecular cation, while the subsequent nuclear motion is propagated using a classical trajectory approach. By systematically varying the deposited energy, we identify different dynamical regimes of motion, determine effective dissociation thresholds, and examine the dependence of dissociation times on internal energy. Ensemble simulations are further employed to explore the statistical distribution of dissociation events in the near-threshold region.

The results provide a transparent physical picture of the transition from bound vibrational motion to dissociation as a function of internal energy. Such an approach offers a useful reference framework for interpreting energy-dependent fragmentation phenomena in electron–molecule collision experiments and contributes to the broader effort of understanding radiation-induced molecular dynamics within the ATMOLCOL project.

While previous work focused primarily on the development and validation of the dynamical model, the present study concentrates on the role of internal energy in determining the fragmentation dynamics.

ENERGY DEPOSITION AND FRAGMENTATION DYNAMICS

When a molecule undergoes electron-impact ionization, a part of the kinetic energy of the incident electron is transferred to the molecular system and appears as internal excitation of the resulting molecular ion. The deposited energy can be redistributed among the vibrational degrees of freedom of the molecule and may eventually lead to bond stretching and dissociation. The amount of internal energy available after ionization therefore plays a central role in determining the subsequent nuclear dynamics of the system and the probability of fragmentation.

In collision experiments the energy transferred during the primary ionization event can vary over a relatively wide range, leading to different dynamical regimes of motion. For low internal energies the molecular ion remains confined within the potential well and performs bound vibrational motion. In this regime the system oscillates around the equilibrium bond length and no dissociation occurs on the simulated time scale. As the internal energy increases, the system approaches the dissociation limit of the molecular potential. In this near-threshold region the dynamics become particularly sensitive to the exact amount of deposited energy.

Close to the dissociation threshold the nuclear motion may remain temporarily trapped in the potential well before eventually escaping toward dissociation. This behaviour leads to long dissociation times and a strong trajectory-to-trajectory variability in the fragmentation dynamics. Such near-threshold behaviour has been discussed in theoretical studies of diatomic dissociation where the competition between vibrational motion and escape toward dissociation produces distinct dynamical regimes [6]. As a consequence, the transition from bound motion to fragmentation does not occur abruptly at a single energy value but rather through a gradual increase in dissociation probability.

Because of the complexity of real molecular systems, simplified model descriptions are often employed in order to isolate the fundamental physical mechanisms governing the dynamics. In particular, diatomic molecular ions provide a convenient reference system for studying the transition from bound vibrational motion to dissociation. Despite their structural simplicity, they capture the essential physics associated with bond stretching, anharmonic motion and the existence of a dissociation limit. The Morse potential offers a realistic representation of such behaviour and has therefore been widely used to model vibrational dynamics and dissociation processes in diatomic molecules [7, 8].

Within this framework, the present study focuses on the role of internal energy as the primary control parameter governing the fragmentation dynamics. By systematically varying the initial energy of the molecular ion, it becomes possible to identify the emergence of different dynamical regimes and to analyze the dependence of dissociation times and probabilities on the deposited energy.

DYNAMICAL MODEL AND NUMERICAL APPROACH

In order to investigate the influence of internal energy on fragmentation dynamics, we consider a simplified model system consisting of a diatomic molecular cation. Although real molecular systems involve many internal degrees of freedom, diatomic systems provide a convenient framework for studying the fundamental mechanisms governing bond stretching and dissociation. Their reduced dimensionality allows the nuclear motions to be analyzed in a transparent manner while retaining the essential physical features associated with anharmonic vibrational motion and the existence of a dissociation limit. In the present study the model is applied to the N^{2+} molecular ion, which serves as a representative diatomic benchmark system.

Analytical potential energy functions are widely used to describe the vibrational motion of diatomic molecules. Among them, Morse-type potential remains particularly useful due to their simplicity and ability to reproduce anharmonic vibrational spectra [9-13]. In the present model this interaction between the two nuclei is described using the Morse potential:

$$V(x) = D\left[1 - e^{-a(x-x_0)}\right]^2$$

where D is the dissociation energy, a determines the curvature of the potential well, and x_0 is the equilibrium bond distance. This potential provides a simple analytical representation of anharmonic molecular bonds and reproduces both vibrational motion near equilibrium and the asymptotic behavior associated with bond dissociation [9]. In the present work, the Morse potential is primarily used to explore how different values of internal energy drive the transition between bound vibrational motion and dissociative trajectories.

The nuclear motion is described within a classical framework where the internuclear coordinate evolves according to the forces derived from the potential energy surface. The primary electron impact ionization event is not treated explicitly. Instead, its effect is represented through controlled initialization of the internal energy of the molecular ion. In practice, the deposited energy is introduced by assigning an initial velocity to the internuclear coordinate while the initial bond distance is chosen close to the equilibrium position. By varying the magnitude of the initial velocity, different values of the total internal energy can be generated, allowing the dependence of fragmentation dynamics on the deposited energy to be systematically explored. The trajectories are propagated numerically and monitored in order to determine whether the molecular system remains in the bound vibrational regime or evolves toward dissociation. A trajectory is considered dissociative once the internuclear distance exceeds a predefined threshold value, providing a practical measure of fragmentation time for each simulated trajectory.

RESULTS

We begin by examining the dynamical behavior of the N^{2+} molecular ion for relatively low values of internal energy. In this regime the total energy of the system remains well below the dissociation limit of the potential energy surface, and the nuclear motion is confined within the potential well. The resulting trajectories correspond to bound vibrational motion around the equilibrium bond distance.

A representative example of such dynamics is shown in Figure 1, where the bond coordinate exhibits periodic oscillations characteristic of anharmonic vibrational motion in the Morse potential. The amplitude of the oscillation increases with increasing internal energy, but the system remains confined within the potential well and no dissociation occurs during the simulated time interval.

This behaviour reflects the fact that, for energies below the dissociation threshold, the molecular ion is dynamically stable and the internal energy is stored in vibrational motion of the bond coordinate. In this regime the nuclear dynamics are dominated by oscillatory motion around the equilibrium configuration, and the probability of fragmentation remains negligible.

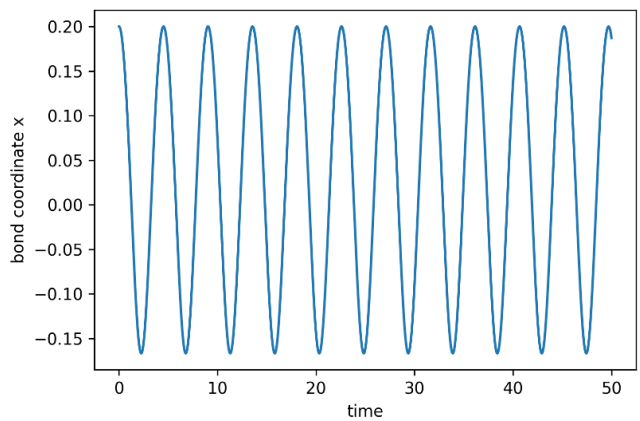

Figure 1. Bound vibrational motion of the diatomic molecular ion in the Morse potential for internal energy below the dissociation threshold. The internuclear distance oscillates around the equilibrium bond length, illustrating stable vibrational dynamics in the bound regime.

As the internal energy of the system approaches the dissociation limit of the potential, the dynamical behaviour changes qualitatively. For sufficiently large initial energies the molecular bond is no longer confined within the potential well and the trajectory eventually escapes toward dissociation. An example of such behaviour is illustrated in Figure 2, which shows the temporal evolution of the bond coordinate for a trajectory that undergoes dissociation. After an initial period

of vibrational motion within the potential well, the bond length increases rapidly and eventually exceeds the dissociation threshold distance defined in the numerical model. This transition marks the onset of fragmentation in the system. Once the internuclear distance becomes sufficiently large, the interaction between the fragments becomes negligible and the molecule can be considered dissociated. The time required to reach this threshold provides a convenient measure of the fragmentation dynamics.

A key objective of the present study is to investigate how the dissociation dynamics depend on the amount of internal energy deposited during the ionization event. To this end, simulations were performed for a range of initial energies and the dissociation time was determined for each trajectory. The resulting dependence of dissociation time on internal energy is shown in Figure 3. A clear trend can be observed: trajectories with higher internal energy tend to dissociate more rapidly, while those with energies close to the dissociation threshold exhibit significantly longer dissociation times. This behaviour can be understood in terms of the available excess energy above the dissociation limit. When the internal energy is only slightly above the threshold, the system may remain temporarily trapped within the potential well before eventually escaping toward dissociation. As the energy increases further, the potential barrier becomes easier to overcome and the dissociation process occurs more rapidly

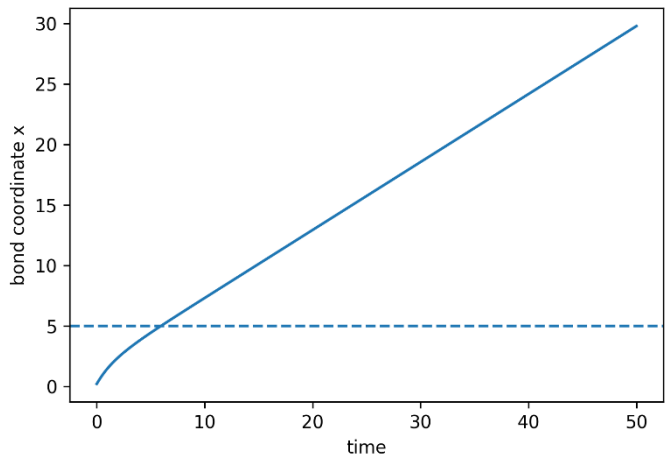

Figure 2. Representative dissociative trajectory for internal energy above the dissociation threshold. Following an initial period of bound vibrational motion, the internuclear distance increases rapidly and crosses the dissociation threshold (dashed horizontal line), indicating fragmentation of the molecular ion.

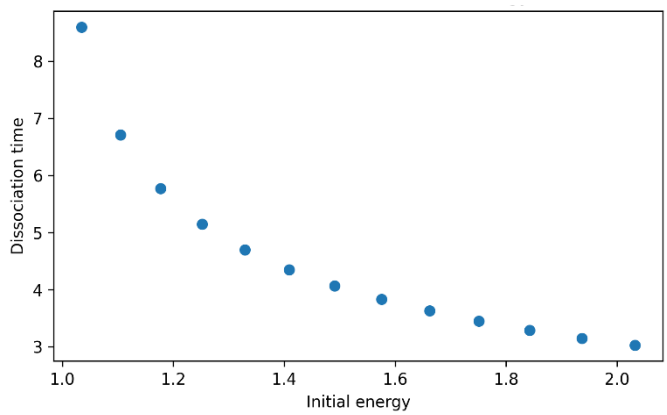

Figure 3. Dependence of the dissociation time on the initial internal energy of the molecular ion. Trajectories with energies close to the dissociation threshold exhibit significantly longer dissociation times, while higher energies lead to faster fragmentation.

In addition to individual dissociation trajectories, ensemble simulations provide information about the probability of fragmentation as a function of internal energy. For each selected energy value multiple trajectories were generated with small variations in the initial conditions, allowing the fraction of dissociative trajectories to be determined. The resulting dissociation probability is presented in Figure 4. For low internal energies the probability of dissociation is close to zero, indicating that the system remains in the bound vibrational regime. As the internal energy increases, the probability of fragmentation rises sharply and eventually approaches unity for sufficiently large energies.This behaviour reflects the existence of an effective dissociation threshold separating bound and dissociative dynamical regimes. Instead of a sharp transition at a single energy value, the onset of fragmentation occurs gradually over a finite energy interval due to the sensitivity of the dynamics to the exact initial conditions.

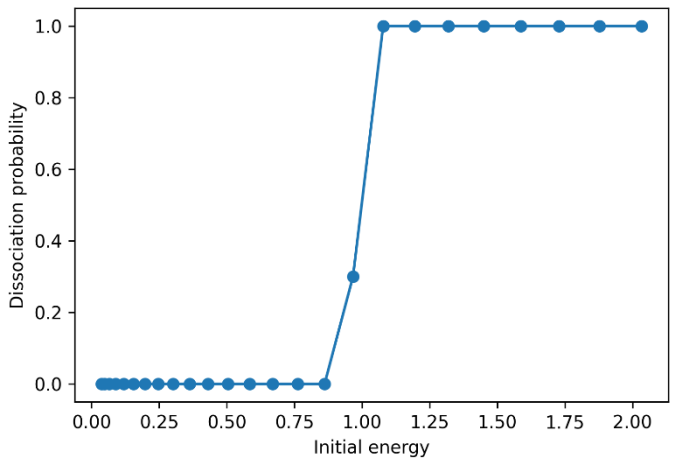

Figure 4. Dissociation probability as a function of internal energy obtained from ensemble simulations. The probability of fragmentation increases gradually as the internal energy approaches and exceeds the dissociation threshold, indicating a transition between bound and dissociative dynamical regimes.

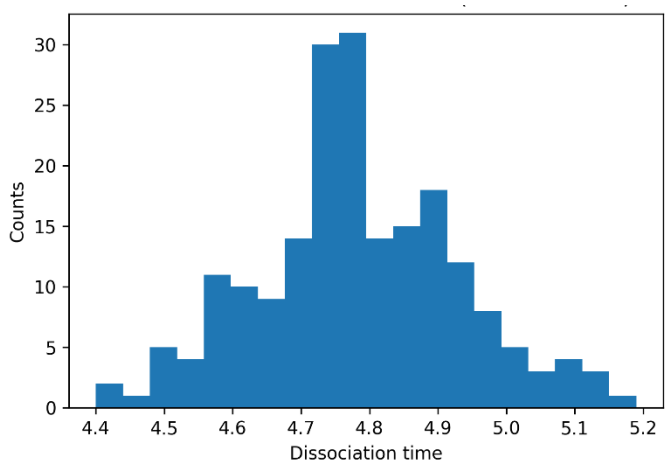

Figure 5. Distribution of dissociation times obtained from ensemble simulations in the near-threshold region. The broad distribution reflects the variability of fragmentation dynamics and the sensitivity of dissociation times to the initial conditions.

Additional insight into the fragmentation dynamics can be obtained by examining the statistical distribution of dissociation times for trajectories with energies close to the threshold region. In this regime the nuclear motion may remain confined within the potential well for extended periods before eventually escaping toward dissociation. The distribution of dissociation times obtained from ensemble simulations is shown in Figure 5. The histogram reveals a broad spread of dissociation times, indicating significant variability between different trajectories. Some trajectories dissociate relatively quickly, while others remain trapped within the potential well for longer times before fragmentation occurs. Such behavior is characteristic of near-threshold dynamical regimes, where the competition between vibrational motion and escape toward dissociation leads to complex trajectory-dependent dynamics. The presence of a wide distribution of dissociation times therefore reflects the sensitive dependence of the fragmentation process on the initial internal energy and the detailed structure of the potential energy surface.

DISCUSSION

The results obtained in the present simulations provide a clear picture of how the internal energy deposited during the ionization process governs the fragmentation dynamics of the molecular ion. The numerical experiments reveal the existence of distinct dynamical regimes that emerge as the internal energy approaches and exceeds the dissociation limit of the molecular potential. For internal energies well below the dissociation threshold the molecular ion remains dynamically stable and the nuclear motion is confined within the potential well. In this regime the system performs bound vibrational motion around the equilibrium bond length and no fragmentation occurs within the simulated time interval. The energy introduced into the system is therefore stored in vibrational excitation rather than being converted into dissociation.

As the internal energy increases toward the dissociation limit, the dynamics become increasingly sensitive to the precise value of the deposited energy. In this near-threshold regime the system may remain temporarily trapped within the potential well before eventually escaping toward dissociation. The numerical simulations show that trajectories with similar initial energies can exhibit significantly different dissociation times, leading to a broad distribution of fragmentation times observed in the ensemble simulations.

Such behaviour reflects the competition between vibrational motion and the gradual escape of the system toward the dissociation region of the potential energy surface. Instead of an immediate rupture of the bond, the system may undergo several oscillations before accumulating sufficient energy along the dissociative coordinate to overcome the effective barrier associated with the potential well. This mechanism naturally leads to the appearance of long dissociation times in the near-threshold region.

The ensemble simulations further demonstrate that the onset of fragmentation occurs over a finite interval of internal energies rather than at a single well-defined threshold value. The dissociation probability increases gradually as the internal energy rises above the dissociation limit. This behaviour reflects the intrinsic sensitivity of nonlinear dynamical systems to initial conditions and highlights the importance of statistical approaches when analysing fragmentation processes near the threshold.

Although the present model represents a simplified description of molecular fragmentation, it captures several essential features of energy-driven dissociation dynamics. In particular, the simulations reproduce the transition from bound vibrational motion to dissociative trajectories and reveal the strong dependence of fragmentation times on internal energy. These results illustrate how relatively simple dynamical models can provide valuable insight into the mechanisms governing fragmentation processes following electron-impact ionization.

Within the broader context of the ATMOLCOL project, such simplified dynamical descriptions can serve as a useful reference framework for interpreting experimental measurements of electron-induced fragmentation. While real molecular systems may involve additional degrees of freedom and more complex potential energy surfaces, the fundamental mechanisms identified here—energy-dependent dissociation thresholds and trajectory-dependent

fragmentation times—are expected to play an important role in a wide range of electron-molecule collision processes.

CONCLUSION

In this work we investigated how the internal energy deposited during electron-impact ionization influences the fragmentation dynamics of a diatomic molecular cation. The dynamical simulations indicate a transition between distinct regimes of motion depending on the available internal energy.

For energies below the dissociation limit, the molecular ion remains in bound vibrational states, while higher energies lead to dissociative trajectories. Near the threshold region the simulations show delayed fragmentation and a broad distribution of dissociation times, reflecting the sensitivity of the dynamics to the initial energy of the system. Although based on a simplified diatomic model, the present approach illustrates how controlled initialization of internal energy can be used to analyze energy dependent fragmentation dynamics. Such descriptions may provide a useful reference for interpreting electron impact induced molecular processes investigated within the ATMOLCOL framework.

Future work will focus on extending the present approach to more complex molecular systems and exploring how additional degrees of freedom influence the fragmentation dynamics and the associated dissociation thresholds.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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PSYHOLOGY
PSIHOLOGIJA

STAV PREMA SNOVIMA KAO IZRAZ SUBJEKTIVNOG ODNOSA PREMA NESVESNOM

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SAŽETAK

Snovi zauzimaju centralno mesto u klasičnim psihoanalitičkim teorijama, gde se posmatraju kao smisleni izrazi nesvesnih psihičkih procesa. U frojdovskoj i jungovskoj teorijskoj tradiciji snovi se posmatraju kao važan izvor uvida u unutrašnju psihičku dinamiku pojedinca, pri čemu se njihova interpretacija i integracija dovode u vezu sa razumevanjem emocionalnih stanja i unutrašnjih konflikata. Cilj ovog istraživanja jeste ispitivanje odnosa između stava prema snovima i različitih aspekata subjektivne psihološke relevantnosti snova u opštoj populaciji. Istraživanje je sprovedeno na uzorku od 172 ispitanika iz opšte populacije. Podaci su prikupljeni putem anonimnog online upitnika koji obuhvata sociodemografski upitnik, skalu stava prema snovima - Attitudes Toward Dreams Scale [1], indikatore korišćenja snova za lični uvid i razumevanje unutrašnjih konflikata - Mannheim Dream Questionnaire [2], kao i mere učestalosti prisećanja i deljenja snova. Rezultati ukazuju na statistički značajne pozitivne povezanosti između stava prema snovima i svih ispitivanih aspekata njihove psihološke relevantnosti: učestalosti prisećanja snova, korišćenja snova za lični uvid i razumevanje unutrašnjih konflikata, kao i učestalosti deljenja snova sa drugima. Ovi nalazi ukazuju na to da subjektivni odnos prema snovima može biti važna psihološka varijabla povezana sa načinima na koje pojedinci pamte, razmatraju i dele svoja iskustva sna.

Ključne reči: snovi, stav prema snovima, deljenje snova, nesvesno, lični uvid.

UVOD

Snovi predstavljaju univerzalno ljudsko iskustvo koje prati čoveka kroz sve istorijske epohe i kulture. Još od najranijih civilizacija, snovi su privlačili pažnju ljudi zbog svoje neobične strukture, emocionalnog intenziteta i prividne odvojenosti od budne stvarnosti. Upravo zbog toga, snovi su dugo smatrani fenomenom koji prevazilazi svakodnevno iskustvo i upućuje na skrivene dimenzije ljudskog postojanja.

U prednaučnom periodu, tumačenje snova bilo je neraskidivo povezano sa religijskim, magijskim i mitološkim predstavama sveta. U mnogim drevnim kulturama snovi su shvatani kao poruke bogova, duhova ili predaka, kao i nagoveštaji budućih događaja. Takva tumačenja bila su prisutna u staroegipatskoj, mesopotamskoj i grčkoj tradiciji, gde su snovi imali važnu ulogu u donošenju političkih i ličnih odluka. Snovi su često bili predmet posebnih rituala i interpretacija, a njihovo značenje tumačili su sveštenici ili proročišta, što ukazuje na njihov društveni i simbolički značaj u prednaučnom razumevanju ljudske psihe.

Iako su ova tumačenja bila zasnovana na verovanjima i simboličkim sistemima karakterističnim za određene kulture, ona ukazuju na jednu trajnu ideju: snovi su smatrani smislenim iskustvima, a ne besmislenim mentalnim pojavama. Čak i u odsustvu naučne metodologije, prednaučna shvatanja snova polazila su od pretpostavke da snovi nose poruku koja zahteva tumačenje. Ova pretpostavka, iako teorijski neujednačena, postavila je temelje kasnijim psihološkim razmatranjima snova kao značajnog psihičkog fenomena.

Sa razvojem moderne nauke i racionalnog mišljenja, dolazi do postepenog napuštanja mitoloških i religijskih objašnjenja snova. Međutim, to ne znači da interesovanje za snove nestaje; naprotiv, ono se transformiše i dobija novi oblik u okviru psihološke i filozofske misli. Krajem XIX i početkom XX veka, snovi postaju predmet sistematskog proučavanja u okviru psihologije, gde se više ne tumače kao spoljašnje poruke, već kao unutrašnji psihički procesi povezani sa ličnošću pojedinca.

Ovaj teorijski zaokret posebno je naglašen u razvoju psihoanalitičke teorije, u okviru koje snovi dobijaju centralno mesto u razumevanju nesvesnih psihičkih procesa. Umesto da budu shvaćeni kao nasumični ili beznačajni, snovi se posmatraju kao smisleni izrazi unutrašnjih konflikata, želja i emocionalnih stanja. Na taj način, snovi postaju most između svesnog i nesvesnog aspekta ličnosti, kao i važan izvor uvida u subjektivno iskustvo pojedinca.

U tom kontekstu, snovi se mogu razumeti kao specifična forma psihičke aktivnosti koja povezuje budni i nesvesni život. Iako se javljaju tokom spavanja, njihovi sadržaji često imaju jasne veze sa dnevnim iskustvima, emocionalnim preokupacijama i unutrašnjim dilemama. Da li će snovi biti zapamćeni ili zaboravljeni, promišljani ili ignorisani, zavisi ne samo od njihovog sadržaja, već i od subjektivnog stava pojedinca prema snovima i njihovom značenju.

Upravo iz tog razloga, savremena psihološka istraživanja sve češće usmeravaju pažnju na individualne razlike u doživljaju snova, uključujući stavove prema snovima, učestalost njihovog prisećanja i načine njihove integracije u budni život. Polazeći od klasičnih teorijskih okvira, naročito onih koje su razvili Sigmund Freud i Carl Gustav Jung, moguće je razmatrati kako subjektivni odnos prema snovima utiče na njihovu psihološku relevantnost i funkciju u savremenom kontekstu.

Freudovo shvatanje snova

U razvoju psihološke misli, sistematsko proučavanje snova neraskidivo je povezano sa radom Sigmund Freuda, koji snovima dodeljuje centralno mesto u razumevanju nesvesnih psihičkih procesa. U delu Tumačenje snova Freud iznosi tezu da snovi nisu slučajni ili besmisleni mentalni proizvodi, već smisleni psihički fenomeni koji imaju određenu funkciju u psihičkom životu pojedinca [3]. Ovim delom Freud pravi jasan otklon od dotadašnjih shvatanja snova kao fiziološkog ili iracionalnog fenomena i uvodi ih u samo središte psihoanalitičke teorije.

Freud snove označava kao „Kraljevski put u nesvesno“, naglašavajući da upravo kroz analizu snova postaje moguće steći uvid u psihičke procese koji su inače nedostupni svesti [3]. Proučavanje snova imalo je ključnu ulogu u razvoju psihoanalize, jer je upravo kroz rad sa snovima Freud razvio i produbio koncept nesvesnog i mehanizam potiskivanja kao osnovne odbrambene procese u psihičkom funkcionisanju. Snovi, prema frojdovskom shvatanju, omogućavaju da potisnuti sadržaji pronađu indirektan put ka svesti, čime postaju dragocen izvor razumevanja unutrašnjih konflikata.

Dodatno, u „Uvodu u psihoanalizu“ Freud sažima osnovne postavke o snovima i nesvesnom, naglašavajući ulogu analize snova u razumevanju psihičke dinamike [4].

Prema frojdovskom shvatanju, san predstavlja ispunjenje potisnute želje, pri čemu se ta želja ne pojavljuje u neposrednom obliku, već je prerušena kroz složen proces rada sna [3]. Freud razlikuje manifestni sadržaj sna, koji se odnosi na ono čega se sanjač seća po buđenju, i latentni sadržaj, koji obuhvata nesvesne želje, impulse i konflikte koji stoje u osnovi sna. Ova razlika ima ključni značaj za razumevanje psihološke funkcije snova, jer ukazuje na to da je san rezultat intrapsihičke dinamike između nesvesnih sadržaja i cenzure svesti.

Rad sna, prema Freudu, odvija se putem nekoliko osnovnih mehanizama: sažimanja, pomeranja, simbolizacije i sekundarne obrade [3]. Ovi mehanizmi omogućavaju da se nesvesni sadržaji izraze na način koji ne ugrožava kontinuitet spavanja. Na taj način, san istovremeno služi očuvanju spavanja i delimičnom razrešenju intrapsihičkih tenzija.

U okviru Freudove teorije, odnos svesti prema snovima ima značajnu ulogu u tome da li će se san zapamtiti ili zaboraviti. Freud ističe da zaboravljanje snova nije slučajno, već da je povezano sa delovanjem cenzure i otpora, koji sprečavaju da se neprihvatljivi ili anksiozni sadržaji zadrže u svesti. On je smatrao da kod svakog čoveka postoje želje za koje niti on sam ne bi želeo da zna, niti bi želeo da iko na svetu sazna za njih. Takve želje se stoga potiskuju i putem različitih mehanizama, koji štite kako naš san, tako i nas same, od onoga što je potisnuto, maskiraju i uobličavaju u slike i sadržaje koji nam deluju nerazumljivo i teško shvatljivo [3]. Snovi koji sadrže intenzivne emocionalne konflikte mogu biti delimično ili u potpunosti zaboravljeni, naročito ukoliko se snevač prema njima odnosi sa ravnodušnošću ili otporom. Iz ovakvog shvatanja proizlazi da se dostupnost sna svesti može razlikovati u zavisnosti od jačine cenzure, a ne od njegove psihološke relevantnosti. Na osnovu toga može se dalje pretpostaviti da subjektivni stav prema snovima može biti povezan sa učestalošću njihovog prisećanja.

Pored toga, Freud naglašava da se psihološki značaj snova ne iscrpljuje samim činom sanjanja, već se ostvaruje kroz njihovu interpretaciju. Interpretacija sna podrazumeva aktivno bavljenje njegovim sadržajem, razmišljanje o slobodnim asocijacijama i emocionalnim reakcijama koje san izaziva [3]. Iako san ima psihološku funkciju nezavisno od toga da li je interpretiran, njegova analiza omogućava da nesvesni sadržaji postanu dostupni razumevanju i uključe se u svesnu psihičku obradu.

Polazeći od Freudovog shvatanja sna kao psihološki smislenog fenomena i sredstva za pristup nesvesnim emocionalnim stanjima i konfliktima može se pretpostaviti da osobe koje snovima pridaju psihološku vrednost i značenje češće obraćaju pažnju na svoje snove i koriste ih u procesu samorazumevanja [3].

Jungovo shvatanje snova

Za razliku od Freudovog shvatanja snova kao prerušene realizacije potisnutih želja, Carl Gustav Jung razvija pristup u kome snovi predstavljaju neposredan i spontan izraz nesvesnog. U okviru Jungove analitičke psihologije, snovi se ne posmatraju prvenstveno kao produkt cenzure, već kao prirodni psihički proces koji ima za cilj uspostavljanje ravnoteže između svesnog i nesvesnog dela ličnosti. Jung je dao doprinos psihološkom shvatanju pojma nesvesnog, koji nije poput Frojdovog podsvesnog samo riznica potisnutih želja, „nego svet podjednako stvaran kao život pojedinca. Jezik i „stanovnici“ nesvesnog su simboli, a sredstva javljanja snovi“ [5].

Ovakvo stanovište je u skladu i sa Jungovim autobiografskim promišljanjima o značenju snova i simboličkog jezika nesvesnog [6].

Jung smatra da snovi imaju kompenzatornu funkciju, odnosno da nadoknađuju jednostranosti svesnog stava. Kada je svest previše rigidna, racionalna ili emocionalno ograničena, snovi donose sadržaje koji ukazuju na zanemarene ili potisnute aspekte ličnosti. U tom smislu, san ne prikriva značenje, već ga izražava na simbolički način, koristeći jezik slika koji zahteva psihološko razumevanje, a ne dekodiranje prema unapred zadatim šemama [5]. Centralni pojam u Jungovoj teoriji snova jeste simbol. Jung razlikuje simbol od znaka, naglašavajući da simbol nikada nema jednoznačno i fiksno značenje, već upućuje na sadržaje koji prevazilaze neposredno svesno razumevanje [5]. Zbog toga se značenje sna ne može odrediti univerzalnim tumačenjem, već mora biti sagledano u kontekstu ličnog iskustva, emocionalnog stanja i životne situacije snevača.

Ovakav pristup naglašava značaj odnosa koji svesni ego uspostavlja prema snovima u procesu njihovog psihološkog razumevanja.

Pored ličnog nesvesnog, Jung uvodi i koncept kolektivnog nesvesnog, koje obuhvata arhetipske sadržaje zajedničke svim ljudima. U snovima se, pored ličnih iskustava, mogu pojaviti i arhetipske slike koje nose univerzalne teme, poput odnosa prema životu, smrti, promeni i razvoju. Međutim, Jung naglašava da čak i arhetipski simboli dobijaju svoje specifično značenje tek u odnosu na ličnost pojedinca i njegovu svesnu strukturu, te da se njihova psihološka vrednost ne može odvojiti od konkretnog subjektivnog konteksta [5]. U popularnoj jungovskoj tradiciji često se navodi stav da snovi predstavljaju bliske unutrašnje „sagovornike“ sa kojima se vredi susretati. U tom duhu, Franz Alt, koji se u literaturi pominje kao popularizator njegove misli, opisuje snove kao unutrašnje prijatelje kojima se raduje svake večeri. Ovakve formulacije ilustrativno izražavaju jedno od ključnih jungovskih polazišta: da snovi nisu varljive ili obmanjujuće pojave, već izrazi nesvesnog, čije poruke mogu ostati neiskorišćene ukoliko ih svest ignoriše ili odbaci.

Prema Jungovom shvatanju, san poseduje psihološko značenje kao spontani izraz nesvesnih procesa, ali njegov razvojni i transformativni potencijal nije automatski. Tek kroz svesno razmatranje i postupnu integraciju sadržaja sna on može ostvariti korektivni efekat u odnosu na svesni stav ličnosti; u suprotnom, san može ostati bez značajnijeg uticaja na lični razvoj. Refleksija o snu, razmišljanje o njegovom mogućem značenju i njegovo povezivanje sa ličnim iskustvom omogućavaju da san postane izvor uvida i samorazumevanja. Jung upozorava da nagli ili nekritički uvid može imati destabilizujući efekat, zbog čega proces razumevanja snova zahteva postepenost i psihološku zrelost. „Otrov uvida“, kako navodi Jung, „treba davati u malim dozama“, što se odnosi kako na arhetipske simbole, tako i na snove koji potiču iz ličnog nesvesnog [5].

U tom kontekstu, Jungovo shvatanje snova povezuje odnos svesnog ega prema snovima sa njihovim razvojnim i korektivnim potencijalom. Ukoliko snovi predstavljaju pokušaj nesvesnog da uspostavi ravnotežu u odnosu na svesni stav, tada njihova psihološka relevantnost zavisi od spremnosti ega da se tim porukama posveti. Osobe koje snovima pripisuju lično i psihološko značenje sklonije su da se bave njihovim sadržajem, razmišljaju o simbolima koji se u njima pojavljuju i koriste ih kao sredstvo za razumevanje unutrašnjih konflikata i razvoja ličnosti. Snovi se, u okviru analitičke psihologije, mogu posmatrati kao potencijalni izvor ličnog uvida, ali samo ukoliko postoji otvorenost prema njihovom simboličkom jeziku.

Polazeći od Jungovog teorijskog okvira, može se dalje pretpostaviti da će osobe koje snovima pridaju psihološko i lično značenje češće koristiti snove kao izvor ličnog uvida i razumevanja unutrašnjih konflikata, kao i da će biti sklonije deljenju snova sa drugima. Ove pretpostavke čine teorijsku osnovu za ispitivanje odnosa između subjektivnog odnosa prema snovima, ličnog uvida i učestalosti deljenja snova u okviru ovog istraživanja.

Razlike u frojdovskom i jungovskom shvatanju psihološke funkcije snova

Žarko Trebješanin, razmatrajući klasične psihoanalitičke teorije, ukazuje da se razlike između Freudovog i Jungovog shvatanja snova ne odnose na pitanje da li snovi imaju psihološko značenje, već na način na koji se to značenje razume i tumači [7]. Frojd i Jung se slažu u tome da: a) snovi imaju smisao, b) snovi predstavljaju derivat nesvesnog, c) da je tumačenje snova „via regia“ za izučavanje nesvesnog i njegovih mehanizama. Frojd i Jung se duboko razilaze u pogledu: prirode sna, funkcije sna i metode tumačenja. [7].

U frojdovskom teorijskom okviru, snovi se pre svega razumeju u kontekstu individualne istorije ličnosti, potisnutih želja i intrapsihičkih konflikata. Psihološka funkcija sna povezana je sa dinamikom između nesvesnih impulsa i cenzure svesti, pri čemu san omogućava simboličko ispunjenje potisnutih želja i očuvanje kontinuiteta spavanja. Značenje sna, prema Freudu, nalazi se u njegovom latentnom sadržaju i ne zavisi od svesnog odnosa pojedinca prema snu, iako analiza sna omogućava da to značenje postane dostupno svesti.

Nasuprot tome, Jungovo shvatanje snova naglašava njihovu kompenzatornu i samoregulativnu funkciju u odnosu na svesni stav ličnosti. Jung snove posmatra kao spontani izraz nesvesnog koji teži uspostavljanju ravnoteže između svesnog i nesvesnog dela psihe. U tom

smislu, psihološki potencijal sna ne ogleda se samo u njegovom postojanju, već i u mogućnosti da bude razmatran, simbolički shvaćen i postupno integrisan u svesno iskustvo.

Kod Junga snovi ne svode se isključivo na lične konflikte i potisnute želje, već mogu sadržati i arhetipske motive koji upućuju na šire psihičke obrasce. Ipak, čak i u tom slučaju, psihološka vrednost sna ne može se odvojiti od konkretnog subjektivnog konteksta i odnosa svesnog ega prema simbolima sna. Na taj način, Jungovo shvatanje snova eksplicitnije povezuje psihološki efekat sna sa odnosom koji pojedinac uspostavlja prema njegovom značenju.

Ova teorijska razlika ne dovodi u pitanje psihološku relevantnost snova, već ukazuje na to da se odnos između snova i svesti u klasičnim teorijama razume na različite načine. Istovremeno otvara prostor za savremeno empirijsko ispitivanje subjektivnog odnosa prema snovima kao varijable povezane sa njihovim prisećanjem i psihološkom upotrebom.

Stav prema snovima kao psihološka varijabla

U okviru klasičnih psihoanalitičkih teorija, snovi se ne posmatraju samo kao psihički proizvodi, već kao fenomeni koji imaju psihološko značenje u odnosu na unutrašnju psihičku dinamiku pojedinca. Iako se ni Sigmund Freud ni Carl Gustav Jung eksplicitno ne bave pojmom stava prema snovima u savremenom, empirijskom smislu, njihova teorijska razmatranja otvaraju pitanje odnosa između snova i svesti u procesu njihove dalje psihičke obrade.

U frojdovskom teorijskom okviru, snovi predstavljaju smislen izraz nesvesnih želja i intrapsihičkih konflikata [3]. Međutim, Freud istovremeno naglašava ulogu otpora i cenzure, koji mogu dovesti do delimičnog ili potpunog zaboravljanja snova. Iz toga proizlazi da dostupnost sna svesti nije neutralna, već zavisi od jačine cenzure i otpora, a ne od njegove psihološke relevantnosti. Na osnovu toga može se dalje pretpostaviti da subjektivni odnos prema snovima može biti povezan sa učestalošću njihovog prisećanja, iako takva pretpostavka ne predstavlja eksplicitnu Freudovu tvrdnju.

Jungovo shvatanje snova još jasnije naglašava ulogu subjektivnog odnosa prema snovima. Prema Jungu, snovi predstavljaju spontani izraz nesvesnog koji teži komunikaciji sa svesnim stavom ličnosti. Ukoliko svesni ego snove doživljava kao besmislene ili nevažne, poruka nesvesnog ostaje neintegrisana. Nasuprot tome, otvorenost prema snovima i spremnost da se o njima razmišlja omogućavaju da snovi ispune svoju kompenzatornu i samoregulativnu funkciju [5].

Polazeći od ovih teorijskih razmatranja, može se zaključiti da se stav prema snovima u savremenom istraživačkom kontekstu može posmatrati kao relativno stabilna psihološka dispozicija koja utiče na način na koji pojedinac doživljava, pamti i koristi snove. Stav prema snovima obuhvata uverenja o njihovom značenju, interesovanje za njihove sadržaje i spremnost da im se posveti pažnja. Takav stav može biti povezan sa učestalošću prisećanja snova, kao i sa načinima na koje se snovi koriste kao izvor ličnog uvida i razumevanja unutrašnjih konflikata.

Erich Fromm snove razume kao poseban simbolički jezik nesvesnog, u kome se unutrašnji psihički procesi izražavaju posredno, slično kao u mitovima i bajkama. Prema Frommu, snovi ne služe prikrivanju istine, već predstavljaju pokušaj komunikacije nesvesnih sadržaja sa svešću, pri čemu njihovo razumevanje zavisi od sposobnosti tumačenja tog simboličkog jezika [8]. Ovakvo shvatanje naglašava aktivnu ulogu subjekta u odnosu prema snovima, jer psihološka vrednost sna zavisi od spremnosti pojedinca da taj „jezik“ razume i interpretira.

U savremenim istraživanjima, stav prema snovima sve češće se operacionalizuje kao subjektivna procena psihološke relevantnosti snova i njihove korisnosti za razumevanje sebe. Iako ovaj konstrukt ne potiče direktno iz klasične psihoanalize, on predstavlja empirijski način da se operacionalizuju pitanja koja su Freudova i Jungova teorijska razmatranja snova otvorila — pre svega odnos između snova, svesti i njihove upotrebe u procesu samorazumevanja. U tom smislu, stav prema snovima može se posmatrati kao konceptualni most između klasičnih teorijskih uvida i savremenog kvantitativnog istraživanja.

Polazeći od navedenog, opravdano je pretpostaviti da će osobe koje imaju pozitivniji stav prema snovima češće pamtiti svoje snove i koristiti ih kao sredstvo za lični uvid. Ovakve pretpostavke predstavljaju teorijsku osnovu za ispitivanje povezanosti između stava prema

snovima i učestalosti prisećanja snova, kao i između pripisivanja značenja snovima i korišćenja snova za razumevanje unutrašnjih konflikata, što je u skladu sa postavljenim hipotezama istraživanja.

Deljenje snova kao nastavak simbolizacije i verbalizacije

U klasičnim psihoanalitičkim teorijama, značaj snova ne iscrpljuje se samim činom sanjanja, već se razmatra u kontekstu njihove dalje psihičke obrade. Iako se san pojavljuje kao intrapsihički događaj, njegovo razumevanje često podrazumeva prelazak iz sfere unutrašnjeg iskustva u sferu simbolizacije i verbalizacije. U tom smislu, deljenje snova sa drugima može se posmatrati kao jedan od mogućih načina integracije nesvesnih sadržaja u svesno iskustvo.

U frojdovskom teorijskom okviru, san predstavlja kompromisnu formaciju između nesvesnih želja i cenzure svesti [3]. Međutim, Freud naglašava da se psihološki smisao sna ne može u potpunosti ostvariti bez njegove interpretacije, koja podrazumeva aktivno bavljenje sadržajem sna kroz slobodne asocijacije i verbalno izražavanje. Govorenje o snovima omogućava da se nesvesni materijal postepeno prevede u svesno razumljive oblike, čime se smanjuje njegov konfliktni potencijal. Iako Freud interpretaciju snova razmatra prvenstveno u terapijskom kontekstu, njegova teorija implicira da verbalizacija sna ima značajnu ulogu u procesu njegove psihičke obrade, bez pretpostavke da sama verbalizacija menja osnovnu psihološku funkciju sna.

Slično tome, u analitičkoj psihologiji Carl Gustav Jung naglašava da snovi koriste simbolički jezik koji zahteva refleksiju i dijalog kako bi bio integrisan u svest [9]. Jung smatra da san, ukoliko ostane neizgovoren i nereflektovan, može izgubiti svoju transformativnu funkciju. Deljenje sna, bilo kroz unutrašnji dijalog ili kroz komunikaciju sa drugima, omogućava da se simboli sna sagledaju iz različitih perspektiva, čime se produbljuje njihovo značenje.

Deljenje snova može se razumeti kao produžetak procesa simbolizacije, u kome se nesvesni sadržaji prevode u jezik, slike i narative dostupne svesti. Ovaj proces ne podrazumeva nužno formalnu interpretaciju, već samo čin govorenja o snu i njegovom subjektivnom doživljaju. Na taj način, san prestaje da bude izolovano unutrašnje iskustvo i postaje deo šireg psihičkog i interpersonalnog konteksta.

Važno je istaći da deljenje snova nije neutralan čin, već zavisi od subjektivnog stava prema snovima. Ukoliko se snovi doživljavaju kao besmisleni ili nevažni, mala je verovatnoća da će biti zapamćeni, a još manja da će biti podeljeni sa drugima. Nasuprot tome, osobe koje snovima pripisuju psihološku vrednost i značenje verovatnije će osećati potrebu da o njima govore, razmišljaju i traže njihovo razumevanje. U tom smislu, deljenje snova može se posmatrati kao indikator aktivnog odnosa prema sopstvenom unutrašnjem svetu.

U okviru geštalt tradicije, Fritz Perls snove posmatra kao izraz različitih delova ličnosti koji nisu u potpunosti integrisani u svesno iskustvo. Prema Perlsu, svaki element sna može se razumeti kao aspekt ličnosti sanjača, a psihološki značaj sna ostvaruje se kroz njegovo osvešćivanje i integraciju [10]. Iako Perlsov pristup potiče iz drugačijeg teorijskog okvira, njegova razmatranja dodatno naglašavaju važnost aktivnog odnosa prema snovima i njihovoj verbalizaciji. Deljenje snova, u ovom kontekstu, omogućava da se različiti aspekti unutrašnjeg iskustva artikulišu i povežu u koherentniju celinu, što je u skladu sa shvatanjem snova kao psihološki relevantnih sadržaja.

Polazeći od ovih teorijskih pretpostavki, može se pretpostaviti da će pozitivan stav prema snovima biti povezan sa većom učestalošću njihovog deljenja. Deljenje snova tada ne predstavlja samo socijalni čin, već deo šireg psihološkog procesa u kome snovi bivaju priznati kao relevantni i smisleni sadržaji. Ovakvo razumevanje deljenja snova pruža teorijsku osnovu za ispitivanje povezanosti između stava prema snovima i učestalosti deljenja snova, što je u skladu sa trećom hipotezom ovog istraživanja.

Bez obzira na teorijske razlike između frojdovskog, jungovskog i drugih pristupa, zajedničko polazište ovih teorija jeste pretpostavka da snovi nisu slučajni ili besmisleni psihički fenomeni, već imaju psihološko značenje povezano sa unutrašnjim životom pojedinca. Razlike među teorijama odnose se prvenstveno na način razumevanja tog značenja i njegov odnos prema svesti, ali ne

dovode u pitanje shvatanje da snovi predstavljaju relevantan materijal za razumevanje psihičke dinamike. Upravo na toj osnovi moguće je u savremenom istraživačkom kontekstu razmatrati subjektivni odnos prema snovima i njegovu povezanost sa ličnim uvidom, prisećanjem i deljenjem snova u okviru ovog istraživanja.

METODOLOGIJA

Cilj je da se ispita odnos između stava prema snovima i tri aspekta njihove psihološke relevantnosti kod odraslih: a) učestalosti prisećanja snova, b) indikatora korišćenja snova za lični uvid, c) učestalosti deljenja snova sa drugima. Dodatno, cilj je da se doprinese razumevanju subjektivnog odnosa prema snovima u savremenom kontekstu, na osnovu klasičnih psihoanalitičkih teorija.

Hipoteze istraživanja

H1. Pozitivniji stav prema snovima povezan je sa češćim prisećanjem snova.

H2. Pozitivniji stav prema snovima pozitivno je povezan sa indikatorima korišćenja snova za lični uvid i razumevanje sopstvenog unutrašnjeg iskustva.

H3. Pozitivniji stav prema snovima povezan je sa većom učestalošću deljenja snova sa drugima.

Uzorak i postupak istraživanja

Uzorak istraživanja činilo je 172 ispitanika iz opšte populacije, uzrasta 18–65 godina M=37,95 godina (SD=12,68), od kojih je bilo 138 žena (80,2%) i 33 muškarca (19,2%), dok se jedan ispitanik (0,6%) nije želeo izjasniti o polu. Riječ je o neslučajnom prigodnom uzorku sa elementima dobrovoljačkog uzorkovanja (online regrutacija).

Istraživanje je sprovedeno online, anonimnim upitnikom. U instrukciji za popunjavanje upitnika učesnici su dobili informaciju o cilju, dobrovoljnosti i pravu na odustajanje. Prosečno vreme popunjavanja bilo je 5–7 minuta. Prikupljeni podaci obrađeni su u statističkom programu IBM SPSS Statistics 26.

Instrumenti

Stav prema snovima meren je prevedenom verzijom standardizovane skale *Attitudes Toward Dreams Scale* [1], koja procenjuje uverenja o značenju snova, interesovanje za snove i spremnost da im se posveti pažnja (npr. „Snovi nemaju nikakvo značenje.“, „Snovi mi mogu pomoći u samorazumevanju.“). Odgovori se daju na Likert skali od 1 = uopšte se ne slažem do 5 = u potpunosti se slažem. Ukupan skor dobija se kao prosečna vrednost stavki, pri čemu viši rezultat označava pozitivniji stav. Stavke su ordinalne, dok se kompozitni skor tretira kao skalarna mera u skladu sa praksom u korelacionim nacrtima. Skala je korišćena u skladu sa originalnom strukturom instrumenta (Cernovsky, 1984), pri čemu su stavke preuzete iz kasnijeg empirijskog istraživanja u kome je skala korišćena u celini (Governale, 1990).

Korišćenje snova za lični uvid operacionalizovano je putem pojedinačnih stavki koje su konceptualno usklađene sa konstruktom „dream use“, u skladu sa pristupom kojim se u savremenim empirijskim istraživanjima snova ispituje uloga snova u samorefleksiji i budnom životu, poput pristupa primenjenog u *Mannheim Dream Questionnaire – MADRE* [2].

Stavke procenjuju u kojoj meri ispitanici razmišljaju o snovima, povezuju ih sa sopstvenim emocionalnim iskustvima i doživljavaju ih kao izvor ličnog uvida. Odgovori se daju na petostepenoj Likertovoj skali (1–5). Stavke se analiziraju kao pojedinačni indikatori konstrukta, „dream use“, pri čemu se svaka stavka tretira kao zasebna zavisna varijabla u analizama povezanosti.

Pored navedena dva standardizovana psihološka merna instrumenta, korišteni su i sociodemografski upitnik, sa ciljem prikupljaja se podataka o polu, godinama starosti i nivou obrazovanja ispitanika, kao i uputnik o merama učestalosti prisećanja i deljenja snova. Učestalost prisećanja snova meri se jednim frekventnim pitanjem na sedmostepenoj skali, u skladu sa standardnom praksom u empirijskim istraživanjima snova [11]. Učestalost deljenja snova sa

drugima meri se jednim frekventnim pitanjem, u skladu sa prethodnim empirijskim istraživanjima u kojima se deljenje snova operacionalizuje kao single item mera [12]. Viši skorovi označavaju češće prisećanje, odnosno češće deljenje. Po nivou merenja reč je o ordinalnim single item merama (bez procene interne konzistentnosti, koja se primenjuje na višestavkovne skale); rešenje je izabrano radi jednostavnosti i manjeg opterećenja ispitanika, u skladu sa korelacionim presečnim nacrtom planiranog istraživanja.

REZULTATI

Uzorak je činilo 172 ispitanika iz opšte populacije. Prosečna starost ispitanika iznosila je 37,95 godina (SD = 12,68), u rasponu od 18 do 65 godina. U uzorku je bilo 138 žena (80,2%) i 33 muškarca (19,2%), dok se jedan ispitanik (0,6%) nije želeo izjasniti o polu. U pogledu obrazovanja, najveći deo ispitanika imao je završene osnovne studije (40,1%), zatim master studije (27,9%) i srednju školu (20,3%), dok je manji broj ispitanika imao završenu višu školu (7,6%), doktorske studije (2,9%) ili je naveo drugo obrazovanje (1,2%).

Nakon provere pouzdanosti skale stava prema snovima sprovedene su deskriptivne i korelacione analize glavnih varijabli istraživanja.

Unutrašnja konzistentnost skale stava prema snovima na prikupljenom uzorku proverena je pre sprovođenja korelacionih analiza i bila je dobra (Cronbach $\alpha = .85$).

Korišćenje snova za lični uvid operacionalizovano je putem pojedinačnih indikatora, koji su analizirani kao zasebne varijable u analizama povezanosti.

Tabela 1. Deskriptivne statistike glavnih varijabli istraživanja

Varijabla	N	M	SD
Stav prema snovima	172	3.77	0.55
Učestalost prisećanja snova	172	3.77	1.45
Deljenje snova sa drugima	172	3.35	1.71

Napomena. M = aritmetička sredina; SD = standardna devijacija.

Tabela 2. Spearmanove korelacije između stava prema snovima, učestalosti prisećanja snova i deljenja snova

Varijabla	1	2	3
Stav prema snovima	—		
Učestalost prisećanja snova	.21**	—	
Deljenje snova sa drugima	.39***	.49***	—

Napomena. N = 172. Spearmanov koeficijent korelacije (ρ). **p < .01, ***p < .001

Tabela 3. Spearmanove korelacije između stava prema snovima i indikatora korišćenja snova za lični uvid

Indikator	ρ
Razmišljam o značenju svojih snova	.58***
Snovi mi pomažu da bolje razumem svoja osećanja	.59***
Snovi mi ukazuju na unutrašnje konflikte	.59***
Nakon sna razmišljam o povezanosti sa životom	.54***
Snovi mi pomažu da sagledam probleme iz druge perspektive	.58***
Koristim snove kao izvor ličnog uvida	.61***

Napomena. N = 172. Spearmanov koeficijent korelacije (ρ). ***p < .001.

Deskriptivna analiza pokazala je da je prosečan stav prema snovima relativno pozitivan (M = 3.77, SD = 0.55). Učestalost prisećanja snova takođe je bila umerena (M = 3.77, SD = 1.45), dok je učestalost deljenja snova sa drugima bila nešto niža (M = 3.35, SD = 1.71).

Spearmanova korelaciona analiza pokazala je da postoji statistički značajna pozitivna povezanost između stava prema snovima i učestalosti prisećanja snova ($\rho = .21$, $p = .006$), kao i između stava prema snovima i deljenja snova sa drugima ($\rho = .39$, $p < .001$). Takođe je utvrđena statistički značajna pozitivna povezanost između učestalosti prisećanja snova i deljenja snova ($\rho = .49$, $p < .001$). Iako nije bila direktno predviđena hipotezama, korelacija između prisećanja i deljenja snova prikazana je radi potpunijeg uvida u međuodnos varijabli. Ona pokazuje da su osobe koje češće pamte snove sklonije i da ih dele, što je u skladu sa shvatanjem da oba aspekta pripadaju širem obrascu angažmana prema snovima.

Analiza povezanosti između stava prema snovima i indikatora korišćenja snova za lični uvid pokazala je statistički značajne pozitivne korelacije sa svim indikatorima. Koeficijenti korelacije kretali su se u rasponu od $\rho = .54$ do $\rho = .61$ ($p < .001$), što ukazuje na umereno do snažnu povezanost između ovih varijabli. Ovi rezultati ukazuju na to da ispitanici sa pozitivnijim stavom prema snovima češće razmišljaju o značenju svojih snova, povezuju ih sa sopstvenim emocionalnim iskustvima i doživljavaju ih kao izvor ličnog uvida.

Jačina utvrđenih povezanosti varirala je u zavisnosti od ispitivanog aspekta. Dok je povezanost stava sa prisećanjem snova bila relativno slaba ($\rho = .21$), povezanost sa deljenjem snova bila je umerena ($\rho = .39$). Najsnažnije korelacije utvrđene su između stava prema snovima i indikatora ličnog uvida, koje su se kretale u rasponu od $\rho = .54$ do $\rho = .61$, što ukazuje na umerenu do snažnu povezanost.

Rezultati istraživanja pružaju podršku hipotezama H1, H2 i H3. Pozitivniji stav prema snovima povezan je sa češćim prisećanjem snova, većom učestalošću deljenja snova sa drugima, kao i sa većom sklonošću da se snovi koriste kao izvor ličnog uvida.

DISKUSIJA

Cilj ovog istraživanja bio je da se ispita povezanost između stava prema snovima i tri aspekta njihove psihološke relevantnosti: učestalosti prisećanja snova, korišćenja snova za lični uvid i razumevanje unutrašnjih konflikata, kao i učestalosti deljenja snova sa drugima. Dobijeni rezultati ukazuju na postojanje statistički značajnih pozitivnih povezanosti između stava prema snovima i svih ispitivanih varijabli, čime su potvrđene postavljene hipoteze.

Rezultati pokazuju da osobe koje imaju pozitivniji stav prema snovima češće pamte svoje snove. Ovaj nalaz može se razumeti u svetlu klasičnih psihoanalitičkih teorija, u kojima se snovi posmatraju kao psihološki smisleni fenomeni povezani sa nesvesnim procesima. Freud je ukazivao na to da se zaboravljanje snova može dovesti u vezu sa delovanjem cenzure i otpora, koji otežavaju zadržavanje snova u svesti. U tom smislu, otvoreniji i zainteresovaniji odnos prema snovima može doprineti većoj pažnji koja se posvećuje snovima, što povećava verovatnoću njihovog prisećanja. Savremena empirijska istraživanja takođe pokazuju da su individualne razlike u prisećanju snova povezane sa interesovanjem za snove i spremnošću da se o njima razmišlja [11].

Rezultati ovog istraživanja ukazuju i na značajnu povezanost između stava prema snovima i indikatora njihovog korišćenja za lični uvid. Ispitanici koji snovima pripisuju veće značenje češće razmišljaju o njihovom sadržaju, povezuju ih sa sopstvenim emocionalnim iskustvima i doživljavaju ih kao potencijalni izvor samorazumevanja. Ovaj nalaz je u skladu sa jungovskim shvatanjem snova kao spontanog izraza nesvesnog koji može imati kompenzatornu i samoregulativnu funkciju u odnosu na svesni stav ličnosti. Prema Jungu, psihološka vrednost sna ne ostvaruje se automatski, već zavisi od spremnosti svesnog ega da se njegovim simboličkim sadržajem bavi i integriše ga u lično iskustvo. U tom smislu, pozitivan stav prema snovima može predstavljati važan psihološki preduslov za njihovu refleksiju i potencijalnu integraciju u proces samorazumevanja.

Pored toga, rezultati pokazuju da je pozitivan stav prema snovima povezan i sa većom učestalošću deljenja snova sa drugima. Deljenje snova može se posmatrati kao produžetak procesa simbolizacije i verbalizacije unutrašnjeg iskustva, kroz koji se sadržaji sna prevode u jezik i

uključuju u interpersonalni kontekst. U psihoanalitičkoj i analitičkoj tradiciji verbalizacija snova smatra se važnim korakom u njihovoj psihološkoj obradi, jer omogućava da nesvesni sadržaji postanu dostupni refleksiji i razumevanju. Dobijeni rezultati sugerišu da osobe koje snovima pripisuju veće značenje ne samo da ih češće pamte i razmatraju, već su i sklonije da o njima govore sa drugima, što može doprineti njihovoj daljoj simboličkoj elaboraciji.

Zašto je svest o snovima važna za psihološko blagostanje

Aktivna orijentacija prema snovima (interes, beleženje, refleksija) povećava verovatnoću da san bude zadržan i verbalizovan nakon buđenja, što omogućava povezivanje snovnih simbola sa budnim emocionalnim iskustvima i prepoznavanje unutrašnjih konflikata. Grupne i strukturisane tehnike (npr. Ullmanova tehnika — pričanje sna, asocijacije slušalaca, refleksija sanjača) dovode do značajnih subjektivnih uvida; učesnici prijavljuju dublje samopercepcije i „aha“ iskustva nakon vođene obrade sna, a efekti su jači kod osoba sa pozitivnim stavom prema snovima [13].

REM-san i procesi spavanja podržavaju konsolidaciju emocionalnih sećanja i hiperasocijativne veze koje omogućavaju metaforičko povezivanje iskustava; razmatranje snova nakon buđenja može pomoći u procesuiranju snažnih emocija i smanjenju njihove disfunkcionalne tenzije u budnom životu [14]. Ovi mehanizmi objašnjavaju zašto osobe koje obraćaju pažnju na snove češće koriste snove za razumevanje emotivnih tema.

Eksperimentalne studije pokazuju da vođeno usmeravanje snova ili sanjanje o određenoj temi može poboljšati kreativno rešavanje zadataka povezanih s tom temom. Targeted Dream Incubation (TDI) je eksperimentalna procedura kojom se namerno „inkubira“ određena tema pre spavanja i potom se tokom uspavljivanja ili sna daje kratak senzorni podsticaj povezan s tom temom, s ciljem da se poveća verovatnoća pojave relevantnog sadržaja u snu; nakon buđenja taj snovni materijal se koristi za uvid ili rešavanje problema. Eksperimentalni radovi pokazuju da spavanje poboljšava uvid u probleme [15], da REM i hipnagogične slike olakšavaju stvaranje novih asocijacija [16] i da tehnike reaktivacije/inkubacije tokom sna mogu povećati pojavu ciljane teme i time poboljšati performanse u zadacima koji zahtevaju kreativno rešavanje. To implicira da rad sa snovima može imati direktnu korist za kreativno mišljenje.

Deljenje snova u sigurnom interpersonalnom kontekstu omogućava testiranje i obogaćivanje interpretacija, što povećava osećaj povezanosti i empatije; studije grupne obrade pokazuju da povratna informacija od drugih može produbiti značenje sna i podržati emocionalnu integraciju [13].

Ovi empirijski obrasci mogu se sintezom povezati sa klasičnim teorijama: Frojdova ideja o cenzuri i otporu objašnjava zašto odsustvo interesa može otežati prisećanje i pristup latentnim sadržajima, dok Jungova teza o kompenzatornoj i simboličkoj funkciji snova naglašava da otvorenost ega prema snovima omogućava njihov razvojni i korektivni potencijal.

Obzirom na ove nalaze, preporučljivo je u kliničkoj i preventivnoj praksi razmotriti jednostavne intervencije koje podstiču pozitivan stav prema snovima — npr. vođenje snovnog dnevnika, kratke radionice o radu sa snovima ili strukturisane grupne sesije — jer takve prakse mogu povećati prisećanje, olakšati lični uvid i doprineti emocionalnoj regulaciji i socijalnoj povezanosti.

OGRANIČENJA ISTRAŽIVANJA I PREDLOZI ZA BUDUĆA ISTRAŽIVANJA

Istraživanje je sprovedeno na prigodnom uzorku ispitanika iz opšte populacije, što ograničava mogućnost generalizacije rezultata. Podaci su prikupljeni putem samoprocene u okviru online upitnika, što može biti pod uticajem subjektivnih procena ispitanika i potencijalnih pristrasnosti u odgovaranju. Pored toga, istraživanje je zasnovano na korelacionom presečnom nacrtu, zbog čega nije moguće donositi zaključke o uzročno-posledičnim odnosima između ispitivanih varijabli.

U budućim istraživanjima bilo bi korisno primeniti eksperimentalne pristupe, kao i uključiti dodatne psihološke varijable koje bi mogle doprineti potpunijem razumevanju odnosa između stava prema snovima i načina na koji pojedinci koriste snove u procesu samorazumevanja.

ZAKLJUČAK

Rezultati ovog istraživanja ukazuju na postojanje značajne povezanosti između stava prema snovima i različitih aspekata njihove psihološke relevantnosti. Osobe koje snovima pripisuju veće značenje češće pamte svoje snove, sklonije su da razmišljaju o njihovom sadržaju i koriste ih kao izvor ličnog uvida, kao i da ih dele sa drugima. Ovi nalazi sugerišu da subjektivni odnos prema snovima može predstavljati važnu psihološku varijablu povezanu sa načinima na koje pojedinci integrišu iskustvo sna u budni život. Na taj način, rezultati istraživanja doprinose povezivanju klasičnih psihoanalitičkih teorijskih uvida o psihološkom značaju snova sa savremenim empirijskim pristupima njihovom proučavanju

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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ATTITUDE TOWARDS DREAMS AS AN EXPRESSION OF THE SUBJECTIVE RELATION TO THE UNCONSCIOUS

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ABSTRACT

Dreams occupy a central place in classical psychoanalytic theories, where they are seen as meaningful expressions of unconscious psychic processes. In the Freudian and Jungian theoretical tradition, dreams are viewed as an important source of insight into the inner psychic dynamics of an individual, whereby their interpretation and integration are linked to the understanding of emotional states and internal conflicts. The aim of this research is to examine the relationship between the attitude towards dreams and different aspects of the subjective psychological relevance of dreams in the general population. The research was conducted on a sample of 172 respondents from the general population. Data were collected through an anonymous online questionnaire that includes a sociodemographic questionnaire, the Attitudes Toward Dreams Scale [1], indicators of the use of dreams for personal insight and understanding of internal conflicts - Mannheim Dream Questionnaire [2], as well as measures of the frequency of recalling and sharing dreams. The results indicate statistically significant positive associations between the attitude towards dreams and all examined aspects of their psychological relevance: the frequency of recalling dreams, using dreams for personal insight and understanding of internal conflicts, as well as the frequency of sharing dreams with others. These findings suggest that the subjective attitude toward dreams may be an important psychological variable related to the ways in which individuals remember, consider, and share their dream experiences.

Keywords: dreams, attitude towards dreams, sharing dreams, unconscious, personal insight.

INDIKATORI AGRESIVNOSTI NA PSIHOLOŠKIM INVENTARIMA LIČNOSTI

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SAŽETAK

Čovek je, još od najranijih vremena, ustanovio dva tabua: tabu incesta i tabu ubijanja, što govori koliki značaj se oduvek pridavao agresivnom ponašanju i destrukciji. Kada govorimo o agresiji i njenoj motivaciji i posledicama, treba naglasiti da je ona predmet interesovanja pre svega u forenzici, ali u poslednje vreme istražuje se i u okvirima neuropsiholoških i neurobioloških radova. Za razliku od benigne agresivnosti, koja ima biološki adaptivnu funkciju i svojstvena je kako ljudima, tako i životinjama, maligna agresija može biti „umotana" u različite forme i oblike nasilničkog ponašanja sa ciljem da zadovolji agresora i karakteristično se javlja samo kod ljudi. U radu se razmatra sam koncept agresije i njeni indikatori na dva inventara ličnosti, koji se u poslednje vreme intenzivnije koriste u psihološkom psihodijagnostičkom radu: PAI i MCMI III.

Ključne reči: agresivnost, PAI, MCMI III

UVOD

Da bi neki fenomen bilo moguće naučno istraživati potrebno je najpre definisati njegove osnovne elemente. Agresija se, u principu, može definisati kao svaka fizička ili verbalna akcija, koja je preduzeta s namerom da se nekom drugom nanese šteta ili povreda bilo koje vrste, bez obzira da li je ta namera do kraja realizovana [1]. Sam termin *agresija* potiče od latinske reči *aggredi*, što znači navaliti, napasti, nasrnuti. U suštini, pojam je ambivalentan: upotebljava se najčešće za označavanje neke destruktivne aktivnosti, kada je akcija sa napadačkim ciljem usmerena prema drugoj osobi (homicidalno ponašanje), ali i u slučajevima njene usmerenosti ka samom sebi (suicidalno ponašanje).

Agresivnost je veoma kompleksan fenomen, pa stoga i postoje tendencije da se razgraniči normalna (zdrava) od patološke (maligne) agresivnosti. S tim u vezi je i činjenica da kanalisano verbalno suprotstavljanje stavovima roditelja, koje nalazimo kod adolescenata u fazi formiranja sopstvenog identiteta, u stvari predstavlja zdravu, pozitivnu formu agresivnosti, koja vodi postizanju njihove društvene afirmacije. Međutim, valja napomenuti da normalna agresivnost, kada

prestane da bude kontrolisana, može lako preći u patološku. Možemo primetiti da u aktuelnoj civilizaciji ima previše ograničenja, zabrana i imperativa koji se detetu nameću od najranijih godina života, čime se sputava njegova individualnost i fiksira zavisnost, u čemu Gutović (2003) vidi razloge pojave akumulacije potiskivanja iz kojih u kasnijem životu mogu proisteći veoma opasne agresivnosti i destruktivno ponašanje [2].

Patološka agresivnost može biti verbalna i fizička. U savremenoj literaturi pominju se dva oblika agresivnog ponašanja i to: impulsivno (ponašanje motivisano emocionalnim promenama u organizmu) i instrumentalno (ponašanje motivisano težnjom za postizanjem određenih spoljašnjih ciljeva) [1].

Dimitrijevićeva (2010) navodi da još uvek postoji dilema da li je agresija samostalan nagon (poput seksualnosti), ili se ona stiče i razvija u ranom detinjstvu (pod uticajem vaspitanja i važećih društvenih normi i ideologije) [3]. Zanimljiva je paralela koju autorica daje u vezi sa odnosom agresivne i seksualne energije kroz istoriju čovečanstva: naime, ispostavilo se da je tokom perioda kada je seksualni nagon bio ili strogo potiskivan ili potpuno oslobođen da je i ispoljavanje patološke agresije tada bilo na visokom nivou.

Prema nekim novijim istraživanjima, može se govoriti i o agresivnosti kao osobini ličnosti, koja se stabilizuje veoma rano, već oko četvrte godine života i može se ispoljiti na dva nivoa: kao latentna agresivnost (relativno trajna i stabilna karakteristika ličnosti da u provocirajućim situacijama reaguje porastom emocionalne tenzije i tendencijom za napadom na izvor provokacije) i kao manifestna agresivnost (relativno trajna i stabilna karakteristika ličnosti da u provocirajućim situacijama reaguje fizičkom ili verbalnom agresivnoću usmerenom ka izvoru provokacije) [1].

Teorije o poreklu agresivnosti

Postoji više teorija o poreklu agresivnosti u ljudskoj vrsti. U tom smislu, razmatrajući pitanje šta pokreće agresivno ponašanje, teorije se mogu podeliti u nekoliko grupa.

Jedna od teorijskih postavki su *instiktivističke teorije*, koje agresivno ponašanje tumače kao rezultat postojanja biološki determinisanog pokretača na agresivno ponašanje, a to su instikti. U okviru ove grupe, kao najznačajnije se izdvajaju psihoanalitičke, neoanalitičke i etološke teorije.

U okviru psihoanalitičkih teorija ne možemo a da ne spomenemo teoriju Sigmunda Frojda, koja ujedno predstavlja i prvu psihološku teoriju agresivnosti. On je najpre o agresivnosti govorio kao o parcijalnom nagonu u službi seksualnosti, da bi nešto kasnije o njoj govorio kao o ambivalentnom nagonu, a tek 1920.godine definiše agresivnost kao strukturalni konstrukt ličnosti (gde agresija potiče iz pojedinih razvojnih faza ličnosti, kada one doživljavaju konflikte i bivaju frustrirane). Frojd (1994) dinamiku našeg psihičkog života tumači preko recipročnog delovanja instikta života (Eros) i instikta smrti (Tanatos) [4]. Po njemu, karakteristika instikata je da im je imanentna težnja za ispunjenjem. Delovanje instikata smrti izaziva težnju za samouništenjem ili autoagresivnost, dok delovanje Erosa rezultira sublimacijom, tako da se instikt smrti ne ispunjava samouništenjem već agresivnošću prema drugima. S obzirom na navedene konceptualne promene u Frojdovom definisanju agresivnosti, njegove pristalice su se podelile u dve struje: jedni su, na čelu sa Melani Klajn, ostali verni postulatu postojanja instikta smrti, dok su drugi, poput Hartmana, prihvatili teoriju postojanja primarnih agresivnih sklonosti kod čoveka [3].

U sklopu neoanalitičkih teorija može se reći da je Adler napustio osnove psihoanalitičkog učenja i fenomenu agresivnosti nije pridavao posebnu pažnju, stavljajući u fokus volju za moć, za koju je smatrao da je čoveku urođena i da je njegov osnovni pokretač. Po njegovom tumačenju se i agresivnost javlja kao njen rezultat: agresija je u stvari mehanizam menjanja individue (osećanje manje vrednosti se agresijom kompenzuje i natpompenzuje) [5]. Prema Kohutu, agresivnost nije manifestacija primarnog nagona, već „produkt dezintegracije“, odnosno psihopatologije ličnosti. S druge strane, From (1984) je izneo koncept benigne i maligne agresije, gde je benigna agresija instiktivističke prirode i karakteristična i za životinje i za ljude, dok je maligna agresija svojstvena samo ljudima [7]. On celokupno ljudsko ponašanje, pa u sklopu toga i agresivnost, određuje preko dve grupe faktora: prvi faktor je karakter samog čoveka (sindrom strasti), a drugi faktor su sopstveni interesi (glad, sigurnost, izbegavanje bola).

U okviru etoloških teorija možemo pomenuti Lorentza koji je dao teoriju hidrauličnog modela, gde je agresija u stvari urođeni borbeni instikt – energija napetosti koja se kontinuirano

stvara u mozgu [2]. Mej [6] ne prihvata ideju o tanatosu, ali agresivnost itekako uvažava tvrdeći da je ona način na koji se postiže moć.

Druga grupa teorija umanjuje značaj urođenog u pojavi agresije a prednost daje sredinskim uticajima. Pretpostavlja se postojanje kauzalnog odnosa između frustracije i agresivnosti, a agresivnost se objašnjava reakcijom na određenu situaciju. Ovde, kao najpoznatiju, nalazimo *frustracijsku teoriju agresivnosti*, čini predstavnici agresivnost vide kao ponašanje koje se javlja iskuljučivo kao odgovor na neku frustrativnu situaciju, a ne kao rezultat delovanja instikata. Dollard smatra da se agresija javlja kao odgovor na frustracije, dok Salliven iznosi teoriju da se agresivnost pojavljuje kao posledica interpersonalnih sukobljavanja [8]. Autorima ove teorije je prigovoreno što su frustraciju shvatili kao stanje koje se javlja pri sprečavanju određene reakcije usmerene ka cilju, jer svaka frustracija ne dovodi nužno do agresije, kao što ni svaka agresija nije izazvana frustracijom. Po Berkowitz-u, frustracija ne izaziva direktnu agresivnost, već određeno emocionalno stanje – emociju besa – koja onda, uz prisustvo nekih drugih uslova, dovodi do agresije [5].

U treću grupu spadaju bihejviorističke teorije, koje agresivno ponašanje tumače kao naučeno, te smatraju da se ono usvaja na više načina: posredno (oponašanjem agresivnog modela), neposrednim potkrepljenjem (nagrađivanjem nekih oblika agresivnog ponašanja) ili „vikarijskim“ učenjem (posmatranjem aktivnosti drugih osoba). Kao najznačajnija teorija u ovoj grupi je Bandurina teorija agresivnosti, po kojoj do učenja agresivnog ponašanja ne mora doći kroz sopstvenu aktivnost već se ono može naučiti i preko ponašanja drugih ljudi. Pri tom je važno naglasiti da, što je model realniji, bliži i sličniji posmatraču, to će ponašanje modela imati više efekta na ponašanj posmatrača [9].

Četvrta grupa teorija se nadovezuje i kombinuje saznanja situacijskih i socijalnih teorija. Predstavnici *kognitivno-informacijskih teorija* smatraju da način na koji osoba percipira i interpretira događaje iz okoline odeđuje hoće li ona reagovati agresivno ili nekim drugim ponašanjem. Po njima, strah je najčešća emocionalna reakcija na psihičku ili fizičku opasnost, a uobičajena reakcija na strah je beg ili agresivnost. Šta će osoba izabrati zavisi od njegovih intelektualnih procesa u kombinaciji s emocijama.

Peta grupa teorija se oslanja na novija saznanja koja pružaju neuronauke. Predstavnici *bioloških teorija* posmatraju agresivnost kao rezultat funkcionisanja određenih biološko-fizioloških struktura ili promena u organizmu. Danas se smatra da su mnogi neurotransmiteri uključeni u modulaciju agresivnosti: serotonin, gama aminobuteralna kiselina, noradrenalin i dopamin se vezuju sa pojavom agresivnosti i kod ljudi i kod životinja. Skorija istraživanja ukazuju i na ulogu pojedinih enzima i receptora. Provedena istraživanja identifikovala su u mozgu tzv. olakšavajuća i iritabilna polja. Utvrđeno je da se agresivnošću odlikuju sledeće strukture mozga – hipotalamus, hipokamps, srednji talamus, amigdala, itd, jednom rečju – ceo limbički sistem.

Na pitanje da li postoje neki unutrašnji pokretači, koji dovode do agresivne reakcije ili je agresija uvek reakcija na određenu situaciju može se odgovoriti da se agresija uvek rađa kao reakcija na odeđene situacije, koje osoba percipira kao provocirajuće, bez obzira da li se radi o frustracijskim, averzivnim ili nekim drugim situacijama (npr. takmičenje). To praktično znači da, osim biološke spremnosti, ispoljavanje agresije zavisi i od nekih drugih faktora, kao što su emocionalno-motivacioni faktori, kognitivno-informacijski faktori, socijalni faktori i situacioni faktori [5].

Ipak, individualne razlike u pogledu ispoljavanja agresivnosti su velike i moguće ih je izraziti psihološkim mernim instrumentima. S druge strane, procena agresivnog ponašanja je komplikovana zbog velikog broja različitih načina da se ovaj fenomen reprezentuje. Usled toga se često dešava da empirijska istraživanja pokažu minimalnu međusobnu povezanost mera agresivnosti. U nastojanju da se jasno razgraniče elementi agresivnosti, Spielberger i saradnici [10] su napravili distinkciju između *ljutnje (odnosno besa)*, kao jedne emocije, *neprijateljstva*, koje podrazumeva skup stavova, i *agresije*, koja se odnosi na destruktivno ponašanje usmereno ka drugim ljudima ili objektima. Riley i Treiber [10] su pregledali podatke dobijene različitim skalama, kojima se mere hostilnost i bes (Buss-Durkee-ov inventar hostilnosti, Multidimenzionalni inventar besa, Samoizveštavajuća skala besa, itd). Analizom dobijenih podataka izdvojili su tri faktora: jedan opšti faktor koji „prepoznaje“ iskustvo besa i neprijateljstva i dva faktora koji

identifikuju razlike u načinu ekspresije agresivnog ponašanja (jedan faktor se odnosi na verbalnu ekspresiju besa, a drugi uključuje fizičku, maladaptivnu formu ekspresije besa, odnosno bacanje i razbijanje stvari).

U ovom radu fokusiraćemo se na indikatore agresivnosti na dva inventara ličnosti (PAI i MCMI III).

Indikatori agresivnosti na PAI inventaru ličnosti

Inventar procene ličnosti PAI je samoizveštavajući, objektivni inventar, namenjen odraslim osobama, sa ciljem prikupljanja informacija o kritičnim kliničkim varijablama. Razvio ga je 1991.godine Lesli Morey, a sadrži ukupno 344 ajtema, koji su uključeni u 22 kliničke skale, koje se ne preklapaju. Sve stavke su raspoređene u četiri kategorije:

- 4 skale validnosti,
- 11 kliničkih skala,
- 5 skala tretmana, i
- 2 interpersonalne skale.

Razvoj testa je prošao kroz četiri faze, pri čemu je od najveće važnosti bila pretpostavka da nijedan pojedinačni kvantitativni parametar ajtema neće biti korišćen kao jedini kriterijum za selekciju ajtema. U pozadini ovoga je činjenica da preterano poverenje u jedan parametar u selekciji ajtema obično dovodi do skala sa jednom poželjnom psihijatrijskom prednošću i brojnim neželjenim.

Proveravanje validnosti PAI skale u proceni agresivnog ponašanja podržava upotrebu ovog inventara [11], [12], [13]. Kao upitnik, PAI je veom popularan u forenzici zbog sveobuhvatne evaluacije agresivnog potencijala, besa i hostilnosti. Iako nije posebno razvijen za procenjivanje rizika od nasilja, on može pomoći psiholozima u proceni ove vrste rizika. PAI nudi više korisnih skala i indeksa za procenu agresije, rizika od nasilja i mogućnosti recidiva [14]. Studija Battaglie i saradnika (2021) otkrila je da skala agresije efikasno pravi razliku između nasilnih prestupnika i zdravih ispitanika iz kontrolne grupe [13].

Skala agresije (AGG)

Očigledna polazna tačka u proceni agresivnosti na PAI inventaru je AGG skala. Ova skala je u testu pozicionirana u grupi skala koje se odnose na tretman. Ona nije direktno povezana ni sa jednom dijagnostičkom kategorijom u DSM klasifikaciji: umesto toga ona se dotiče fundamentalnih afekata i ponašanja koja su uključena u više dijagnostičkih kategorija. DSM je inače kritikovan zato što ne uključuje klasifikaciju problema srodnih besu i agresivnosti. S druge strane, klasifikacija uključuje poremećaje ličnosti od kojih su neki (antisocijalni, Border-Line i pasivno-agresivni) povezani sa agresivnošću i njenom kontrolom.

Prema Waltersovom istraživanju (2007), provedenom na 120 muških zatvorenika u zatvoru sa maksimalnim stepenom obezbeđenja, skala agresivnosti (AGG) je dobro predvidela ukupan broj agresivnih i broj incidenata bez agresije tokom dvogodišnjeg praćenja [15]. Međutim, ima i drugačijih nalaza. Tako, Prosnik Domjan (2022), tokom procene agresivnog potencijala, nije našla značajne razlike između forenzičkih i pacijenata iz opšte psihijatrije u pogledu skale agresivnosti (AGG) i indeksa potencijala za nasilje (VPI) [16]. Slično, počinioci nasilnih krivičnih dela i počinioci imovinskog krivičnog dela u studiji Fernandeza (2022) nisu se statistički značajno razlikovali u odnosu na izraženost agresivnosti (skala AGG) [17].

Ipak, može se reći da AGG skala pruža korisne informacije širom spektra dijagnoza. Ona je sastavljena iz tri elementa agresivnosti, koje su identifikovali Rilex i Treiber [10] (1989, prema Morey, 1996), a o kojima smo govorili nešto ranije. Prva supskala je namenjena opštoj proceni besa i hostilnosti kao karakteristike samog temperamenta individue, a druge dve procenjuju tipičan način ponašanja, odnosno način na koji se bes i hostilnost izražavaju. Dakle, ova kombinacija supskala dozvoljava procenu broja diferencijalnih aspekata agresije i njene kontrole (ili nedostatka kontrole).

Agresivni stav (AGG-A)

Morey (1996) je konceptualizovao ovu supskalu tako, da obuhvati opšte afekte i stavove koji dovode do agresivnog ponašanja (tj. „nagli temperament ili pak verovanje u instrumentalnu korist od agresije) [10]. On navodi da je ovaj koncept posebno uočljiv u ekspresiji besa: osoba može da bude naizgled mirna – bez vidljive ekspresije besa, a da u stvari bes potiskuje i drži ga u sebi. Isto tako, supskala otkriva i sklonost besu, odnosno prisustvo tendencije da se postepeno postaje frustriran, pa se ljutito reaguje na kritike i loš tretman od strane drugih.

Osoba, koja na ovoj supskali dobije niske skorove može se opisati kao mirna, staložena i tolerantna, te kao osoba koja se veoma sporo ljuti i koja oprašta drugima. Umerena povišenja (60 T -70 T) ukazuju na osobu koja se lako ljuti i frustrirana je, pa je drugi često doživljavaju kao nekoga ko je hostilan i lako ga je isprovocirati. Skorovi koji prelaze 70 T na ovoj supskali govore o osobi koja je veoma sklona izražavanju besa, obično gubi kontrolu nad emocijama i na malu provokaciju. Ovako visoki skorovi mogu da ukazuju i na osobu koja koristi bes da bi zastrašila ili kontrolisala druge, i koja postaje besna kada je drugi kritikuju ili opstruišu na bilo koji način. Međutim, treba imati na umu da toliko besa ne mora odmah da se ispolji: prema Moreyu (1996), ako je AGG-A povišen a AGG-V i AGG-P su u rangu ispod srednje vrednosti, osoba očigledno potiskuje bes (što je često povezano i sa niskim skorovima na supskali dominantnosti DOM), ili ga možda drži u sebi (što je u vezi sa povišenim skorovima na supskali kognitivne depesije DEP-C i niskim skorovima na grandioznosti u okviru supskale manije MAN-G) [10].

Verbalna agresija (AGG-V)

Ova supskala uključuje ajteme koji ukazuju na spremnost da se ispolji verbalna ljutnja u blagoj formi (kroz sarkazam ili kritiku), ili pak u ekstremnijoj formi (kroz viku i vređanje). Morey (1996) navodi da niski skorovi pokazuju napor da se od drugih sakrije bes, a visoki skorovi govore o malo ili nimalo napora da se kontroliše spoljna ekspresija besa, tako da visoki skorovi na ovoj supskali signališu da će osoba pre ispoljiti doživljeni osećaj besa i ljutnje, nego što će ga potisnuti [10]. Prema autoru, niski skorovi na AGG-V govore o osobi koja ne voli da pokaže svoj bes kada ga doživljava, već ga radije kontroliše, držeći ga u sebi. Iako je kontrola besa poželjna, preterana kontrola može dovesti do pasivizacije i povlačenja (ide sa niskim skorovima na DOM), samokažnjavajućeg ponašanja (što je povezano sa povišenjem na DEP-C i sniženjem na MAN-G), ili epizodno slabo kontrolisanog, slobodnog izliva besa (što je povezano sa povišenjem na AGG-P).

Skorovi na AGG-V koji su umereno povišeni (60 T – 70 T) reflektuju osobe koje su samopouzdane i ne plaše se konfrontacije. Što su rezultati bliži gornjem skoru, to ove osobe mogu biti verbalno agresivnije i na manje provokacije (da kritikuju, vređaju, prete). Skorovi preko 70 T su povišeni i ukazuju na osobe sklone uvredljivim verbalnim izlivima, tako da nisu popularne među drugima i drugi ih doživljavaju kao ekstremno hostilne.

Fizička agresija (AGG-P)

Ova supskala prezentuje stavove prema fizičkoj ekspresiji agresije. Kako Morey (1996) navodi, ajtemi uključuju istoriju tuča i fizičkog nasilja tokom odrastanja, tako da povišenja na ovoj supskali govore o problematičnom ponašanju tokom perioda adolescencije, ali i za vreme odraslog doba [10]. Kada se dobiju skorovi u okvirima proseka, onda se zaključuje da ova osoba izveštava o generalno dobroj kontroli osećanja besa i impulsa, i retkim izlivima besa. Umereno povišeni rezultati upućuju na veću sklonost ka ispoljavanju fizičke agresije (preko lomljenja predmeta ili učestvovanjem u tučama), mada se ove osobe trude da održe kontrolu nad svojim besom. Ako skorovi prelaze 70 T, kod ovih osoba kontrola obično popušta, što rezultuje mnogo ekstremnijim ponašanjem, uključujući uništavanje imovine i napad na druge osobe. Neka od ovih ponašanja mogu da se ispolje iznenada i neočekivano, pa je verovatno da je okolina zaplašena njihovim temperamentom i potencijalnim fizičkim nasiljem, usled čega ih izbegavaju.

Interpretacija cele AGG skale

AGG skala omogućava globalnu procenu stavova i ponašanja relevantnih za agresiju, bes i neprijateljstvo. Prosečni skorovi na ovoj skali (<60 T) govore o razumnoj kontroli nad ekspresijom besa i neprijateljstva, dok skorovi ispod 40 T uglavnom ukazuju na mirne, blage i nesamopouzdane osobe, koje imaju poteškoća da ostanu dosledne sebi. Skorovi između 60 T i 70 T su indikovani za osobe koje drugi doživljavaju kao nestrpljive, iritantne, nagle u situacijama kada su frustrirane ili povređene. Ispitanici sa skorovima preko 70 T su hronično besni i oni će otvoreno izraziti svoj bes i neprijateljstvo. U ovom rangu najmanje jedna od supskala je uvećana i ovi skorovi će nam pokazati koji je tipičan modalitet kroz koji će se agresija ispoljiti (verbalni ili fizički).

AGG skorovi koji su upadljivo povišeni (>82) signaliziraju značajan bes i visok potencijal za agresiju, pa se ovakve osobe lako isprovociraju i mogu da reaguju eksplozivnim besom kada su frustrirani. Ukoliko je AGG-V nisko a AGG-P uvećano, ekspresija besa može doći skoro bez upozorenja. Verovatno je da u istoriji ovih osoba postoje tuče i situacije kada bes zamagljuje njihovo rasuđivanje, što često dovodi do profesionalnih i teškoća sa zakonom.

Profili AGG skala

Specifična kombinacija supskala koje vode povišenju AGG je veoma imformativna u utvrđivanju prirode i ozbiljnosti bilo kod agresivnog ponašanja. U sledećem delu opisane su neke od implikacija različitih kombinacija povišenja na ove tri supskale [10]. Pri tom se visok skor odnosi na skorove iznad 70 T.

AGG-A visok, AGG-V visok, AGG-P visok

Ovakav obrazac ukazuje na osobu koja se lako ljuti i koju drugi verovatno doživljavaju kao hostilnu i veoma besnu. Osobe sa ovim obrascem uglavnom imaju teškoća u kontrolisanju svog besa, jer ulažu malo napora da ga kontrolišu i otvoreno pokazuju bes onda kada su ga doživeli. Čak i u nisko provocirajućim situacijama postaju veoma ratoborne i ne plaše se konfrontacije, a njihov bes može lako da eskalira i ekstremno se ispolji preko uništavanja imovine i napada na druge.

AGG-A visok, AGG-V visok, AGG-P prosečan

Ovakak obrazac opisuje osobu koju drugi doživljavaju kao neprijateljski nastrojenu i ljutu, sa teškoćama u kontrolisanju ekspresije besa. Kada je besna, osoba će pre pokazati svoj bes odmah nego što će trpeti uvredu. Ona se ne boji verbalnog sukoba i upravo će reagovati verbalnom agresijom i u situaciji niskog stepena provokativnosti. Ekstremniji izrazi besa (u smislu uništavanja imovine i napada na druge) mogu, ali ne moraju da budu deo kliničke slike. Ovaj obrazac pre opisuje osobu koja „laje a ne ujeda“. Moguće je da kod osoba sa ovim obrascem ventiliranje besa služi kao prevencija dramatičnijeg i prevelikog gubitka kontrole nad sobom.

AGG-A visok, AGG-V prosečan, AGG-P visok

Ovaj obrazac govori o veoma agresivnoj osobi, koja se bori da održi kontrolu nad svojim temperamentom, ali je brzo gubi. Kada se to desi, izlivi besa podrazumevaju i uništavanje imovine i napade na druge osobe. U slučajevima kada je razlika između AGG-V i AGG-P velika (tj. ≥ 20 T), ovo ukazuje da su izlivi besa po pravilu iznenadni i neočekivani, a bes se ispoljava odmah, u trenutku kada se i doživljava. Stoga okolina zazire od ovakve osobe, boji se njihove nepredvidivosti, njihove eksplozivne naravi i potencijalnog fizičkog nasilja.

AGG-A prosečan, AGG-V visok, AGG-P visok

Ovo je veoma neobičan obrazac. Osoba sa ovim obrascem veruje da je samopouzdana i da dobro kontroliše bes i impulse. Ipak, njeno ponašanje ukazuje da njena kontrola naravi nije ni blizu toliko dobra, koliko ova osoba veruje. Ljudi ovoj osobi prilaze veoma oprezno, jer imaju iskustvo da ona može da postane mnogo hostilnija i ljuća nego što to sama veruje, te da bes izražava odmah, a nivo izraženosti može da bude i ekstreman (uništavanje stvari i maltretiranje drugih).

Indeks potencijala za nasilje (VPI)

Vrlo je teško proceniti rizik od nasilja određenog pojedinca, a istraživanja u literaturi, bar do sada, daju slabu empirijsku bazu za donošenje takve procene. Često su bolji prediktori demografski faktori (kakvi su godine i pol, ili istorija nasilnog ponašanja), nego što su to klinički znaci i simptomi, ili pak merenje instrumentima kao što je PAI. I pored toga, PAI uključuje razne faktore koji se odnose na neprijateljstvo, agresiju, podozrivost, socijalno povlačenje, isl.

Indeks potencijala za nasilje na PAI inventraru ličnosti se sastoji od 20 karakteristika, koje su prikazane u tabeli 1.

Tabela 1. Indeks potencijala za nasilje na PAI (N=1246) [10]

Faktori rizika od nasilja	PAI markeri	Frekvencije kliničkog uzorka
Eksplozivna ekspresija besa	AGG-P 15 T veća od AGG-V	26%
Bes usmeren ka spolja	AGG 10 T veća od SUI	18%
Kontrola hostilnosti u vezama	DOM 10 T veća od VRM	26%
Istorija traume bez straha	ARD-T 15 T veća od ARD-P	33%
Istorija antisocijalnog ponašanja	ANT-A >70 T	22%
Ograničeni kapacitet za empatiju	ANT-E >60 T	24%
Traženje senzacija	ANT-S >60 T	25%
Brzo menjanje raspoloženja	BOR-A >70 T	26%
Problematične bliske veze	BOR-N >70 T	27%
Impulsivnost	BOR-S >70 T	21%
Agitiranost	MAN-A >60 T	24%
Samocentričnost	MAN-G >60 T	19%
Negativan pogled na svet	NIM >70 T	19%
Neprijateljska podozrivost	PAR-H >70 T	17%
Osećaj progonjenosti	PAR-P >70 T	14%
Psihotični simptomi	SCZ-P >70 T	8%
Socijalno otuđenje	SCZ-S >70 T	20%
Alkohol kao dezinhibitor	ALC >70 T	27%
Narkomanija kao dezinhibitor	DRG >70 T	24%
Otuđenje od podrške sistema	NON > 70 T	22%

Rezultati indeksa potencijala za nasilje (VPI) zasnivaju se na prisustvu (1 bod) ili odsustvu (0 bodova) dvadeset navedenih karakteristika PAI profila. Pretvaranje T-skorova u VPI je prikazano u Tabeli 2, a kao standardizacione reference korišćeni su opšti i klinički uzorak.

Prema autorici, VPI skorovi na 9.ajtemu i iznad njega (do 16.ajtema) kod obe grupe ukazuju na umeren rizik od nasilnog ponašanja, dok skorovi na 17.ajtemu i iznad njega upućuju da je navedeni rizik visok. Takvi slučajevi, posebno ukombinaciji sa povišenim skorovima na AGG skali treba da upozore na faktor nasilja i faktor ličnosti u vezi sa opasnošću od nasilja.

Tabela 2: Odgovarajući T-skorovi za Indeks potencijala za nasilje (VPI), standardizovani na opštem (N=1000) i kliničkom uzorku (N=1246)

VPI skor	T skor (opšti uzorak)	T-skor (klinički uzorak)
0	**43**	**39**
1	**47**	**42**
2	**52**	**44**
3	**57**	**46**
4	**61**	**49**
5	**66**	**51**
6	**70**	**54**
7	**75**	**57**
8	**79**	**59**
9	**84**	**62**
10	**89**	**64**
11	**93**	**67**
12	**98**	**69**
13	**102**	**72**
14	**107**	**74**
15	**111**	**77**
16	**116**	**79**
17	**121**	**82**
18	**125**	**84**
19	**130**	**87**
20	**134**	**89**

Antisocijalne karakteristike (ANT)

Osim AGG skale i VPI indeksa, u istraživanjima provedenim uz pomoć PAI inventara, pominje se i skala antisocijalnih karakteristika (ANT) kao potencijalno povezana sa tendencijom ka kršenju pravila u popravnim ustanovama i zatvorima [18]. Sama skala sadrži ajteme koji se odnose na prisustvo egocentričnosti, neempatičnosti i antisocijalnog ponašanja. Prema inventaru, umeren nivo impulsivnosti i rizičnog ponašanja pokazuju osobe čiji se skorovi na skali kreću u rasponu od 60 T do 69 T, s tim da već rang od 65 T i iznad signalizira uvećanu samocentričnost i neosećajnost u interpersonalnim relacijama. Kada je reč o uvećanim skorovima (70 T i više) onda se radi o osobama koje prezentuju impulsivnost, hostilnost i antisocijalno ponašanje, a izrazito uvećani skorovi (82 T i više) impliciraju da je verovatno reč o izrazito nepouzdanim i neodgovornim osobama, koje su sklone eksploataciji drugih kako bi zadovoljile svoje potrebe i koje su sklone konfrontiranju sa figurama autoriteta, te pokazuju izražene karakteristike antisocijalnog poremećaja ponašanja.

Indikatori agresivnosti na MCMI III inventaru ličnosti

MCMI je alat za procenu ličnosti koji se kontinuirano razvija i koji je, za razliku od drugih inventara, relativno sažet, teorijski zasnovan i validiran u tri stadijuma. Razvio ga je Teodor Millon, a prva verzija inventara objavljena je 1977.godine i odgovarala je DSM-III klasifikaciji bolesti.

Kao teoretska osnova uzeta je evoluciona teorija poremećaja ličnosti, po kojoj je ličnost multioperacioni fenomen ispoljen kroz bihejvioralne, terminološke, intrapsihičke i biološke domene, a pri tom se ličnost ne može proceniti samo sa jednog od navedenih aspekata. Milon je svoj model ličnosti revidirao 1990.godine kada, radi boljeg razumevanja geneze poremećaja ličnosti, uvodi faze neuropsihološkog razvoja kao jedan od četiri elementa svog evolutivnog modela [1].

Sa dolaskom DSM-IV klasifikacije, Milon je dijagnostičke kategorije specifikovao i operativno definisao tako da je struktura MCMI i dalje bila paralelna sa strukturom DSM na mnogo nivoa: skale MCMI su grupisane u kategorije ličnosti i psihopatologije, kako bi odslikavale DSM razliku između OSE II (trajne personalne osobine pacijenata) i OSE I (akutni klinički poremećaji koje ispoljavaju) [19].

Inventar ukupno sadrži 175 ajtema, koji su uključeni u 4 skale validnosti i 24 kliničke skale:

- 11 skala kliničkih prototipova ličnosti,
- 3 skale ozbiljne patologije ličnosti,
- 7 skala kliničkih sindroma,
- 3 skale ozbiljnih kliničkih sindroma.

MCMI koristi bazne stope (BR), što su transformisani rezultati koji odražavaju stope prevalencije određenih karakteristika unutar standardizovanog uzorka i kreću se u rasponu od 0 do 115. Pri tom, BR rezultat ≥ 75 ukazuje na prisustvo osobine odnosno crte ličnosti, dok BR rezultat ≥ 85 ukazuje na prisustvo poremećaja [20].

Sam inventar je veoma koristan u kliničkoj praksi za razumevanje i procenu poremećaja linosti, ali i kliničkih sindroma kod psihijatrijskih pacijenata. Prema nekim istraživanjima, MCMI spada među 25 najčešće korišćenih psiholoških testova u kliničkoj praksi, gde je rangiran na trećem mestu, odmah iz MMPI i Rorschach-tehnike [21]. U samom upitniku ne postoji posebna skala koja bi procenjivala agresivnost, tako da se prisustvo agresivnosti može ceniti preko izraženosti pojedinih kliničkih prototipova ličnosti.

Prema nekim istraživanjima, najčešće su sa nasilnim ponašanjem povezani antisocijalni, paranoidni, narcistički, granični i izbegavajući poremećaji ličnosti [22], [23]. Tako, upitnik je korišćen u istraživanju nasilja u porodici, gde se pokazalo da u profilima zlostavljača dominiraju antisocijalni, sadistički, negativistički i, donekle, narcistički poremećaji, dok u proceni partnerskog nasilja nije nađen određeni MCMI profil prestupnika [24], što Loinaz i saradnici (2012) objašnjavaju preko značajne raznolikosti patologije ličnosti među njima [20]. Ipak, istraživanje Romero-Martíneza i saradnika (2016) ukazalo je da počinioci partnerskog nasilja imaju izraženije antisocijalne, granične i narcističke osobine ličnosti i lakše izražavaju bes u odnosu na ispitanike iz kontrolne grupe [25].

Po Craigu (2005), skale antisocijalnog, sadističkog, negativističkog, graničnog i paranoidnog poremećaja na MCMI III inventaru se koriste kao pokazatelji agresije u forenzičkom kontekstu [20].

Antisocijalni poremećaj (skala 6)

U Milonovoj teoriji, antisocijalna ličnost teži nezavisnosti i motivisana je da izbegne kontrolu i dominaciju drugih. U istoriji ovih osoba se u adolescentnom periodu mogu naći podaci o bežanju iz škole i delinkventnom ponašanju.

Visoki skorovi na ovoj skali impliciraju da ove osobe karakteriše narcizam, agresivnost, neustrašivost, ratobornost, odvažnost, osvetoljubivost, potreba za dominacijom i drugi ih obično doživljavaju kao zastrašujuće. Ove osobe često imaju ljutito i neprijateljsko držanje, obično ne podnose blagost, a toplinu i intimnost doživljavaju kao znak slabosti. Oni pokušavaju da izazovu strah kod drugih, jer ih na taj način kontrolišu (koriste acting-out kao glavnu odbranu). Skloni su zloupotrebi supstanci, imaju probleme u bliskim odnosima, profesionalnom funkcionisanju i sa zakonom. Neosetljivost i okrutnost su njihova jedina sredstva za izbegavanje situacija u kojima bi mogli biti zloupotrebljeni ili žrtve.

Važno je napomenuti da osoba može imati antisocijalnu ličnost, a da pri tom ne pokazuje kriminalno ponašanje, mada je kod visokih skorova ovako nešto malo verovatno [26].

Sadistički (agresivni) poremećaj (skala 6B)

Sadržaj stavki koje ulaze u ovu skalu obuhvata agresivnost i njenu kontrolu. Visoki skorovi na ovoj skali upućuju na osobu koja je sklona da druge vređa. Ove osobe karakteriše neprijateljsko, zastrašujuće i agresivno ponašanje, dominantne su, arogantne, eksplozivne i razdražljive. Mogu reagovati brutalnom silom ako su isprovocirane ili ljute: i one, kao i antisocijalne ličnosti, koriste

acting-out kao glavnu odbranu. Eksplozivni izlivi su za njih uobičajeni. Po Stacku (2002) neki pripadnici ove grupe su u stanju da sublimiraju ove osobine preko društveno prihvatljivih zanimanja [26]. Takođe, neke od ovih osoba ne pokazuju antisocijalno ponašanje, ali imaju agresivan obrazac ličnosti. Pacijenti sa ovakvom ličnošću su skloni bračnim i problemima sa zakonom (preporučuje se da se, ako se ovaj obraza pojavi, potraže dokazi o zlostavljaju partnera ili dece).

Negativistični (pasivno-agresivni) poremećaj (skala 8A)

Stavke na ovoj skali se odnose na razdražljivost, impulsivnost, neprijateljstvo, verbalne napade, gubitak kontrole nad besom, surovo ponašanje. Osobine koje opisuje ovaj obrazac uključuju neraspoloženje, razdražljivost, negativizam, pesimizam, zabrinutost, bes. Osobe sa ovim obrascem su stalno razočarane, osećaju da ih drugi ne uvažavaju i ne cene dovoljno njihova osećanja, te su često nepravedni prema njima. Usled sopstvene mrzovolje često upadaju u probleme sa autoritetom, saradnicima, prijateljima i porodicom. Visoke skorove mogu imati oni pacijenti, koji su u jednom trenutku pacitno kontaktibilni i poslušni, a u drugom negativistični i opozicioni. Stack (2002) smatra da je visina skorova na ovoj skali odličan prediktor gubitka kontrole nad emocijama [26].

Granični poremećaj (skala C)

Sadržaj stavki ove skale odnosi se na nestabilnost raspoloženja, bes, krivicu, buntovničko ponašanje i reakcije, ponašanje traženja zavisnosti, nestabilne odnose. Osobe sa visokim skorivima na ovoj skali pokazuju poremećaj vezivanja sa obrascima intenzivnih ali nestabilnih emocija, imaju istoriju impulsivnog ponašanja, jaku potrebu za zavisnošću sa strahom od napuštanja. Oni su okupirani traženjem emocionalne podrške i posebno su podložni separacionoj anksioznosti. Nedostaje im jasan osećaj sopstvenog identiteta, pa stalno traže odobravanje, pažnju i reafirmaciju. Oni koriste spliting i devaluaciju kao svoje glavne odbrane. Skloni su kratkim psihotičnim reakcijama, kao i samopovređivanju i suicidalnom ponašanju. Kliničke manifestacije ovog poremećaja uključuju i aspekte negativnog afekiviteta (depresivni simptomi, povišena anksioznost naročito u situacijama separacije) ali i manifestacije dezinhibicije (impulsivno, samo-destruktivno ponašanje, proboji agresivnosti, sklonost zloupotrebi supstanci) [27].

Zanimljivo je istraživanje Taşkalea i saradnika (2025), po kome su muškarci sa graničnim poremećajem ličnosti skloniji počinjenju nasilja nad intimnim partnerom, dok su žene sa graničnim poremećajem ličnosti u većem riziku od viktimizacije [28].

Paranoidni poremećaj (P)

Prema Milonovom modelu, paranoidni poremećaj ličnosti karakteriše rigidnost, ideoafektivni blok i beskompromisnost u odnosu prema sebi i prema drugima [1]. Stavke na ovoj skali odnose se na kognitivnu sumnjičavost i nepoverenje u interpersonalnim odnosima, ogorčenost, ljutnju, neopraštanje, svadljivost, traženje skrivenih ili zavereničnih namera drugih osoba.

S obzirom na nepoverenje prema drugima, paranoidne osobe pokazuju anksioznost vezivanja, što može usloviti pojavu agresivnog i optužujućeg, pa i progoniteljskog ponašanja. Izrazito su osetljivi na neprihvatanje i hostilnost iz okoline, što pogoduje razvoju sumnjičavosti i pojačane budnosti sa anticipiranjem potencijalne malicioznosti i omalovažavanja. Skloni su proveravanju lojalnosti bliskih osoba. U strukturi ličnosti nalazimo napetost, uvredljivost, ljubomoru, nizak prag frustrativne tolerancije i sklonost reagovanju na najmanji povod. Glavni regulatorni mehanizmi su projekcija i fantazija, kojima svoje neprihvatljive misli, motive i osećanja pripisuju drugima (projekcija) i kroz komplikovane samoobmane konstruišu dokaze o sopstvenoj grandioznosti (fantazija) [1].

ZAKLJUČAK

Istraživanja koja su uključivala upitnike novije generacije, u ovom slučaju Inventar procene ličnosti PAI i Milonov multiaxijalni inventar ličnosti MCMI III potvrdila su njihovu relevantnost za upotrebu na kliničkoj populaciji. Ovi inventari nisu prevashodno napravljeni za procenu agresivnosti i rizika od iste, već se prvenstveno bave strukturom i poremećajima ličnosti,

zloupotrebom supstanci i psihotičnim poremećajima (poput shizofrenije), koji potencijalno mogu biti važni u donošenju odluka vezanih za pacijenta (otpust, premeštanje u drugu ustanovu, izricanje kazne, isl).

Međutim, veoma su popularni među instrumentima kliničke procene u forenzičkim uslovima, gde se često koriste kao alati za procenu nivoa agresivnosti i sklonosti nasilnom agiranju. Poseban značaj ima njihova sposobnost predikcije agresivnog i antisocijalnog ponašanja, što u kliničkoj praksi znači veću bezbednost osoblja i drugih pacijenata u zatvorenim institucijama. Ipak, proces psihološke obrade i razumevanja pacijenta, pa i procena rizika od ispoljavanja nasilja ne treba da se zasniva na samo jednom inventaru, već se preporučuje upotreba baterije testova.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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INDICATORS OF AGGRESSIVENESS ON PSYCHOLOGICAL PERSONALITY INVENTORIES

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SUMMARY

Man, since the earliest times, established two taboos: the taboo of incest and the taboo of killing, which shows how much importance has always been attached to aggressive behavior and destruction. When we talk about aggression and its motivation and consequences, it should be emphasized that it is the subject of interest primarily in forensics, but lately it has also been investigated in the framework of neuropsychological and neurobiological works. Unlike benign aggression, which has a biologically adaptive function and is characteristic of both humans and animals, malignant aggression can be "wrapped" in various forms and forms of violent behavior with the aim of satisfying the aggressor and characteristically occurs only in humans. The paper discusses the very concept of aggression and its indicators on two personality inventories, which have recently been more intensively used in psychological psychodiagnostic work: PAI and MCMI III.

Keywords: aggressiveness, PAI, MCMI III

EMOCIJE U BELIM MANTILIMA: PILOT STUDIJA O STAVOVIMA PREMA EMOCIJAMA I EMOCIONALNOJ PISMENOSTI KOD LEKARA I MEDICINSKIH SESTARA

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SAŽETAK

Cilj ovog empirijskog istraživanja bio je da se ispitaju razlike u stavovima prema emocijama između lekara i medicinskih sestara, kao i da se sagledaju aspekti njihove emocionalne pismenosti u kontekstu svakodnevnog profesionalnog funkcionisanja. U ovom pilot istraživanju je učestvovalo ukupno 89 ispitanika, skoro ravnomerno raspoređenih po profesiji. Korišćen je upitnik stavova prema emocijama koji obuhvata kognitivne, afektivne i regulatorne dimenzije emocionalnog funkcionisanja. Analizom hi-kvadrat testa utvrđeno je 16 tvrdnji sa statistički značajnim razlikama između posmatranih grupa ($p < .01$). Rezultati su pokazali da lekari češće izražavaju emocionalnu inhibiciju, sklonost potiskivanju emocija, strah od emocionalne procene i oslanjanje na racionalizaciju, dok medicinske sestre pokazuju veću emocionalnu otvorenost, prihvatanje funkcionalnosti emocija i spremnost za izražavanje afekta. Diskutovani su uticaji profesionalne socijalizacije, obrazovnog sistema i organizacione kulture na formiranje specifičnih obrazaca emocionalne pismenosti. Nalazi ovog istraživanja imaju značajne implikacije za razvoj edukativnih programa usmerenih na emocionalne veštine zdravstvenih radnika, unapređenje međuprofesionalne komunikacije i prevenciju sagorevanja. Takođe, ukazuju na potrebu za dubljim razumevanjem emocionalnog rada u zdravstvu, sa akcentom na prilagođene intervencije koje uzimaju u obzir profesionalni kontekst i izazove svake pojedinačne struke.

Ključne reči: emocije, emocionalna pismenost, lekari, medicinske sestre, profesionalna socijalizacija

UVOD

Emocije su ključna komponenta ljudskog funkcionisanja, a njihovo razumevanje i regulacija igraju presudnu ulogu u mnogim profesionalnim kontekstima, posebno u oblasti zdravstvene zaštite. Zdravstveni radnici, poput lekara i medicinskih sestara, svakodnevno se suočavaju sa

emocionalno zahtevnim situacijama koje podrazumevaju brigu o bolesnima, patnju pacijenata, stres zbog vremenskih pritisaka i donošenje odluka od životne važnosti [1]. Zdravstveni radnici su svakodnevno izloženi emocionalno intenzivnim situacijama koje uključuju patnju, gubitak, nesigurnost i moralne dileme, zbog čega se emocionalna pismenost sve više prepoznaje kao ključna kompetencija u njihovom radu [2], [3]. Uprkos sličnom profesionalnom okruženju, očekivanja, uloge i obuke lekara i medicinskih sestara značajno se razlikuju, što može doprineti razlikama u njihovim emocionalnim stavovima i strategijama emocionalne regulacije. Lekari se tradicionalno socijalizuju u kontekstu visoke odgovornosti, odlučivanja u uslovima neizvesnosti i potrebe za racionalnošću i kontrolom [4]. U tom smislu, emocionalna ekspresija može biti percipirana kao slabost ili čak profesionalna neprikladnost. S druge strane, medicinske sestre se obučavaju za neposrednu negu pacijenata, koja uključuje saosećanje, emocionalnu prisutnost i interpersonalnu podršku [5]. Ova razlika u akcentima profesionalne socijalizacije može oblikovati razlike u emocionalnim stavovima, od percepcije emocija, preko tolerancije prema emocionalnom izrazu, do načina na koji se emocije koriste i regulišu u radnom kontekstu.

U teorijskom smislu, Grossov model emocionalne regulacije [6] razlikuje strategije kao što su suzbijanje i reinterpretacija, koje se mogu razlikovati među profesionalcima u zavisnosti od konteksta i socijalnih normi. Takođe, koncept emocionalnog rada koji je uvela [7] posebno je relevantan za zdravstvene profesije, jer implicira stalno prilagođavanje emocionalnog izraza očekivanjima organizacije i pacijenata. Kod lekara, emocionalni rad često se odvija kroz distancu i profesionalni jezik, dok su sestre češće uključene u direktne emocionalne interakcije sa pacijentima [8]. Empirijska istraživanja pokazuju da lekari češće koriste kognitivne i defanzivne strategije suočavanja sa emocijama, dok su sestre sklonije izražavanju i verbalizaciji emocija [9]. Ovakve razlike nisu bez posledica: način na koji zdravstveni radnici razumeju i upravljaju emocijama može uticati na kvalitet nege, zadovoljstvo poslom, kao i na pojavu profesionalnog sagorevanja i psihološke disfunkcije [10]. Uprkos značaju ove teme, relativno je malo istraživanja koja sistematski porede stavove prema emocijama između lekara i medicinskih sestara. Ova studija ima za cilj da istraži razlike u emocionalnim uverenjima i tendencijama izražavanja emocija kod ove dve profesionalne grupe, oslanjajući se na kvantitativnu analizu odgovora na niz stavki koje se tiču emocionalnog razumevanja, kontrole i interpersonalne ekspresije. Razumevanje ovih razlika može doprineti razvoju prilagođenih edukativnih programa i strategija mentalne podrške unutar zdravstvenog sistema.

TEORIJSKI OKVIR: EMOCIJE I EMOCIONALNA PISMENOST

Emocije predstavljaju osnovnu komponentu ljudskog psihološkog funkcionisanja i imaju ključnu ulogu u regulaciji ponašanja, donošenju odluka, interpersonalnim odnosima i adaptaciji na promene u okruženju. One se definišu kao kompleksne, višedimenzionalne reakcije koje uključuju subjektivni doživljaj, neurofiziološke promene, izražavanje kroz govor tela i facijalne ekspresije, kao i kognitivnu procenu situacije [11], [12]. Emocije nisu samo pasivne reakcije, već aktivni procesi koji organizuju i usmeravaju pažnju, vrednuju iskustva i motivišu ponašanje. Aktuelne i opšte prihvaćene teorije emocija, poput teorije osnovnih emocija [13], teorije emocionalne procene [14] i konstrukcionističkih pristupa [15], naglašavaju da su emocije rezultat interakcije između bioloških predispozicija i socijalno-kulturnih faktora. Bez obzira na teorijski okvir, postoji konsenzus da sposobnost pojedinca da identifikuje, razume, izrazi i reguliše sopstvene emocije ima značajan uticaj na mentalno zdravlje, akademski i profesionalni uspeh, kao i kvalitet socijalnih odnosa.

U tom kontekstu se razvija koncept emocionalne pismenosti, koji se odnosi na skup veština koje omogućavaju osobi da bude svesna svojih emocija, da ih precizno identifikuje, izrazi na prikladan način, razume njihove uzroke i posledice, te da ih konstruktivno reguliše [16], [17]. Emocionalna pismenost uključuje i sposobnost prepoznavanja emocija kod drugih ljudi, što doprinosi empatičnom ponašanju i uspešnoj socijalnoj interakciji. Razlikuje se od emocionalne inteligencije u tome što se emocionalna pismenost češće posmatra kao naučiva veština, dok je emocionalna inteligencija često konceptualizovana kao stabilna crta ličnosti ili sposobnost [18].

Emocionalna pismenost je takođe temelj za razvoj socijalnih kompetencija, rešavanje konflikata i sprečavanje nasilnog ponašanja, zbog čega se sve češće integriše u obrazovne kurikulume [19]. Istraživanja dosledno pokazuju da viši nivo emocionalne pismenosti korelira sa većom emocionalnom stabilnošću, boljom samoregulacijom, većim životnim zadovoljstvom i nižim stepenom anksioznosti i depresivnosti [20], [21]. S obzirom na to da je emocionalna pismenost razvojna i promenljiva kategorija, edukativni programi koji se fokusiraju na emocionalno obrazovanje mogu imati dugoročne pozitivne efekte na psihološku otpornost i socijalnu adaptaciju. U današnjem svetu, koji je često preplavljen socijalnim, profesionalnim i informativnim zahtevima, emocionalna pismenost postaje neophodna komponenta ne samo ličnog razvoja već i kolektivnog blagostanja. Razvijanje ove veštine kod pojedinaca svih uzrasta i profesija ima potencijal da unapredi kako individualno funkcionisanje, tako i međuljudske odnose u društvu u celini.

EMOCIJE I EMOCIONALNA PISMENOST KOD ZDRAVSTVENIH RADNIKA

I lekari i medicinske sestre deluju u intenzivno emocionalnom kontekstu rada, u kojem se svakodnevno suočavaju sa patnjom, bolešću, tugom, nadom i smrću. Uprkos sličnim izazovima, ove dve profesionalne grupe ne razvijaju identične obrasce emocionalne obrade i regulacije. Razlike proizlaze ne samo iz profesionalnih uloga i hijerarhijske strukture zdravstvenog sistema, već i iz načina socijalizacije, obrazovanja, očekivanja i kulturnih normi koje se vežu za „prihvatljivu“ emocionalnost unutar njihovih struka [22], [4].

Lekari se tokom obrazovanja i specijalističke prakse uče da donose racionalne i brze odluke pod pritiskom, često potiskujući ili racionalizujući emocionalne reakcije kako bi sačuvali profesionalni integritet [1]. Emocionalna distanca često se doživljava kao neophodan mehanizam samoodbrane, ali i kao profesionalna veština koja omogućava objektivnost i efikasnost [23]. Ovo dovodi do izražene emocionalne inhibicije, koja se može manifestovati kao smanjena emocionalna ekspresivnost, potiskivanje osećanja, pa i emocionalna konfuzija. Nasuprot tome, medicinske sestre se tokom obrazovanja i rada podstiču da neguju empatični kontakt sa pacijentima, da izražavaju emocionalnu podršku i da se aktivno uključuju u emocionalno stanje bolesnika [5]. Profesionalna socijalizacija sestara ohrabruje emocionalnu otvorenost, interpersonalnu toplinu i izražavanje saosećanja kao centralne profesionalne vrednosti. Kao rezultat toga, sestre u većem stepenu razvijaju emocionalnu pismenost u dimenzijama emocionalne svesnosti, izražavanja i empatičke rezonancije [9]. U istraživanjima se pokazuje da lekari češće koriste kognitivno-distancirane strategije regulacije, kao što su intelektualizacija, racionalizacija i suzbijanje, dok sestre teže izražavanju emocija, traženju socijalne podrške i emocionalnoj validaciji kroz interpersonalni kontakt [8]. Iako su i jedni i drugi izloženi visokim emocionalnim zahtevima, načini na koje se sa tim zahtevima nose se razlikuju, lekari su skloniji da interno procesuiraju emocije, često bez mogućnosti izražavanja, dok sestre češće ulaze u dijalog sa svojim emocijama i emocijama drugih. Međutim, sličnosti se takođe uočavaju, odnosno i lekari i sestre mogu razviti emocionalni zamor, sagorevanje i poteškoće u regulaciji afekta usled kontinuiranog izlaganja emocionalno stresnim situacijama. Obe grupe pokazuju potrebu za dodatnom emocionalnom edukacijom, jer formalni kurikulumi često ne uključuju sistemsku obuku u prepoznavanju, obradi i konstruktivnom izražavanju emocija [10].

Iako se i lekari i medicinske sestre svakodnevno susreću sa emocionalno izazovnim situacijama, razlike u profesionalnim ulogama, obrazovanju i socijalizaciji mogu oblikovati njihove emocionalne stilove na različite načine. Lekari su često obučavani u okruženjima koja naglašavaju racionalnost, kontrolu i kliničku distancu [3], dok su medicinske sestre češće podsticane na emocionalnu dostupnost i saosećanje kao deo negujuće uloge [9]. Zbog toga je važno istraživati njihove stavove prema emocijama odvojeno, jer takva analiza omogućava dublje razumevanje specifičnih obrazaca emocionalne pismenosti u okviru svake profesije. Poređenjem ove dve grupe moguće je identifikovati potencijalne nedostatke i resurse unutar profesionalnog razvoja, kao i osmisliti edukativne intervencije prilagođene konkretnim izazovima koje svaka struka nosi.

U tom smislu, emocionalna pismenost predstavlja važan resurs i za lekare i za medicinske sestre, ali se ona razvija u različitim pravcima i stilovima, u skladu sa profesionalnim okruženjem i kulturološkim obrascima unutar zdravstvenog sistema. Razumevanje ovih razlika i sličnosti je od ključne važnosti za dizajniranje intervencija usmerenih ka unapređenju mentalnog zdravlja zdravstvenih radnika, kao i za kreiranje balansiranih edukativnih programa koji podjednako vrednuju emocionalne potrebe svih članova zdravstvenog tima.

PRAKTIČNI ZNAČAJ ISTRAŽIVANJA

Rezultati ovog istraživanja imaju višestruki praktični značaj, kako za pojedince u zdravstvenim profesijama, tako i za organizacije koje upravljaju radom zdravstvenih timova. Uočene razlike između lekara i medicinskih sestara u stavovima prema emocijama i načinima emocionalne regulacije pružaju osnovu za kreiranje **ciljanih edukativnih programa i psihološke podrške**, koji bi bili prilagođeni specifičnim potrebama i izazovima sa kojima se svaka grupa suočava. Razumevanje obrasca emocionalne inhibicije i distanciranosti kod lekara može doprineti razvoju obuka koje podstiču **sigurno emocionalno izražavanje**, prevenciju sagorevanja i unapređenje profesionalne empatije bez ugrožavanja funkcionalnosti u donošenju odluka. Sa druge strane, osnaživanje medicinskih sestara u pogledu emocionalne samoregulacije i granica može pomoći u smanjenju emocionalne iscrpljenosti i sekundarne traumatizacije koje proističu iz njihove neposredne bliskosti s pacijentima. Na organizacionom nivou, rezultati mogu doprineti unapređenju međuprofesionalne saradnje kroz **bolje razumevanje različitih emocionalnih stilova**, čime se može smanjiti potencijal za konflikte i nesporazume unutar zdravstvenih timova. Takođe, rezultati mogu biti od koristi u selekciji i profesionalnom usmeravanju zdravstvenih radnika, kao i u oblikovanju kurikuluma za medicinske škole i fakultete, uvođenjem sadržaja iz oblasti emocionalne pismenosti i psihološke otpornosti. S obzirom na sve veću učestalost sagorevanja i mentalnog opterećenja u zdravstvenom sektoru, posebno nakon pandemije COVID-19, ovakva istraživanja predstavljaju važan korak ka izgradnji **zdravijeg i psihološki održivijeg radnog okruženja,** u kojem se emocionalne potrebe zaposlenih prepoznaju, razumeju i sistematski adresiraju.

PROBLEM I CILJ ISTRAŽIVANJA

U savremenom zdravstvenom sistemu, emocionalna kompetentnost zdravstvenih radnika prepoznaje se kao ključna komponenta kvalitetne nege, profesionalne efikasnosti i prevencije sagorevanja. Iako lekari i medicinske sestre svakodnevno funkcionišu u emocionalno intenzivnom okruženju, njihovi obrasci razumevanja, izražavanja i regulacije emocija mogu se značajno razlikovati usled profesionalne socijalizacije, organizacione hijerarhije i kulturnih očekivanja. Doktori su često podsticani da razvijaju emocionalnu distancu i racionalnost, dok se od medicinskih sestara očekuje emocionalna dostupnost i empatička komunikacija. Ipak, sistematska istraživanja koja ispituju stavove prema emocijama i dimenzije emocionalne pismenosti kod ovih grupa su retka. Naročito nedostaju studije koje se kvantitativno bave specifičnim stavovima prema emocijama, kao što su njihova funkcionalnost, opravdanost izražavanja, prihvatljivost u profesionalnom kontekstu i strategije regulacije. Razumevanje tih razlika nije samo teorijski značajno, već i praktično važno za oblikovanje edukativnih i suportivnih intervencija unutar zdravstvenih ustanova. Odsustvo ovakvih podataka otežava kreiranje ciljanih programa emocionalne edukacije i podrške koji bi odgovarali specifičnim potrebama različitih profesionalnih profila.

Cilj ovog istraživanja jeste da se ispita postojanje razlika između lekara i medicinskih sestara u stavovima prema emocijama. Istraživanje je usmereno na identifikaciju specifičnih oblasti u kojima se ovi stavovi razlikuju, kao što su: razumevanje emocija, emocionalna ekspresivnost, percepcija emocionalne funkcionalnosti, strah od emocionalnog izražavanja, strategije suočavanja i tendencije potiskivanja emocija. Poseban akcenat stavljen je na analizu statistički značajnih razlika po pojedinačnim tvrdnjama koje se odnose na emocionalna uverenja i ponašanja. Na osnovu toga, cilj je i da se identifikuju obrasci emocionalne pismenosti koji karakterišu svaku od posmatranih

profesionalnih grupa, te da se na osnovu nalaza daju preporuke za dalje usmereno emocionalno obrazovanje i mentalnozdravstvenu podršku u zdravstvenim ustanovama.

METOD

Uzorak i procedura

U istraživanju je učestvovalo ukupno 89 ispitanika, radnika u zdravstvenoj delatnosti. Ukupan uzorak je podeljen na dve grupe u odnosu na zaposlenje - 56 (63%) su bili zaposleni na poziciji medicinske sestre / medicinskog tehničara (47 žena i 9 muškaraca). Više od trećine ukupnog uzorka, tačnije 37% su činili lekari. Od 33 uključena lekara njih 8 je bilo muškog, a njih 25 ženskog pola. Ispitanici prikupljeni snowball metodom putem googl upitnika tokom mesec dana.

Instrument

Za potrebe ovog istraživanja formiran je ankentni upitnik koji sadrži 22 tvrdnje u vezi sa emocijama i emocionalnom pismenošću. Pitanja su formatirana tako da skala odgovora bude dihotomna, odnosno ispitanik treba u odgovoru da se složi (*da*) ili ne složi (*ne*) sa datom tvrdnjom. Ovako formirana anketa omogućava ispitanicima da se jasno izraze u kontekstu poznavanja emocija i emocionalne pismenosti.

Statistička obrada podataka

Kako bi se dao odgovor na pitanje razlika u stavovima između lekara i medicinskih sestara u kontekstu poznavanja funkcionisanja emocija i izraženosti emocionalne pismenosti, korišćen je hi-kvadrat test (χ^2) za nezavisne uzorke.

REZULTATI

U kontekstu statističke obrade podataka korišćen je hi-kvadrat test za nezavisne uzorke, sa odgovorima na ajtemima kao zavisnom varijablom, a grupom ispitanika (lekar/medicinska sestra) kao nezavisnom varijablom. Rezultati istraživanja prikazani su u Tabeli 1. Analizom razlika u stavovima lekara i medicinskih sestara prema emocijama korišćenjem hi-kvadrat testa, identifikovano je ukupno 16 ajtema sa statistički značajnim razlikama ($p < 0.01$ ili $p < 0.05$).

Analizom razlika u stavovima lekara i medicinskih sestara prema emocijama korišćenjem hi-kvadrat testa, identifikovano je ukupno 16 ajtema sa statistički značajnim razlikama ($p = 0.01$). Ovi nalazi ukazuju na postojanje sistematskih razlika u emocionalnim uverenjima i regulacionim strategijama između dve profesionalne grupe. Lekari su češće nego medicinske

sestre poistovećivali pojmove osećanja i osećaji ($\chi^2 = 31.20$), kao i izražavali stav da se emocije osećaju stalno ($\chi^2 = 32.09$), što može ukazivati na njihovu veću emocionalnu svesnost ili sklonost pojednostavljivanju emocionalnih pojmova. Nasuprot tome, medicinske sestre su se češće slagale s tvrdnjom da se istovremeno može osećati i razmišljati ($\chi^2 = 4.96$), što sugeriše njihovu veću spremnost na integraciju kognitivnog i emocionalnog procesa. Dalje, lekari su češće izražavali uverenje da su emocije opravdanje za ponašanje ($\chi^2 = 11.33$) i da često pokazuju emocije kako bi zadobili pažnju drugih ($\chi^2 = 17.48$), što može ukazivati na veće korišćenje emocija u svrhu interpersonalne regulacije. Istovremeno, lekari su u većem procentu izražavali zabrinutost da emocije mogu dovesti do gubitka kontrole („ludila“) ($\chi^2 = 6.25$) i da bi izražavanje straha ($\chi^2 = 31.19$), ljutnje ($\chi^2 = 30.42$), ili ljubavi ($\chi^2 = 38.66$) moglo biti negativno vrednovano ili zloupotrebljeno od strane drugih. Ovi nalazi ukazuju na izraženiju emocionalnu inhibiciju i defanzivan emocionalni stil među lekarima, potencijalno oblikovan profesionalnim normama samokontrole i odgovornosti. Značajne razlike uočene su i u percepciji funkcionalnosti emocija. Dok su lekari u većoj meri isticali da prijatna osećanja imaju svoju funkciju ($\chi^2 = 6.07$), češće su negirali korisnost neprijatnih osećanja ($\chi^2 = 27.61$), za razliku od sestara koje su pokazale veću spremnost da prihvate funkcionalnu vrednost i negativnih afekata. U interpersonalnom domenu, sestre su se češće slagale s tvrdnjom da bi bliska osoba trebalo da zna kako se one osećaju ($\chi^2 = 47.84$), što ukazuje na izraženiju potrebu za implicitnim emocionalnim razumevanjem. S druge

strane, lekari su u većoj meri priznavali da skrivaju ili modulišu svoje emocije ($\chi^2 = 48.81$) i da ponekad glume emocije koje ne osećaju ($\chi^2 = 21.70$), što može biti refleksija profesionalno naučene emocionalne prezentacije. Kada je reč o strategijama suočavanja, lekari su u značajnom procentu navodili da neprijatne emocije suzbijaju pomoću alkohola, tableta ili psihoaktivnih supstanci ($\chi^2 = 7.46$), što može ukazivati na disfunkcionalne mehanizme regulacije afekta. Takođe, češće su izveštavali da ih emocije ponekad preplave i dezorganizuju ($\chi^2 = 38.66$) i da imaju snažna osećanja, ali ne znaju uvek koja ($\chi^2 = 33.11$), što može ukazivati na elemente emocionalne zbunjenosti i niži nivo emocionalne introspekcije.

U celini, ovi rezultati sugerišu da lekari, u poređenju sa medicinskim sestrama, pokazuju izraženiji obrazac emocionalne regulacije zasnovan na potiskivanju, glumi i defanzivnosti, uz istovremenu veću zabrinutost zbog posledica emocionalne ekspresije. Medicinske sestre, s druge strane, iskazuju veću otvorenost, integraciju emocija u mišljenje i interpersonalno poverenje. Ovakve razlike potencijalno odražavaju različite profesionalne zahteve i obrasce socijalizacije unutar medicinskog sistema.

Tabela 1. Razlike u odgovorima između lekara i medicinskih sestara

Ajtem	**Lekari**		**Medicinske sestre**		$\chi^2(1)$	***p***
	DA	**NE**	**DA**	**NE**		
Osećanja su isto što i osećaji.	79%	21%	20%	80%	31.20	**0.01**
Emocije se osećaju stalno.	82%	18%	21%	79%	32.09	**0.01**
Može se istovremeno osećati i razmišljati.	33%	67%	41%	59%	0.36	0.40
Svako ima sposobnost da izabere na koji način će se ponašati.	39%	61%	54%	46%	1.28	0.26
Emocije su opravdanje za ponašanje.	64%	36%	29%	71%	11.33	**0.01**
Često pokazujem određenu emociju kako bih zadobio/la nečiju pažnju.	88%	12%	45%	55%	17.48	**0.01**
Snažne emocije mogu izazvati smrt.	85%	15%	88%	12%	0.10	0.90
Emocije mogu dovesti do gubitka kontrole tj. do „ludila“.	64%	36%	89%	11%	6.25	**0.05**
Ako pokažem osećanje straha, drugi će me smatrati kukavicom	79%	21%	20%	80%	31.19	**0.01**
Ako izrazim osećanje ljutnje, drugi će me smatrati primitivnim	77%	23%	18%	82%	30.42	**0.01**
Ako izrazim osećanje ljubavi, partner će manipulisati samnom	81%	19%	17%	83%	38.66	**0.01**
Ako pokazujem tugu i plačem, smatraće me „slabićem“	82%	18%	86%	14%	0.01	0.90
Sva prijatna osećanja imaju svoju funkciju	60%	40%	52%	48%	0.67	0.41
Sva neprijatna osećanja nemaju funkciju	85%	15%	28%	72%	27.61	**0.01**
Neko ko mi je blizak trebalo bi da zna kako se osećam	12%	88%	89%	11%	47.84	**0.01**
Često skrivam svoje emocije ili ih predstavljam kao slabije ili jače nego što jesu	91%	9%	16%	84%	48.81	**0.01**
Ponekad glumim neku emociju, a zapravo je ne osećam	82%	18%	32%	68%	21.70	**0.01**
Neprijatnu emociju suzbijam konzumiranjem alkohola, tabletama, psiho-aktivnim supstancama	85%	15%	34%	64%	22.85	**0.01**
Uglavnom težim prijatnim osećanjima, a neprijatna potiskujem	45%	55%	16%	84%	1.07	0.30
Ponekad pre važnog razgovora osećam lupanje srca, grčeve u stomaku, suvoću usta, ubrzano disanje...	94%	6%	82%	18%	.471	**0.01**
Ponekad me preplave emocije koje me zbune i dezorganizuju	85%	15%	36%	64%	38.66	**0.01**
Znam da imam jaka osećanja, ali u glavnom ne znam koja.	82%	18%	23%	77%	33.11	**0.01**

DISKUSIJA

Cilj ovog istraživanja bio je usmeren na ispitivanje postojanja razlika između lekara i medicinskih sestara u stavovima prema emocijama. Rezultati istraživanja ukazuju na statistički značajne razlike između lekara i medicinskih sestara u stavovima prema emocijama, što potvrđuje pretpostavku da profesionalna socijalizacija, uloge i obrazovni modeli značajno oblikuju način na koji pojedinci percipiraju, izražavaju i regulišu emocije.

Iako obe grupe funkcionišu u emocionalno intenzivnom okruženju, obrasci emocionalne pismenosti i emocionalne ekspresivnosti kod lekara i medicinskih sestara pokazuju različite karakteristike. Lekari su, u poređenju sa medicinskim sestrama, češće izražavali stavove koji ukazuju na emocionalnu distancu, inhibiciju i racionalizaciju. Više su poistovećivali osećanja i osećaje, smatrali da su emocije stalno prisutne, te su iskazivali zabrinutost da bi izražavanje emocija (posebno straha, ljutnje i ljubavi) moglo izazvati negativnu socijalnu procenu. Ovi nalazi su u skladu sa prethodnim istraživanjima koja pokazuju da se lekari često socijalizuju u profesionalni identitet koji vrednuje emocionalnu kontrolu, racionalnost i samodisciplinu [23], [4]. Emocionalna inhibicija, iako funkcionalna u određenim kliničkim kontekstima, može dovesti do emocionalne iscrpljenosti i smanjene empatijske dostupnosti. Nasuprot tome, medicinske sestre su pokazale veću emocionalnu otvorenost. Češće su izražavale stavove koji ukazuju na integraciju emocija i mišljenja, priznavanje funkcionalnosti neprijatnih emocija, kao i očekivanje da bliski ljudi intuitivno razumeju njihove emocije. Ovi nalazi se mogu objasniti činjenicom da su sestre tokom obrazovanja i rada podsticane na izražavanje empatije, emocionalnu prisutnost i interpersonalnu bliskost u odnosu sa pacijentima [9], [5]. Takva emocionalna pismenost doprinosi većoj sposobnosti regulacije afekta putem socijalne podrške i emocionalnog izražavanja. Zanimljiv je nalaz da su lekari češće prijavljivali glumu emocija, prikrivanje stvarnog emocionalnog stanja i korišćenje maladaptivnih strategija suočavanja poput konzumiranja alkohola ili psihoaktivnih supstanci. Ova kombinacija spoljne emocionalne kontrole i unutrašnje disonance ukazuje na tzv. „emocionalni rad“ koji, ako nije podržan adekvatnim resursima i obukom, može dovesti do sagorevanja [7], [8].

Ove razlike u stavovima prema emocijama ukazuju na potrebu za diferenciranim pristupom emocionalnom obrazovanju unutar zdravstvenog sistema. Dok lekari mogu imati koristi od programa koji podstiču emocionalnu svesnost i sigurno izražavanje emocija, kod medicinskih sestara je važno jačati veštine emocionalne regulacije i postavljanja profesionalnih granica. Takođe, razlike u emocionalnoj pismenosti između ovih grupa mogu uticati na kvalitet timske saradnje i komunikacije, te ih je potrebno integrisati u obuke koje promovišu međuprofesionalno razumevanje i poštovanje. Na kraju, rezultati ovog istraživanja doprinose boljem razumevanju profesionalnih obrazaca emocionalnog funkcionisanja u zdravstvenom sektoru, te mogu poslužiti kao osnova za razvoj ciljanih intervencija u prevenciji sagorevanja, unapređenju empatijske prakse i jačanju emocionalne otpornosti zdravstvenih radnika. U okviru medicinskog obrazovanja, lekari često pohađaju više kurseva iz oblasti psihologije, komunikacije i profesionalne etike u poređenju sa medicinskim sestrama, što bi, barem teorijski, trebalo da doprinese višem nivou razumevanja emocionalnih procesa, komunikacije sa pacijentima i samorefleksije. Međutim, rezultati ovog istraživanja ukazuju na paradoks: uprkos većem formalnom izlaganju psihološkim sadržajima tokom studija, lekari češće izražavaju emocionalnu inhibiciju, konfuziju i defanzivne mehanizme regulacije emocija, u poređenju sa medicinskim sestrama. Ovaj paradoks moguće je objasniti time što se psihološki kursevi u okviru medicinskih fakulteta često tretiraju formalistički i teorijski, bez direktne primene na lično iskustvo i bez stvaranja prostora za emocionalnu obradu sadržaja. Takođe, dominantna kultura u medicinskom obrazovanju i praksama (posebno u kliničkom delu) favorizuje racionalnost, samokontrolu i emocionalnu distancu, što može potisnuti ili neutralisati efekte psiholoških kurseva [24]. Dodatno, psihološki kursevi u medicini češće se fokusiraju na razumevanje ponašanja drugih (npr. pacijenata) i dijagnostičke kategorije, a manje na emocionalnu pismenost lekara kao ličnu i profesionalnu veštinu [3]. Bez iskustveno orijentisanih pristupa (npr. simulacije, supervizije, reflektivne grupe), znanje iz psihologije ostaje deklarativno i nedovoljno integrisano u emocionalno funkcionisanje lekara. Stoga bi se moglo reći da prisustvo psiholoških

kurseva jeste važan resurs, ali njihov kvalitet, kontekst primene i emotivna relevantnost određuju stvarni efekat. Za stvarno unapređenje emocionalne pismenosti kod lekara, potrebni su kursevi koji kombinuju kognitivno razumevanje emocija, emocionalnu samorefleksiju i praktične veštine emocionalne regulacije, uz podršku edukatora iz oblasti psihologije i psihijatrije.

Uprkos značajnim nalazima i praktičnim implikacijama, ovo istraživanje ima nekoliko važnih ograničenja koja je potrebno uzeti u obzir pri interpretaciji rezultata. Istraživanje je sprovedeno na osnovu samoiskaznih podataka, što otvara mogućnost društveno poželjnih odgovora i iskrivljenih predstava o sopstvenim emocionalnim navikama. U kontekstu profesionalne uloge, posebno kod lekara, postoji dodatna tendencija potiskivanja ili racionalizacije emocija i na nivou izveštavanja. Drugo, korišćen je kvantitativni pristup zasnovan na zatvorenim ajtemima, koji ne omogućava dublje razumevanje složenih značenja i ličnih interpretacija emocija u svakodnevnom radu. Buduća istraživanja mogla bi uključiti kvalitativne metode, poput intervjua ili fokus grupa, kako bi se došlo do bogatijih narativa i subjektivnih perspektiva lekara i sestara. Dodatno, uzorak ispitanika može predstavljati ograničenu geografsku ili institucionalnu varijabilnost, te nalazi možda nisu u potpunosti generalizabilni na sve zdravstvene ustanove ili kulture. Buduće studije bi trebalo da obuhvate veći i raznovrsniji uzorak iz različitih regija, specijalnosti i nivoa zdravstvene zaštite. Isto tako, analiza je bila deskriptivno-komparativna, bez kontrole potencijalnih spoljašnjih varijabli poput pola, godina radnog iskustva, nivoa stresa ili prethodne edukacije iz oblasti emocionalne pismenosti. U budućim istraživanjima bilo bi korisno uključiti multivarijantne modele kako bi se preciznije utvrdili prediktori emocionalnih stavova. Kada se govori o samoj metodologiji, iako su hi-kvadrat testovi pokazali statistički značajne razlike, ne može se doneti zaključak o uzročnosti. Longitudinalne ili eksperimentalne studije mogle bi dodatno ispitati kako profesionalno okruženje i edukacija utiču na promene u emocionalnim uverenjima tokom vremena. Na kraju, korišćenje jedinstvenog upitnika za različite profesije može biti ograničenje samo po sebi, jer neki ajtemi možda ne podjednako reflektuju specifične izazove profesije lekara i sestara. Buduće verzije instrumenta mogle bi biti profesionalno prilagođene, uz dodatak kontekstualnih stavki relevantnih za svaku grupu ponaosob. Uprkos ovim ograničenjima, rezultati istraživanja pružaju vredne uvide u obrasce emocionalne pismenosti i regulacije kod lekara i medicinskih sestara, te predstavljaju osnovu za dalje, dublje i metodološki složenije proučavanje ove važne oblasti.

ZAKLJUČAK

Istraživanje je potvrdilo postojanje značajnih razlika između lekara i medicinskih sestara u stavovima prema emocijama i aspektima emocionalne pismenosti. Dok lekari češće ispoljavaju emocionalnu inhibiciju, racionalizaciju i strah od izražavanja emocija, medicinske sestre pokazuju veću otvorenost, spremnost za emocionalnu ekspresiju i viši nivo prihvatanja funkcionalnosti emocija. Ove razlike odražavaju uticaj profesionalne socijalizacije, uloga i obrazovnog sistema na emocionalni stil zdravstvenih radnika. Nalazi ukazuju na potrebu za uvođenjem sistematskih edukativnih programa iz oblasti emocionalne pismenosti, prilagođenih specifičnostima svake profesije. Razumevanje emocionalnih obrazaca unutar zdravstvenih timova može doprineti boljoj međuprofesionalnoj saradnji, prevenciji sagorevanja i unapređenju kvaliteta zdravstvene zaštite.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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EMOTIONS IN WHITE COATS: A PILOT STUDY ON ATTITUDES TOWARD EMOTIONS AND EMOTIONAL LITERACY AMONG PHYSICIANS AND NURSES

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ABSTRACT

The aim of this study was to examine differences in attitudes toward emotions between physicians and nurses, as well as to explore aspects of their emotional literacy in the context of everyday professional functioning. The pilot study included a total of 89 participants, evenly distributed by profession. A questionnaire assessing attitudes toward emotions was used, encompassing cognitive, affective, and regulatory dimensions of emotional functioning. Chi-square analysis identified 16 items with statistically significant differences between the two groups ($p < .01$). The results indicated that physicians more frequently expressed emotional inhibition, a tendency to suppress emotions, fear of emotional evaluation, and reliance on rationalization. In contrast, nurses demonstrated greater emotional openness, acceptance of the functionality of emotions, and a higher readiness to express affect. The discussion focused on the influence of professional socialization, educational systems, and organizational culture on the formation of specific patterns of emotional literacy. The findings of this study have important implications for the development of training programs aimed at enhancing the emotional competencies of healthcare professionals, improving interprofessional communication, and preventing burnout. Furthermore, they highlight the need for a deeper understanding of emotional labor in healthcare, with an emphasis on tailored interventions that consider the professional context and specific challenges of each occupation.

Keywords: emotions, emotional literacy, physicians, nurses, professional socialization.

FENOMENOLOGIJA I OBRASCI VRŠNJAČKOG NASILJA U SREDNJIM ŠKOLAMA

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APSTRAKT

Rad se bavi fenomenologijom vršnjačkog nasilja u srednjim školama na području Banje Luke, s ciljem ispitivanja njegove učestalosti, oblika i percepcije među učenicima. Vršnjačko nasilje se definiše kao namjerno i ponavljano agresivno ponašanje među vršnjacima, koje može imati verbalne, fizičke, socijalne i digitalne manifestacije, te značajne posljedice po psihološko i socijalno funkcionisanje mladih.

Istraživanje je sprovedeno na uzorku od 100 učenika Gimnazije i Elektrotehničke škole u Banjoj Luci, primjenom anonimnog anketnog upitnika koji je obuhvatio 15 pitanja o učestalosti, oblicima i kontekstu vršnjačkog nasilja. Poseban fokus stavljen je na komparativnu analizu između škola, kao i na subjektivnu percepciju sigurnosti učenika.

Rezultati ukazuju na prisustvo vršnjačkog nasilja u obje škole, pri čemu je verbalno nasilje najzastupljenije, posebno kroz širenje glasina i upućivanje uvredljivih sadržaja. Fizičko i socijalno nasilje javljaju se u manjoj mjeri, dok ekonomski oblici nasilja nisu registrovani. Elektronsko nasilje pokazuje značajnu prisutnost, što ukazuje na sve veći uticaj digitalnog okruženja na obrasce vršnjačke agresije. Uočene su i određene statistički značajne razlike između škola u pojedinim oblicima nasilja i percepciji žrtava.

Zaključno, nalazi potvrđuju da vršnjačko nasilje predstavlja relevantan problem u školskom kontekstu, sa dominacijom verbalnih i digitalnih formi. Dobijeni nalazi predstavljaju preliminarni uvid u fenomen vršnjačkog nasilja i ukazuju na potrebu sprovođenja obimnijih istraživanja kao i na potrebu razvoja i implementacije preventivnih programa, unapređenja školskog okruženja i osnaživanja učenika za adekvatno suočavanje sa nasiljem.

Ključne riječi: vršnjačko nasilje, srednjoškolci, digitalno nasilje, prevencija, školsko okruženje.

UVOD

Nasilje je svaki čin protiv volje pojedinca koji ugrožava njegov lični integritet, bilo da se radi o psihičkom, fizičkom, seksualnom ili ekonomskom vidu nasilja [1]. Prema definiciji Svjetske zdravstvene organizacije, nasilje se definiše kao: “namjerna primjena fizičke sile ili moći, sa ciljem

zastrašivanja ili stvarna, nad samim sobom, drugim licem, grupom ili zajednicom, a koja rezultira ili je velika vjerovatnoća da će rezultirati povređivanjem, smrću, osjećanjem uskraćenosti, psihičkim poremećajima ili smetnjama u razvoju." Pod pojmom vršnjačkog nasilja podrazumijeva se svaka namjerna i ponovljena agresivna radnja koju vršnjaci upućuju jedni drugima, a koja može biti verbalna, fizička, socijalna ili ekonomska. Posljedice ovakvog ponašanja mogu uključivati osjećaj straha, anksioznosti, smanjeno samopouzdanje, slabiji školski uspjeh, pa čak i ozbiljnije psihološke probleme.

Pojam vršnjačkog nasilja

Postoji nekoliko definicija vršnjačkog nasilja, ali je svima zajedničko da govore o namjernom povređivanju, o učestalom ponavljanju nasiija, o neproporcionalnom odnosu snaga, o namjeri da se kod žrtve izazove psihička i fizička bol. O podjeli nasilja na fizičko, verbalno i seksualno nasilje zna se i piše odavno i tako su ga definisali i Protokoli o postupanju u slučajevima vršnjačkog nasilja među djecom i mladima u obrazovnom sistemu u BiH. Međutim, sve češće se javlja i nasilje koje djeca doživljavaju putem interneta ili SMS poruka prijetećeg, uvredljivog ili provokativnog sadržaja [2]. Po svemu sudeći, nasilje u školama je endemska pojava, poznata svakome ko se školovao. Ispoljavajući se u veoma raznovrsnim oblicima i intenzitetima, ono obično postane socijalno vidljivo tek kada pojedinačni incidenti zadobiju medijsku pažnju. Pod nasiljem ćemo podrazumjevati neopravdano nanošenje štete drugome. Ponašanje kojim se nanosi šteta može biti verbalno i neverbalno, i može se sastojati u fizičkom povređivanju, nanošenju materijalne štete, ili psihološkom povređivanju kao što je zastrašivanje, sramoćenje, socijalna izolacija i slično. Neopravdanost se sastoji u nelegitimnosti, nezasluženosti, prekomjernosti ili neprimjerenosti takvog postupka [3]. Termini nasilje i agresija se kod nas uglavnom koriste kao sinonimi, s tim što agresivnost i agresija više upućuju na motivaciju koja je vodila ka povređivanju drugoga i na dispoziciju, dok termin nasilje, po mišljenju nekih autora, u većoj meri sugeriše *nedozvoljenost* nanošenja štete, često i nezavisno od namjere [3]. Generalno posmatrano, oblici školskog nasilja spadaju u agresivnost, ali može se desiti da neki postupci koje ubrajamo u nasilje nisu agresivni akti, u smislu da ih počinilac vrši ne uzimajući u obzir da nekoga povređuju (npr. različite disciplinske mjere koje nastavnik preduzima), ili previđajući njihov uticaj (smatrajući ih za šalu).

Oblici vršnjačkog nasilja

Najčešća podjela vrsta i oblika nasilja je sljedeća: fizičko nasilje, verbalno ili emocionalno nasilje, ekonomska manipulacija, socijalno nasilje, seksualno nasilje [4]. Drugi autori, pak smatraju da su najvažniji oblici fizičko i verbalno nasilje, dok su ostali oblici podvrste. U istraživanju je učestvovalo 100 ispitanika, učenika osnovnoškolskog uzrasta. Uzorak je ravnomjerno raspoređen u odnosu na pol (50% djevojčica i 50% dječaka).

Karakteristike vršnjačkog nasilja

Prema Olweusu, dijete je zlostavljano kada je učestalo i trajno izloženo negativnim postupcima od strane jednoga ili više djece [5]. U okviru definicije ističu se tri bitna elementa: trajanje, negativni postupci i neravnopravan odnos snaga. lako se pojedinačni slučaj ozbiljnijeg nasilja može smatrati nasilništvom, u definiciji se naglašava trajnost i ponavljanje negativnih postupaka. Pod negativnim postupcima podrazumijeva se djelovanje pojedinca kada on namjerno zadaje ili nastoji zadati ozljedu ili bilo kakvu neugodnost drugom pojedincu. Dijete koje je izloženo nasilju teško se brani i donekle je bespomoćno u odnosu prema onome ko se nasilno ponaša [6].

Na različite načine pokušalo se odrediti podvrste ili oblike vršnjačkog nasilja, odnosno u nekim slučajevima agresivnosti među djecom uopšte. Djeca sa posebnim potrebama pod većim su rizikom za izloženost nasilju u odnosu na ostalu djecu [7]. Holzbauer i Berven pisali su o »maltretiranju«, praktički sinonimu za *bullying*. Ovaj oblik uznemiravanja autori definišu kao nepoželjno dosađivanje, uznemiravanje, prisiljavanje, izrugivanje ili prijetnje osobi s invaliditetom. Ono podrazumijeva različite oblike neprihvatljivog verbalnog ponašanja, odnosno tjelesnog nasilja ili primjenu sile [8].

Ortega i Mora-Merchan smatraju da postoji potreba za identifikacijom stvarnog vršnjačkog nasilja koje se javlja kada dijete ili mlada osoba koja doživljava nasilje osjeća potpunu bespomoćnost te ne može pobjeći od nasilja koje može biti vidljivo kao šala ili igra koja nema za posljedicu istu blagu anksioznost i bespomoćnost [9]. Rigby smatra da se o vršnjačkom nasilju treba razmišljati kao o aktivnosti koja se javlja uzduž kontinuuma težine [7]. Također, smatra da nije lako postići dogovor o tome što predstavlja blage, umjerene i ekstremne forme vršnjačkog nasilja. To je djelimično zbog toga što posljedice različitih oblika vršnjačkog nasilja mogu varirati od osobe do osobe. Neka osoba može biti povrijeđena zadirkivanjem na neku temu na koju je ona visoko osjetljiva, ali istovremeno se ta ista osoba ne mora osjećati povrijeđeno ako je doživjela blagi fizički napad [7]. Prema Rigbyju, kriteriji koji bi se trebali uzeti u obzir kada se prosuđuje o ozbiljnosti nekog nasilnog ponašanja su: (1) oblik nasilnog ponašanja npr. blago zadirkivanje nasuprot tjelesnom napadu; (2) trajanje nasilja, odnosno traje li kraće ili duže razdoblje; (3) frekvencija nasilnog ponašanja npr. događa li se dnevno, tjedno ili manje često [7]. Manje ozbiljno nasilje podrazumijeva periodično zadirkivanje, nazivanje podrugljivim imenima i situacijsko isključivanje. Ono može biti peckavo i neugodno, može eskalirati, a zatim uključivati i ozbiljnije oblike nasilja. Većina vršnjačkog nasilja odvija se na navedenom nivou. Umjereno ozbiljno vršnjačko nasilje podrazumijeva slučajeve kada je dijete kroz neko vrijeme subjekt sistemskih i bolnih oblika zlostavljanja. To može uključivati okrutno ruganje, kontinuirano isključivanje, prijetnje ili neke relativno umjerene oblike tjelesnog zlostavljanja npr. guranje ili udaranje. Teški oblici nasilja javljaju se kada je zlostavljanje posebno okrutno i intenzivno, naročito ako se javlja u nekom produženom razdoblju i kada je jako uznemiravajuće za dijete koje je izloženo nasilju. Ono često uključuje ozbiljne oblike tjelesnog napada, ali o teškim oblicima nasilja možemo govoriti i u slučajevima kada ne-tjelesni oblici vršnjačkog nasilja uključuju gotovo potpuno ili potpuno isključivanje iz grupe [6].

Karakteristike učesnika i fenomenologija

Polaskom u školu učenici razvijaju prva prava prijateljstva. U prijateljskim vezama koje podrazumijevaju dijadni odnos, prisutno je pomaganje, dijeljenje te drugi oblici prosocijalnog ponašanja. Vrijeme provedeno s prijateljem u zajedničkoj aktivnosti popraćeno je zadovoljstvom i užitkom što je temeljna karakteristika prijateljske veze. Da bi dvoje učenika razvilo prijateljsku vezu, moraju se svidjeti jedno drugome.

Međutim, nisu svi odnosi između vršnjaka pozitivni i prožeti prijateljstvom. U školama je sve zastupljenije međuvršnjačko nasilje koje podrazumijeva različite oblike, odnosno vrste. Postoji mnogo klasifikacija oblika nasilja među djecom. Vrlo je važno poznavati oblike nasilja i karakteristike svakog oblika, kako bismo prepoznali o kojem se nasilju radi i kako bismo znali kako najadekvatnije pomoći djetetu.

Najčešća podjela vrsta i oblika nasilja je sljedeća:

- Fizičko nasilje,
- Verbalno ili emocionalno nasilje,
- Ekonomska manipulacija,
- Socijalno nasilje,
- Seksualno nasilje [4].

Drugi autori, pak smatraju da su najvažniji oblici fizičko i verbalno nasilje, dok su ostali oblici podvrste. Naše istraživanje je u ovoj klasifikaciji nasilja izostavilo seksualno nasilje, s obzirom da su uzorak našeg istraživanja učenici devetih razreda osnovnih škola.

METOD

Predmet i cilj istraživanja

Predmet istraživanja u ovom radu jeste vršnjačko nasilje među učenicima srednjih škola, sa posebnim osvrtom na njegove oblike (fizičko, verbalno, prikriveno i elektronsko), učestalost pojavljivanja, kao i uticaj individualnih i socijalnih faktora na njegovo ispoljavanje.

Cilj ovog rada je bio utvrditi prisustvo i oblike vršnjačkog nasilja među učenicima Gimnazije i Elektrotehničke škole u Banja Luci, analizirati kako učenici doživljavaju nasilje, te u kojoj mjeri sami učestvuju u vršnjačkom nasilju. Poseban fokus stavljen je na razlike između dvije škole u pogledu učestalosti verbalnog, fizičkog i socijalnog nasilja, kao i na percepciju sigurnosti učenika u školskom okruženju.

Hipoteze

Pretpostavka je bila da su različiti oblici vršnjačkog nasilja (fizičko, verbalno, prikriveno i elektronsko) prisutni u značajnoj mjeri među učenicima srednjih škola.

Uzorak i procedura

Istraživanje je sprovedeno na stratifikovanom uzorku koji je činilo 100 ispitanika, sredjoškolaca, i to 50 ispitanika iz Gimnazije i 50 iz Elektrotehničke škole u Banjoj Luci. Uzorak Uzorak je ravnomjerno raspoređen u odnosu na pol (50% djevojčica i 50% dječaka).

Instrumenti

Za prikupljanje podataka od ispitanika korištena je anonimna anketa o pojavama vršnjačkog nasilja među učenicima srednjih škola dizajnirana za potrebe ovog istraživanja. Anketa se sastoji od 15 ajtema i podijeljena je u nekoliko tematskih cjelina, s ciljem dobijanja uvida u učestalost, vrste, učesnike i kontekst vršnjačkog nasilja.

Prva cjelina obuhvata osnovne demografske podatke ispitanika, uključujući pol i starost, što omogućava analizu povezanosti između ovih karakteristika i iskustva vršnjačkog nasilja.

Druga cjelina istražuje opštu percepciju nasilja u školi, uključujući pitanja o tome da li je ispitanik bio žrtva ili svjedok nasilja, te da li bi prijavio nasilje nadležnim osobama. Takođe se ispituje osjećaj sigurnosti u školi.

Treća cjelina se fokusira na karakteristike i vrste nasilja (fizičko, verbalno, prikriveno i elektronsko), te omogućava identifikaciju najčešćih žrtava i počinitelja nasilja kao i faktora koji otežavaju prijavljivanje nasilja.

Četvrta cjelina uključuje skale učestalosti ponašanja(Likertova petostepena skala), gdje ispitanici procjenjuju koliko često su sami doživjeli ili učestvovali u nasilnom ponašanju u posljednjih nekoliko mjeseci. Skale su izražene numeričkim ocjenama od 1 do 5 (1 – gotovo nikad, 5 – gotovo uvijek), što omogućava kvantitativnu analizu intenziteta i učestalosti različitih oblika vršnjačkog nasilja.

REZULTATI I DISKUSIJA

Opšta percepcija vršnjačkog nasilja

U ovom dijelu rezultata analizirana je opšta percepcija vršnjačkog nasilja među ispitanicima pri čemu je posebna pažnja posvećena iskustvu ispitanika kao žrtava ili svjedoka nasilja, njihovoj spremnosti na prijavljivanje nasilja, kao i procjeni osjećaja sigurnosti u školskom okruženju

Dobijeni rezultati ukazuju da većina ispitanika iz obje škole navodi da bi se, u slučaju da budu žrtve, nekome obratili za pomoć. U Gimnaziji je taj procenat veoma visok i iznosi 94%, dok je u Elektrotehničkoj školi nešto niži, 82%. Istovremeno, u Elektrotehničkoj školi je veći udio učenika koji se ne bi nikome obratili (18%) u odnosu na Gimnaziju (6%). Ukupno posmatrano, 88% ispitanika bi potražilo pomoć, što ukazuje na relativno razvijenu svijest o značaju obraćanja drugima u situaciji viktimizacije, iako razlika između škola pokazuje da dio učenika i dalje ostaje suzdržan u traženju podrške. Razlika između škola nije pokazala statističku značajnost na nivou od 0,05 ($p = 0.066$), ali se može uočiti tendencija da učenici gimnazije češće prijavljuju nasilje od učenika elektrotehničke škole (Tabela 1).

Rezultati pokazuju da bi većina ispitanika prijavila nasilje kada bi mu svjedočila. U Gimnaziji je takav stav iskazalo 86% učenika, dok je u Elektrotehničkoj školi taj procenat nešto niži i iznosi 78%. S druge strane, 14% gimnazijalaca i 22% učenika Elektrotehničke škole navodi da nasilje ne bi prijavili. Ukupno posmatrano, 82% ispitanika bi prijavilo nasilje, što ukazuje na preovladavajuću spremnost učenika da reaguju u situacijama vršnjačkog nasilja, ali i na to da i dalje postoji određeni broj onih koji bi ostali pasivni. Iako razlike nisu statistički značajne ($p =$

0.303), može se primijetiti tendencija da su učenici Gimnazije spremniji prijaviti nasilje nego učenici Elektrotehničke škole (Tabela 2).

Tabela 1. **Ukoliko si žrtva, bi li se ikome obratio/la?**

			Ukoliko si žrtva, bi li se ikome obratio/la?		Total
			Da	Ne	
Škola	Gimnazija	Count	47	3	50
		% within Škola	**94.0%**	6.0%	100.0%
	Elektrotenička škola	Count	41	9	50
		% within Škola	**82.0%**	18.0%	100.0%
Total		Count	88	12	100
		% within Škola	88.0%	12.0%	100.0%

Tabela 2. **Ako si bio/bila svjedok nasilja, bi li ga prijavio/la?**

			Ako si bio/bila svjedok nasilja, bi li ga prijavio/la?		Total
			Da	Ne	
Škola	Gimnazija	Count	43	7	50
		% within Škola	**86.0%**	14.0%	100.0%
	Elektrotenička škola	Count	39	11	50
		% within Škola	**78.0%**	22.0%	100.0%
Total		Count	82	18	100
		% within Škola	**82.0%**	18.0%	100.0%

Rezultati pokazuju da je gotovo svaki učenik imao iskustvo sa vršnjačkim nasiljem, bilo kao svjedok ili kao žrtva. U Gimnaziji je 94% učenika navelo da je bilo svjedok ili žrtva vršnjačkog nasilja, dok je u Elektrotehničkoj školi taj procenat još viši i iznosi 96%. Vrlo mali broj učenika izjavio je da nije imao takvo iskustvo, dok je u Elektrotehničkoj školi kod 4% ispitanika zabilježen treći odgovor, što može ukazivati na neodlučnost ili drugačije tumačenje pitanja. Ukupno posmatrano, čak 95% učenika navodi da je bilo svjedok ili žrtva vršnjačkog nasilja, što ukazuje na izrazitu prisutnost ovog problema u školskom okruženju.

Tabela 3. ***Jeste li ikada bili svjedok ili žrtva vršnjačkog nasilja u školi?***

			Jeste li ikada bili svjedok ili žrtva vršnjačkog nasilja u školi?			Total
			Da	Ne	3	
Škola	Gimnazija	Count	47	3	0	50
		% within Škola	**94.0%**	6.0%	0.0%	100.0%
	Elektrotenička škola	Count	48	0	2	50
		% within Škola	**96.0%**	0.0%	4.0%	100.0%
Total		Count	95	3	2	100
		% within Škola	95.0%	3.0%	2.0%	100.0%

Po pitanju osjećaja sigurnosti u školi, rezultati pokazuju da se većina učenika obje škole osjeća sigurno u školskom okruženju, ali sa određenim razlikama u intenzitetu tog osjećaja. Na ukupnom nivou, 26,0% učenika se uvijek osjeća sigurno, 44,0% vrlo često, 20,0% često, dok se 6,0% učenika ponekad i 4,0% rijetko osjeća sigurno u školi. Razlika između škola nije se pokazala statistički značajnom ($p = 0.435$), što ukazuje da su osjećaji sigurnosti učenika Gimnazije i

Elektrotehničke škole prilično slični, iako je kod gimnazijalaca nešto veći procenat onih koji se *uvijek* osjećaju sigurno (tabela 4).

Tabela 4. **Koliko se često osjećaš sigurno u školi?**

			Koliko se često osjećaš sigurno u školi?					Total
			Uvijek	Vrlo često	Često	Ponekad	Rijetko	
Škola	Gimnazija	Count	15	22	8	3	2	50
		% within Škola	30.0%	44.0%	16.0%	6.0%	4.0%	100.0%
	Elektrotenička škola	Count	11	22	12	3	2	50
		% within Škola	22.0%	44.0%	24.0%	6.0%	4.0%	100.0%
Total		Count	26	44	20	6	4	100
		% within Škola	26.0%	44.0%	20.0%	6.0%	4.0%	100.0%

Vrste i karakteristike vršnjačkog nasilja

U narednom dijelu prikazani su rezultati koji se odnose na vrste i karakteristike vršnjačkog nasilja. Analizirani su različiti oblici nasilja (fizičko, verbalno, prikriveno i elektronsko), kao i percepcija najčešćih žrtava i počinitelja, te faktori koji mogu otežati prijavljivanje nasilja.

Rezultati pokazuju da je među djecom najučestaliji oblik nasilja širenje lažnih glasina, koje je kao najčešći oblik prepoznalo 47% ispitanika. Slijedi davanje pogrdnih imena sa ukupno 36%, dok su fizičko nasilje, guranje i vikanje znatno rjeđe zastupljeni. Ovakvi rezultati ukazuju da su psihološki i verbalni oblici vršnjačkog nasilja prisutniji od otvorenog fizičkog nasilja, što potvrđuje da se nasilje među djecom često ispoljava kroz narušavanje ugleda, vrijeđanje i socijalno ponižavanje (Tabela 5). Razlika između škola nije se pokazala statistički značajnom ($p = 0.655$).

Rezultati takođe pokazuju da se neki oblici nasilja veoma rijetko ili gotovo nikada ne javljaju u obe škole. Namjerno isključivanje vršnjaka iz društva od strane učenika ili grupe učenika vrlo rijetko u obje škole. Na ukupnom nivou, 94,0% učenika gotovo nikad ne praktikuje isključivanje vršnjaka, dok 6,0% to čini rijetko. Učenici gotovo nikada ne dovode vršnjake u neugodne situacije pred odraslima**.** Na ukupnom nivou, svih 100 ispitanika (100,0%) nije dovodilo vršnjake u neugodne situacije pred odraslima, što sugeriše da je ovaj oblik samoiniciranog nasilja potpuno odsutan u obje škole. Na ukupnom uzorku, 98,0% učenika gotovo nikad nije vršilo fizičko nasilje prema vršnjacima, dok 2,0% rijetko učestvuje u ovakvom ponašanju. Iznuda novca od strane učenika ili grupe učenika gotovo da ne postoji u obje škole.Na ukupnom uzorku svih 100 ispitanika, niko nije prijavio iznudu novca, što jasno sugeriše da ekonomski oblik samoiniciranog vršnjačkog nasilja nije prisutan u analiziranim školama.

Tabela 5. **Koja je vrsta nasilja među djecom učestalija?**

		Koja je vrsta nasilja među djecom učestalija?					Total
		Davanje pogrdnih imena	Fizičko nasilje	Širenje lažnih glasina	Guranje	Vikanje	
Gimnazija	Count	17	7	21	2	3	50
	% within Škola	34.0%	14.0%	**42.0%**	4.0%	6.0%	100.0%
Elektrotenička škola	Count	19	3	26	1	1	50
	% within Škola	38.0%	6.0%	**52.0%**	2.0%	2.0%	100.0%
Total	Count	36	10	47	3	4	100
	% within Škola	36.0%	10.0%	**47.0%**	3.0%	4.0%	100.0%

Rezultati pokazuju da se kao najčešće žrtve vršnjačkog nasilja izdvajaju mirni učenici, što smatra 61% ispitanika. Ovakav stav je izraženiji kod učenika Elektrotehničke škole, gdje čak 70% navodi mirne učenike kao najčešće žrtve, dok u Gimnaziji taj procenat iznosi 52%. Kao žrtve učenici prepoznaju i nadarene učenike (23%), dok su živahni učenici, učenici sa posebnim potrebama i učenici iz druge etničke skupine znatno rjeđe prepoznati kao žrtve nasilja (Tabela 6).

Dobijeni rezultati ukazuju na to da učenici percipiraju kako su povučenost, nenametljivost i slabija socijalna dominacija osobine koje mogu povećati rizik od izloženost nasilju.

Tabela 6. **Ko su najčešće žrtve nasilja?**

		Ko su najčešće žrtve nasilja?				
		Mirni učenici	**Nadareni učenici**	**Živahni učenici**	**Učenici iz druge etničke skupine**	**Učenici sa posebnim potrebama**
Gimnazija	Count	26	13	6	1	4
	% within Škola	**52.0%**	26.0%	12.0%	2.0%	8.0%
Elektrotenička škola	Count	35	10	4	1	0
	% within Škola	**70.0%**	20.0%	8.0%	2.0%	0.0%
Total	Count	61	23	10	2	4
	% within Škola	**61.0%**	23.0%	10.0%	2.0%	4.0%

Djevojčice se, prema nalazima istraživanja,prepoznaju kao češće žrtve nasilja nego dječaci. U Gimnaziji ovaj stav zastupa 84% učenika, dok je u Elektrotehničkoj školi taj procenat još izraženiji i iznosi 98%. Samo 9% ukupnih ispitanika smatra da su dječaci češće žrtve nasilja, pri čemu je taj odgovor zastupljeniji u Gimnaziji (16%) nego u Elektrotehničkoj školi (Tabela 7).

Rezultati pokazuju da su društvene mreže najčešće mjesto na kojem se prema mišljenju učenika odvija vršnjačko nasilje. Ovaj oblik nasilja navelo je 59% ukupnih ispitanika, pri čemu je udio sličan u obje škole (58% u Gimnaziji i 60% u Elektrotehničkoj školi). Ostala mjesta, poput hodnika (14%), učionice (11%), dvorišta (11%) i puta do škole (5%), znatno su manje zastupljena (Tabela 8). Dobijeni rezultati ukazuju na značajnu ulogu digitalnog okruženja u pojavi vršnjačkog nasilja, odnosno na izraženu prisutnost elektronskog nasilja među učenicima.

Tabela 7. **Nasilje je češće nad?**

			Nasilje je češće nad?		Total
			Djevojčicama	**Dječacima**	
Škola	Gimnazija	Count	42	8	50
		% within Škola	**84.0%**	16.0%	100.0%
	Elektrotenička škola	Count	49	1	50
		% within Škola	**98.0%**	2.0%	100.0%
Total		Count	91	9	100
		% within Škola	91.0%	9.0%	100.0%

Tabela 8. **Mjesto vršenja vršnjačkog nasilja?**

		Mjesto vršenja vršnjačkog nasilja?					Total
		Učionica	**Hodnik**	**Dvorište**	**Put do škole**	**Društvene mreže**	
Gimnazija	Count	7	6	5	3	29	50
	% within Škola	14.0%	12.0%	10.0%	6.0%	**58.0%**	100.0%
Elektrotenička škola	Count	4	8	6	2	30	50
	% within Škola	8.0%	16.0%	12.0%	4.0%	**60.0%**	100.0%
Total	Count	11	14	11	5	59	100
	% within Škola	11.0%	14.0%	11.0%	5.0%	59.0%	100.0%

Dobijeni rezultati ukazuju da emocionalne barijere, posebno osjećaj srama i strah od posljedica, predstavljaju najveće prepreke za prijavljivanje vršnjačkog nasilja među učenicima (Tabela 9).

Osjećaj srama kao razlog neprijavljivanja nasilja navodi 65% ukupnih ispitanika. Ovaj razlog je posebno izražen među učenicima Elektrotehničke škole (70%), dok u Gimnaziji iznosi 60%. Kao drugi najčešći razlog izdvajaju se stavovi da učenici sami trebaju riješiti problem (18%), dok 16% ispitanika navodi strah kao razlog neprijavljivanja nasilja. Nedostatak osobe kojoj bi se mogli obratiti gotovo nije prisutan (1%).

Rezultati pokazuju da bi najveći broj učenika na nasilje reagovao uzvraćanjem istom mjerom, što navodi 59% ukupnih ispitanika. Ovaj način reagovanja posebno je izražen kod učenika Elektrotehničke škole, gdje čak 76% učenika navodi takav odgovor, dok u Gimnaziji taj procenat iznosi 42%. Učenici Gimnazije češće navode da ne bi obraćali pažnju na nasilje (46%), dok je ovaj odgovor znatno manje zastupljen u Elektrotehničkoj školi (10%). Veoma mali broj učenika bi potražio pomoć odraslih (3%), što ukazuje na nedovoljnu spremnost učenika da uključe osobe od povjerenja u rješavanje problema (Tabela 10). Razlike između grupa su statistički značajne ($p = 0.005$). Dobijeni podaci ukazuju na potrebu jačanja preventivnih programa i podsticanja učenika da nasilje ne rješavaju samostalno kroz uzvraćanje, već traženjem adekvatne podrške.

Tabela 9. **Iz kojeg razloga ne bi prijavio/la nasilje?**

		Iz kojeg razloga ne bi prijavio/la nasilje?				Total
		Oni to sami trebaju riješiti	Nemam se kome obratiti	Strah	Sram	
Gimnazija	Count	8	1	11	30	50
	% within Škola	16.0%	2.0%	22.0%	**60.0%**	100.0%
Elektrotenička škola	Count	10	0	5	35	50
	% within Škola	20.0%	0.0%	10.0%	70.0%	100.0%
Total	Count	18	1	16	65	100
	% within Škola	18.0%	1.0%	16.0%	**65.0%**	100.0%

Tabela 10. **Reakcija u slučaju nasilja**

		Kad je neko nasilan prema meni ja…..				Total
		Uzvratim na isti način	Tražim pomoć odraslih	Ne obraćam pažnju, svejedno mi je	Pobjegnem	
Gimnazija	Count	21	2	23	4	50
	% within Škola	42.0%	4.0%	**46.0%**	8.0%	100.0%
Elektrotenička škola	Count	38	1	5	6	50
	% within Škola	**76.0%**	2.0%	10.0%	12.0%	100.0%
Total	Count	59	3	28	10	100
	% within Škola	59.0%	3.0%	28.0%	10.0%	100.0%

Učestalost nasilnog ponašanja

U ovom dijelu rezultata prikazana je učestalost nasilnog ponašanja na osnovu procjena ispitanika na Likertovoj petostepenoj skali. Analiza obuhvata samoprocjenu doživljenog i počinjenog nasilja u posljednjih nekoliko mjeseci, što omogućava kvantitativni uvid u intenzitet i učestalost različitih oblika vršnjačkog nasilja (Tabela 11).

Rezultati pokazuju da je najveći broj učenika naveo da su uvrede ili ružne riječi doživjeli rijetko (32%), dok 25% ispitanika navodi da se to dešavalo ponekad, a 24% često. U poređenju škola, učenici Elektrotehničke škole češće navode učestalo izlaganje uvredama, gdje 34% ispitanika navodi da se to dešavalo često, dok je u Gimnaziji taj procenat 14%. S druge strane, u Gimnaziji najveći broj učenika navodi da su uvrede doživljavali rijetko (46%). Ukupno posmatrano, rezultati ukazuju da je verbalno nasilje prisutno među učenicima, pri čemu je izraženije u Elektrotehničkoj školi. Razlika između škola je statistički značajna ($p = 0.005$).

Tabela 11. **Koliko puta je tebi u školi u posljednjih nekoliko mjeseci neko direktno upućivao/la uvrede ili ružne riječi?**

		Koliko puta je nad tobom ili tebi u školi u posljednjih nekoliko mjeseci neko direktno upućivao/la uvrede ili ružne riječi?					Total
		Gotovo nikad	Rijetko	Ponekad	Često	Gotovo uvijek	
Gimnazija	Count	10	23	9	7	1	50
	% within Škola	**20.0%**	**46.0%**	18.0%	14.0%	2.0%	100.0%
Elektrotenička škola	Count	7	9	**16**	**17**	1	50
	% within Škola	14.0%	18.0%	**32.0%**	**34.0%**	2.0%	100.0%
Total	Count	17	32	25	24	2	100
	% within Škola	17.0%	32.0%	25.0%	24.0%	2.0%	100.0%

Određene varijable su pokazale značajne razlike između grupa (Tabela 12). Statistički značajne razlike utvrđene su kod pitanja „Ko su najčešće žrtve nasilja?“ ($p = 0.023$) i „Nasilje je češće nad?“ ($p = 0.014$), što ukazuje da učenici gimnazije i elektrotehničke škole različito percipiraju profil žrtava i to nad kime se nasilje češće vrši. Također, značajne razlike uočene su i u načinu reagovanja na nasilje („Kad je neko nasilan prema meni ja...“, $p = 0.005$), gdje učenici dvije škole ispoljavaju različite obrasce ponašanja. Posebno je važno naglasiti da se značajne razlike uočavaju i kod sopstvenog nasilničkog ponašanja. Učenici su se razlikovali u tome koliko često su sami vrijeđali druge učenike ($p < 0.001$) i koliko često su naguravali vršnjake ($p < 0.001$).

Tabela 12. **Testiranje značajnosti razlika između učenika Gimnazije i Elektrotehničke škole, ANOVA**

		Sum of Squares	df	Mean Square	F	Sig.
Ko su najčešće žrtve nasilja?	Between Groups	5.290	1	5.290	5.319	.023
	Within Groups	97.460	98	.994		
	Total	102.750	99			
Nasilje je češće nad?	Between Groups	.490	1	.490	6.236	.014
	Within Groups	7.700	98	.079		
	Total	8.190	99			
Kad je neko nasilan prema meni ja	Between Groups	9.610	1	9.610	8.106	.005
	Within Groups	116.180	98	1.186		
	Total	125.790	99			
Koliko puta je tebi u školi u posljednjih nekoliko mjeseci neko direktno upućivao/la uvrede ili ružne riječi?	Between Groups	9.000	1	9.000	8.125	.005
	Within Groups	108.560	98	1.108		
	Total	117.560	99			
Koliko puta je tebe u školi u posljednjih nekoliko mjeseci naguravao/la kako bi se ti loše osjećao/la?	Between Groups	12.250	1	12.250	15.169	.000
	Within Groups	79.140	98	.808		
	Total	91.390	99			
Koliko puta si ti sam/a ili u grupi vršnjaka u posljednjih nekoliko mjeseci direktno upućivao/la uvrede ili ružne riječi?	Between Groups	20.250	1	20.250	33.108	.000
	Within Groups	59.940	98	.612		
	Total	80.190	99			
Koliko puta si ti sam/a ili u grupi vršnjaka u posljednjih nekoliko mjeseci naguravao/la kako bi se on/ona loše osjećao/la?	Between Groups	5.290	1	5.290	35.951	.000
	Within Groups	14.420	98	.147		
	Total	19.710	99			

DISKUSIJA

Rezultati istraživanja potvrđuju da je vršnjačko nasilje značajno prisutan problem među učenicima srednjih škola u kojima je provedeno istraživanje. Iako većina učenika navodi da bi se obratila za pomoć i prijavila nasilje, u stvarnim situacijama i dalje postoje značajne prepreke za prijavljivanje, prije svega osjećaj srama i straha. Ovakvi nalazi u skladu su sa zapažanjima Rigbyja (2002), koji ističe da žrtve vršnjačkog nasilja često izbjegavaju prijavljivanje zbog straha od osvete, nepovjerenja u reakciju odraslih i osjećaja bespomoćnosti [7].

Dobijeni rezultati pokazuju da među ispitanim srednjoškolcima dominiraju verbalni i indirektni oblici nasilja, dok su fizičko nasilje i ekonomski oblici znatno rjeđe zastupljeni. Kao najčešći oblik nasilja ispitanici izdvajaju širenje lažnih glasina i davanje pogrdnih imena, što potvrđuje da se savremeno vršnjačko nasilje sve više manifestuje kroz psihološke i socijalne oblike agresije. Ovakvi rezultati podudaraju se sa nalazima Popadića i Pluta (2007), koji navode da se nasilje među učenicima najčešće ispoljava kroz vrijeđanje, ismijavanje, socijalnu izolaciju i narušavanje ugleda, dok fizički napadi čine manji dio ukupnog nasilnog ponašanja [3].

Značajan nalaz ovog istraživanja odnosi se na elektronsko nasilje. Većina ispitanika smatra da se vršnjačko nasilje danas najčešće odvija putem društvenih mreža, što potvrđuje sve veću ulogu digitalnog okruženja u međuvršnjačkim odnosima. Ovaj rezultat potvrđuje navode Hadžić-Bajrić (2010), koja ističe da razvoj informacionih tehnologija i društvenih mreža dovodi do pojave novih oblika nasilja koji se odvijaju izvan školskog prostora, ali imaju ozbiljne posljedice po emocionalno stanje i socijalno funkcionisanje učenika [2].

Gotovo svi ispitanici naveli su da su barem jednom bili žrtve ili svjedoci vršnjačkog nasilja, što govori o veoma visokoj rasprostranjenosti ovog fenomena u školskom okruženju. Slične zaključke donosi i Olweus (1998), koji smatra da je vršnjačko nasilje jedan od najčešćih problema školskog života te da se ono javlja u gotovo svim obrazovnim sistemima, pri čemu se razlikuje prvenstveno po učestalosti i intenzitetu [5].

Rezultati istraživanja pokazuju da učenici kao najčešće žrtve nasilja prepoznaju mirne i povučene učenike. Ovakav nalaz u skladu je sa istraživanjima Rigbyja (2002), koji navodi da su učenici slabijih socijalnih kompetencija, nižeg samopouzdanja i manje izražene socijalne dominacije izloženi većem riziku od viktimizacije [7]. Slično tome, Olweus (1998) opisuje tipične žrtve kao učenike koji su povučeni, nesigurni i imaju poteškoće u odbrani od agresivnijih vršnjaka [5].

Interesantan rezultat predstavlja činjenica da većina učenika smatra kako su djevojčice češće žrtve vršnjačkog nasilja. Ovakav nalaz djelimično odstupa od pojedinih ranijih istraživanja koja navode da su dječaci češće izloženi fizičkom nasilju, dok su djevojčice češće žrtve verbalnog, relacijskog i elektronskog nasilja [7], [6]. Budući da u ovom istraživanju dominiraju upravo verbalni i elektronski oblici nasilja, ovakav rezultat može se smatrati očekivanim.

Rezultati ANOVA analize pokazuju da se stavovi i iskustva učenika Gimnazije i Elektrotehničke škole u većini analiziranih varijabli ne razlikuju statistički značajno. Međutim, kod pojedinih pitanja utvrđene su značajne razlike. Učenici dvije škole različito procjenjuju koje su osobe najčešće žrtve nasilja ($p = 0,023$), nad kojim polom se nasilje češće vrši ($p = 0,014$), kao i način reagovanja na nasilje ($p = 0,005$). Takođe, statistički značajne razlike uočene su u samoprocjeni nasilnog ponašanja, odnosno u učestalosti vrijeđanja i naguravanja vršnjaka ($p < 0,001$). Ovakvi rezultati potvrđuju da školsko okruženje može imati određeni uticaj na obrasce ponašanja učenika, iako osnovne karakteristike vršnjačkog nasilja ostaju veoma slične u obje škole.

Posebno zabrinjava podatak da bi najveći broj učenika na nasilje odgovorio uzvraćanjem istom mjerom, dok bi veoma mali broj potražio pomoć odraslih osoba. Ovakav obrazac ponašanja potvrđuje tvrdnje Ortege i Mora-Merchan (1999) da učenici često pokušavaju samostalno rješavati nasilne situacije, iako takve reakcije najčešće dovode do produžavanja sukoba i povećanja rizika od ponovljene viktimizacije.

Dobijeni rezultati u cjelini potvrđuju osnovnu hipotezu istraživanja da su različiti oblici vršnjačkog nasilja prisutni među učenicima srednjih škola. Istovremeno, rezultati ukazuju da savremeno vršnjačko nasilje sve manje poprima oblik otvorenog fizičkog sukoba, a sve više verbalne, socijalne i elektronske agresije. Takvi nalazi u skladu su sa savremenim istraživanjima

Hadžić-Bajrić (2010), Sesara (2011), Rigbya (2002), Olweusa (1998) te Popadića i Pluta (2007), koji naglašavaju da se fenomen vršnjačkog nasilja razvija zajedno sa promjenama u društvu i komunikacijskim tehnologijama, zbog čega preventivni programi moraju biti usmjereni ne samo na fizičko nasilje nego i na digitalne i psihološke oblike zlostavljanja [2], [6], [7], [5], [3].

ZAKLJUČAK

Opšti zaključak istraživanja pokazuje da je vršnjačko nasilje prisutno, ali dominantno u verbalnom obliku, te da se fizičko i socijalno nasilje javlja rjeđe. Gimnazija pokazuje niži intenzitet nasilničkih ponašanja u odnosu na Elektrotehničku školu, posebno kada je riječ o agresivnim reakcijama i verbalnom nasilju koje učenici sami iniciraju. Ovo ukazuje na različite obrasce ponašanja među učenicima različitih obrazovnih profila, što može biti povezano s društvenim okruženjem, normama škole i individualnim karakteristikama učenika.

Važno je naglasiti da ovo istraživanje ima preliminarni i eksplorativni karakter. Ono predstavlja početnu fazu šireg istraživanja fenomena vršnjačkog nasilja među srednjoškolcima. Zbog ograničenog uzorka i uključivanja dvije škole, rezultati se ne mogu u potpunosti generalizovati na cjelokupnu populaciju srednjoškolaca, ali pružaju značajan uvid u dominantne obrasce nasilja i percepciju učenika. Cilj je, prije svega, bio identifikovati najzastupljenije oblike vršnjačkog nasilja i otvoriti prostor za dalja, metodološki obimnija istraživanja. Rezultate svakako treba tumačiti s oprezom uzimajući u obzir I to da su podaci prikupljeni putem samoprocjene, što može uključivati subjektivne procjene i socijalno poželjne odgovore. Buduće studije mogle bi uključiti veći broj škola, reprezentativniji uzorak, longitudinalni pristup, kao i kombinovanje kvantitativnih i kvalitativnih metoda radi dubljeg razumijevanja uzroka i posljedica vršnjačkog nasilja.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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PHENOMENOLOGY AND PATTERNS OF BULLYING IN SECONDARYSCHOOLS

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ABSTRACT

This paper analyses the phenomenology of bullying in secondary schools in the area of BanjaLuka, with the aim of examining its prevalence, forms and perception among students. Bullying isdefined as intentional and repeated aggressive behaviour among same-age peers, which may takeverbal, physical, social and digital forms, and may have significant consequences for the psychologicaland social functioning of young people.The study was conducted on a sample of 100 students of Banja Luka Gymnasium and HighSchool of Electrical Engineering, using an anonymous survey questionnaire comprising 15 questionsrelated to prevalence, forms and context of bullying. Particular attention was given to the comparativeanalysis between the two schools, as well as to students' subjective perceptions of safety.The results indicate the presence of bullying in both schools, with verbal violence being the mostprevalent, particularly through spreading rumours and the use of offensive content. Physical and socialviolence were present to a lesser extent, while economic forms of violence have not been recorded.Cyber bullying has been significantly present, indicating the increasing influence of the digitalenvironment on patterns of peer aggression. Certain statistically significant differences were alsoobserved between the schools in specific forms of violence and in the perception of victims.In conclusion, the findings confirm that bullying represents a relevant issue in the school context,with the dominance of verbal and digital forms. The obtained findings represent a preliminary insightinto the phenomenon of bullying and point to the need to conduct more extensive research, as well asthe need for the development and implementation of preventive programmes, the improvement of theschool environment and the empowerment of students to cope effectively with violence.

Keywords: bullying, secondary school students, cyber bullying, prevention, school environment.

ŽIVOTNI SCENARIO I FORMIRANJE ETNIČKIH PREDRASUDA I STEREOTIPA: PERSPEKTIVA TRANSAKCIONE ANALIZE U POSTKONFLIKTNOM DRUŠTVENOM KONTEKSTU

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SAŽETAK

Ovaj stručni rad bavi se ulogom životnog scenarija (skripta), koncepta iz transakcione analize (TA), u formiranju i održavanju etničkih i nacionalnih predrasuda i stereotipa, sa posebnim osvrtom na postkonfliktni društveni kontekst Zapadnog Balkana. Predrasude se posmatraju kao poseban oblik stavova, negativni, emocionalno zasićeni i na promenu otporni stavovi prema pripadnicima drugih grupa, čija se upornost ne može u potpunosti objasniti racionalnim procesima i socijalnim učenjem. Autor analizira na koji način skriptne zabrane, kontrazabrane i rane odluke, usvojene u porodičnom okruženju, učestvuju u nastanku skriptnih generalizacija o „drugima“, kao i kako se one održavaju putem kontaminacije Odraslog ego-stanja sadržajima Roditeljskog ego-stanja, skriptne logike i potcenjivanja (discounting). Posebna pažnja posvećena je transgeneracijskom prenosu predrasuda, kroz kulturni Roditelj, porodični skript i episkript, i to u društvima koja nose iskustvo ratnih sukoba. U završnom delu razmatra se primena koncepata TA u širem društvenom kontekstu (obrazovanje, rad sa mladima, javni diskurs) u cilju podrške fleksibilnoj, podržavajućoj i prihvatajućoj društvenoj klimi, nasuprot rigidnosti, kroz prevođenje životne pozicije „Ja sam OK – Ti si OK“ na međugrupni nivo („Mi smo OK – Vi ste OK“). Zaključuje se da osvešćivanje skriptne osnove predrasuda može biti korisna dopuna socijalnopsihološkim intervencijama zasnovanim na međugrupnom kontaktu, kao i da TA nudi razumljiv pojmovni okvir za preventivni rad usmeren na smanjenje međuetničke distance.

Ključne reči: životni scenario, etničke predrasude, stereotipi, transakciona analiza, transgeneracijski prenos, postkonfliktno društvo

UVOD

Stavovi predstavljaju relativno stabilne kognitivne i afektivne orijentacije pojedinca prema objektima, osobama ili pojavama, koje utiču na ponašanje i donošenje odluka [1]. Među stavovima

posebno mesto zauzimaju predrasude i stereotipi prema pripadnicima drugih etničkih i nacionalnih grupa, jer su izrazito otporni na promenu i imaju neposredne posledice po međugrupne odnose [2]. Ova tema ima poseban značaj u društvima Zapadnog Balkana, a naročito u Bosni i Hercegovini, gde i decenijama nakon ratnih sukoba devedesetih godina međuetnička distanca i nepoverenje ostaju važne odlike društvenog života. Istraživanja sprovedena u Bosni i Hercegovini pokazuju da su učestaliji i kvalitetniji kontakt sa pripadnicima druge grupe i zajednički nadređeni identitet povezani sa većom spremnošću na međugrupno opraštanje i manjom željom za socijalnom distancom [3]. Istraživanje psiholoških i razvojnih mehanizama koji oblikuju predrasude ima važnu ulogu u razumevanju socijalne percepcije, međugrupnih odnosa i procesa identifikacije. U tom kontekstu, teorija životnog scenarija, razvijena unutar transakcione analize, nudi okvir za razumevanje kako rani obrasci mišljenja i ponašanja postaju osnova za formiranje stavova prema „drugima“.

Prema Berneu (2008), životni scenario je nesvesni životni plan koji osoba usvaja tokom ranog detinjstva pod uticajem roditeljskih poruka, porodične dinamike i ranih emocionalnih iskustava [4]. Ovi scenariji mogu oblikovati način na koji pojedinac doživljava sebe, druge ljude i svet oko sebe, često vodeći ka automatizovanim, iracionalnim ili emocionalno obojenim reakcijama. U skladu s tim, životni scenariji deluju kao referentni okvir koji filtrira informacije i tako utiče na formiranje stavova, naročito u domenu socijalnih odnosa i vrednosnih uverenja [5]. Empirijska istraživanja pokazuju da porodica ima važnu ulogu u prenošenju međugrupnih stavova: metaanaliza 131 studije, sa više od 45.000 parova roditelj-dete, utvrdila je umerenu povezanost između međugrupnih stavova roditelja i njihove dece, i to podjednako za afektivnu, kognitivnu i bihejvioralnu komponentu [6]. Osobe koje su internalizovale zabrane tipa „Ne postoj“, „Ne osećaj“ ili „Ne misli“ [7] mogu razviti stavove koji uključuju distanciranost, potiskivanje emocija ili rigidno razmišljanje, što dugoročno može uticati na interpersonalno funkcionisanje i emocionalnu regulaciju. Dodatno, kognitivne teorije ukazuju na to da su ovakvi obrasci blisko povezani sa automatskim mislima i uverenjima, koji predstavljaju osnovu za afektivnu procenu objekata stavova [8]. Shodno tome, razumevanje dinamike životnog scenarija može doprineti dubljoj analizi geneze stavova, naročito onih koji su otporni na promene, poput predrasuda i stereotipa.

Cilj ovog rada jeste da, oslanjajući se na teorijski okvir transakcione analize, analizira kako elementi životnog scenarija, konkretno skriptne zabrane i kontrazabrane, rane odluke, skriptna logika i kontaminacija Odraslog ego-stanja, doprinose formiranju i održavanju etničkih i nacionalnih predrasuda i stereotipa, kao i kako se oni prenose s generacije na generaciju u postkonfliktnom društvu. Dodatni cilj je da se razmotre mogućnosti primene koncepata TA u širem društvenom kontekstu, u cilju podrške fleksibilnoj, podržavajućoj i prihvatajućoj društvenoj klimi. Rad ima karakter teorijske analize i ne donosi nove empirijske podatke, a nalazi iz socijalne psihologije navode se kao oslonac teorijskim tvrdnjama i kao smernica za buduća istraživanja. U radu će se koristiti terminologija usklađena sa standardnim izvorima transakcione analize [9], [4], [5] i sa domaćom literaturom [10].

TEORIJSKI PRISTUP: PREDRASUDE I STEREOTIPI KAO VRSTA STAVOVA

Stavovi predstavljaju psihološke konstrukte koji reflektuju evaluativne tendencije pojedinca prema određenim objektima, osobama, pojavama ili idejama. U psihologiji se najčešće definišu kao trajne organizacije kognitivnih, emocionalnih i bihejvioralnih komponenti koje usmeravaju mišljenje i ponašanje [11]. Drugim rečima, stav uključuje ono što osoba zna, oseća i namerava da uradi u vezi sa objektom stava. Jedna od najprihvaćenijih klasifikacija stavova jeste tzv. trokomponentni model [12], koji obuhvata: kognitivnu komponentu (verovanja i mišljenja o objektu), zatim afektivnu komponentu (emocije koje objekt izaziva) i bihejvioralnu komponentu (namere ponašanja prema objektu). Tako, na primer, negativan stav prema određenoj društvenoj grupi može obuhvatiti verovanje da su pripadnici te grupe inferiorni (kognitivno), osećanje neprijatnosti u njihovoj blizini (afektivno) i izbegavanje kontakta s njima (bihejvioralno).

Upravo se kroz ovaj model mogu razgraničiti pojmovi koji su u središtu ovog rada. Stereotip predstavlja kognitivnu komponentu, odnosno generalizovano uverenje o osobinama pripadnika

neke grupe, a predrasuda predstavlja negativnu afektivno-evaluativnu reakciju prema pripadnicima grupe na osnovu same pripadnosti toj grupi, dok je diskriminacija je njihov bihejvioralni izraz [2]. U ovom radu pod etničkim i nacionalnim predrasudama podrazumevaju se negativni stavovi prema pripadnicima drugih etničkih, nacionalnih i verskih grupa, kakvi su u fokusu istraživanja međugrupnih odnosa u postkonfliktnim društvima [3].

U savremenoj psihologiji razlikuje se više vrsta stavova, zavisno od kriterijuma podele. Za razumevanje predrasuda naročito su važne dve podele:

1. Eksplicitni i implicitni stavovi: Eksplicitni stavovi su oni kojih je pojedinac svestan i koje može verbalizovati, dok su implicitni nesvesni i automatski, često detektovani samo kroz indirektne metode merenja [13]. Implicitni stavovi su naročito važni u razumevanju predrasuda, jer često ostaju van kontrole svesti, što ih, kako će biti pokazano, približava pojmu skriptnih uverenja u transakcionoj analizi.
2. Instrumentalni i ekspresivni stavovi: Instrumentalni su oblikovani na osnovu korisnosti objekta stava, dok ekspresivni izražavaju vrednosti, identitet ili pripadnost [14]. Predrasude najčešće imaju ekspresivnu i egodefanzivnu funkciju: one čuvaju osećaj pripadnosti sopstvenoj grupi i štite samopoštovanje pojedinca, zbog čega se teško menjaju pod uticajem argumenata.

Razumevanje različitih tipova i struktura stavova važno je za analiziranje njihove otpornosti na promene, njihove funkcije (npr. adaptivne, egodefanzivne, ekspresivne) kao i njihove uloge u socijalnim interakcijama i donošenju odluka, a posebno za razumevanje zašto su predrasude stečene u porodici i zajednici toliko postojane.

ŽIVOTNI SCENARIO I ŽIVOTNI SKRIPT

Životni scenario ili životni skript je nesvesni (ili podsvesni) životni plan koji određuje životne izbore, skript je nesvesna motivacija koja upravlja životnim ponašanjem pa tako i utiče na formiranje stavova. Berne (2008) skript definiše kao životni plan koji je zasnovan na odlukama donetim u detinjstvu, osnažen od strane roditelja, koji potvrđuje događaje iz života i koji kulminira u izabranoj alternativi [4]. Roditeljski uticaji su veoma važni za formiranje detetove ličnosti, formiranje sistema vrednosti i odatle sledi da će se oni kasnije odraziti na ponašanje odraslog čoveka kao i na funkcionisanje Odraslog ego-stanja. Izvesno je da ljudi žive u skladu sa svojim uverenjima o životu. Često ljudi na osnovu svojih ranih životnih iskustava formiraju određena uverenja i životne stavove pa na osnovu toga kasnije sebe nesvesno prisiljavaju da žive unutar tih uverenja, ograničavajući sebe na neki način. Iza svakog ponašanja u životu, postoji neka logika, ljudi se nikad ne ponašaju slučajno na način na koji se ponašaju i to se zove logika životnog scenarija ili skripta. Osoba doživi određena rana iskustva, donese određene rane odluke, zauzme određene psihološke pozicije iz kojih reaguje i ponaša se u skladu sa tim [10]. Struktura životnog scenarija (Berne, 2008) obuhvata nekoliko elemenata [4]:

a) Rane skriptne odluke. One se donose uglavnom u predškolskom uzrastu i to su detetove zablude o važnim životnim pitanjima. Te pogrešne zaključke ili zablude dete usvaja u svoj referentni okvir (sistem vrednosti) u skladu sa kojima kasnije određuje svoje ponašanje i formira stavove („Žene ili muškarci su glupi“, „Ljubav ne postoji“, „Ljudi određene nacionalnosti su glupi, lenji, zli...“, „Samo osobe koje završe fakultet su pametne“...). Te skriptne odluke se kasnije ne preispituju i osoba ih smatra istinitim, na osnovu kojih sprovodi životne aktivnosti. Neko ima jednu skriptnu odluku, a neko više – što je više skriptnih odluka, to osoba više kontaminira svoj život skriptom.
b) Roditeljski uticaji. Rane odluke se mogu doneti samostalno, posmatrajući svet oko sebe, ili pod uticajem roditelja i drugih autoriteta. Postoje razne verbalne i neverbalne poruke koje roditelji upućuju svojoj deci i one utiču na to da dete formira rane odluke. Najznačajnije poruke su skriptne zabrane (injunctions) i kontrazabrane (counterinjunctions), koje se u domaćoj literaturi nazivaju i skriptnim imperativima [10].

Skriptne zabrane su roditeljske poruke kojima se osporava neko detetovo pravo. Razlog upućivanja zabrana može biti iracionalno uverenje roditelja ili „vaspitna manipulacija“ koja u osnovi ima dobru nameru. Skriptne zabrane nemaju veze sa običnim zabranama koje roditelj treba da sprovodi u vaspitanju.

Kontrazabrane (skriptni imperativi) su roditeljske poruke kojima se uslovljava detetovo pravo na život ili pravo na ljubav. Na primer, roditelj ponavlja detetu da ono ima pravo da postoji samo ako je takvo i takvo, i da će ga voleti samo ako je takvo i takvo. Skriptni imperativ podrazumeva postojanje zabrane koja se aktivira ako dete ne bude onakvo kakvo roditelj zahteva da bude. Logika imperativa glasi: „Prihvatiću te samo ako si najbolji i sve dok si najbolji.“ Ako dete ne ispuni uslov, sledi zabrana: „Ako nisi najbolji, daćemo te drugoj porodici“ (pretnja odbacivanjem kojom se detetu poručuje da nije dovoljno vredno da bi bilo voljeno).

c) Potvrda životnim tokom – kad neko počne da živi na osnovu svojih skriptnih zaključaka, onda će tok njegovog života „potvrđivati“ upravo te zaključke. Na primer, ako je osoba zaključila da ne može biti voljena, ona će se ponašati (živeti) tako da će „dokazati“ da nju niko ne može voleti. Ona će odustati od traženja ljubavi ili će se zaljubljivati u osobe koje će jasno pokazivati da je ne vole, ili kada poveruje da je neko zaista voli, onda će ga svojim ponašanjem oterati od sebe. Osobe biraju one partnere i situacije kojima će potvrditi svoja skriptna uverenja (stavove).
d) Skriptni izbor – detetovo rano iskustvo, zbog koga je donelo određenu skriptnu odluku, i uticaj autoriteta učvršćuju osobu u uverenju da je njena „sudbina“ takva i takva. Kada je osoba u situaciji da treba da donese neku važnu odluku, ona ima utisak da to čini slobodno, svesno i racionalno, a u stvari je pod uticajem skriptnih mehanizama. Zbog toga su neki važni životni izbori u stvari skriptni izbori (izbor partnera, rađanje dece, izbor zanimanja...) [4].

Gledano u holističkom psihoterapijskom kontekstu, a i sumirano u odnosu na istraživački i praktični rad različitih autora, struktura životnog scenarija je nešto kondenzovanija i obično se prikazuje putem sledeće četiri komponente:

1. Zabrane (engl. injunctions) – negativne poruke koje dete prima, poput „Ne postoj“, „Ne uspevaj“, „Ne misli“, koje ograničavaju njegovu spontanost i razvoj [7].
2. Kontrazabrane (engl. counterinjunctions) – očekivanja i poruke koje nameću poželjno ponašanje („Budi savršen“, „Udovolji drugima“), često u kontradikciji sa zabranama [15].
3. Rane odluke (engl. early decisions) – emocionalni zaključci koje dete donosi da bi se adaptiralo na poruke koje prima (npr. „Ako budem ćutao, biću voljen“).
4. Skriptna matrica – dijagram koji prikazuje kako se poruke iz ego-stanja roditelja prenose na odgovarajuća ego-stanja deteta i koji integriše zabrane, kontrazabrane i odluke u obrazac koji osoba, često nesvesno, prati kroz život [15].

Berne (2008) je uveo i podelu scenarija prema njegovom krajnjem ishodu, odnosno prema konačnom cilju življenja [4]. On razlikuje pobednički scenario (winner’s script) koji vodi do lične ispunjenosti i uspeha, gubitnički scenario (loser’s script), koji vodi do neuspeha i nezadovoljstva, te nepobednički (non-winner) scenario, sa neizvesnim ishodom i mnogo odlaganja odluka, koji Steiner (1974) naziva banalnim [16]. Razumevanje skripta ključno je u psihoterapiji, jer omogućava klijentu da osvesti automatske obrasce ponašanja, poveže ih sa ranom porodičnom dinamikom i postepeno ih zameni funkcionalnijim obrascima. U kontekstu formiranja stavova, životni scenario deluje kao filtrirajući okvir kroz koji osoba tumači svet, procenjuje druge i razvija specifične stavove o sebi i društvu [5]. Za temu ovog rada posebno je važno to što se kroz isti okvir filtriraju i informacije o pripadnicima drugih grupa.

SKRIPTNE ODLUKE I PREDRASUDE KAO VRSTA STAVOVA

Jedan od najtrajnijih i najotpornijih oblika stavova jesu predrasude, koje se definišu kao negativni stavovi prema članovima određene socijalne grupe, zasnovani na pripadnosti toj grupi, a ne na individualnim karakteristikama [2]. Predrasude uključuju i kognitivne stereotipe, afektivne reakcije i dispoziciju za diskriminatorno ponašanje. Njihova upornost i emocionalna snaga često ukazuju na to da nisu samo proizvod društvenog učenja, već i duboko ukorenjenih unutrašnjih uverenja. Upravo tu se može uspostaviti veza između skriptnih odluka i razvoja predrasuda.

Skriptne odluke koje dete donosi u ranom uzrastu, pod uticajem porodične dinamike i emocionalnih poruka roditelja, mogu sadržati opšte negativne zaključke o ljudima, svetu i sebi („Ljudi su opasni“, „Ne možeš nikome verovati“, „Svet je nepravedan“). Kada se takve poruke ukrste sa porukama koje se odnose na određene grupe, npr. nacionalne, etničke, verske, rodne ili klasne, dolazi do formiranja skriptnih generalizacija koje kasnije postaju osnova predrasuda [10]. Opšte uverenje „Ljudi su opasni“ tada se sužava na „Oni su opasni“, pri čemu se „oni“ određuju etničkom ili nacionalnom pripadnošću. Za razliku od stavova koji mogu biti fleksibilni i racionalno preispitani, predrasude koje su deo skriptne strukture imaju nesvesnu, emocionalno zasićenu osnovu. Osoba ne prepoznaje da je njeno mišljenje kontaminirano: sadržaji preuzeti od roditelja i drugih autoriteta (Roditeljsko ego-stanje) ili rani strahovi i zaključci (ego-stanje Dete) doživljavaju se kao proverene činjenice, pa osoba veruje da „uvek tako misli“ i da je to „jednostavno tačno“. Berne (1961) je predrasude upravo naveo kao tipičan primer kontaminacije Odraslog ego-stanja Roditeljskim ego-stanjem, dok zablude zasnovane na detinjim strahovima predstavljaju kontaminaciju Odraslog ego-stanjem Dete; kod mnogih predrasuda prisutna je dvostruka kontaminacija [9]. Takva vrsta kontaminacije racionalnog mišljenja otežava dekonstrukciju stavova kroz edukaciju ili logičku argumentaciju [5].

Održavanju predrasuda doprinosi i mehanizam potcenjivanja (discounting), koji u TA označava nesvesno ignorisanje informacija relevantnih za rešavanje problema [17]. Osoba sa skriptnom predrasudom potcenjuje postojanje individualnih razlika među pripadnicima druge grupe, značaj sopstvenih pozitivnih iskustava sa njima („on je izuzetak“) i sopstvenu mogućnost da promeni stav. Na taj način svako iskustvo koje bi moglo da opovrgne predrasudu biva neutralisano pre nego što dospe do Odraslog ego-stanja.

Na primer, ako je osoba kao dete internalizovala poruku „Stranci su opasni“ zbog roditeljske anksioznosti ili rigidnosti, ta poruka može postati deo njenog skripta, iako nikada nije imala lično negativno iskustvo sa pripadnicima drugih grupa. Kasnije u životu, takva osoba može izražavati negativne stavove, ali istovremeno biti nesvesna njihovog porekla i otporna na njihovu promenu.

U postkonfliktnom kontekstu ovakve poruke često imaju specifičan sadržaj, poput „Nikad ne zaboravi šta su nam uradili“, „Njima se ne može verovati“ ili „Drži se svojih“. One se retko izgovaraju kao eksplicitna pouka; češće se prenose kroz porodične priče o stradanju, kroz ćutanje o određenim temama, kroz emocionalne reakcije roditelja na pominjanje druge grupe i kroz ograničen svakodnevni kontakt sa pripadnicima drugih zajednica, uključujući i sredine u kojima je obrazovanje delimično etnički podeljeno. Dete koje odrasta u takvom okruženju može doneti ranu odluku poput „Sigurno je samo među našima“, koja kasnije deluje kao osnova etničke distance, iako sama osoba nije neposredno iskusila sukob.

Zato je razumevanje skriptne osnove predrasuda važno ne samo u terapijskom kontekstu, već i u obrazovanju, interkulturalnoj komunikaciji i prevenciji socijalne diskriminacije. Samo kroz osvešćivanje nesvesnih poruka i odluka, moguće je raskinuti obrazac koji vodi ka negativnim i rigidnim stavovima.

TRANSGENERACIJSKI PRENOS PREDRASUDA: KULTURNI RODITELJ, PORODIČNI SKRIPT I EPISKRIPT

Predrasude se ne formiraju samo na nivou pojedinačne porodice. Transakciona analiza je od svojih početaka prepoznavala da se Roditeljsko ego-stanje oblikuje i pod uticajem šire kulture. Pojam kulturnog Roditelja (cultural Parent) označava deo Roditeljskog ego-stanja u kome su pohranjena pravila, vrednosti i „istine“ zajednice kojoj osoba pripada, uključujući i slike o drugim

grupama [18]. Kultura, prema ovom shvatanju, ima sopstveni skript koji se prenosi kroz porodicu, obrazovanje, verske institucije, medije i javni diskurs [19]. James (1994) ukazuje na to da se pripadnici različitih kultura u susretu često ne opažaju neposredno, već kroz filter sopstvenog kulturnog referentnog okvira, što susret čini podložnim nesporazumima i potvrđivanju postojećih stereotipa [20].

Za postkonfliktna društva posebno je značajan koncept transgeneracijskog skripta, odnosno ideja da se skriptne poruke prenose kroz više generacija, tako da dete usvaja zaključke koji potiču iz iskustava koja ono samo nije proživelo [21]. Srodan je i pojam episkripta koji je uvela Fanita English (1969): episkript označava nesvesni pokušaj roditelja da se oslobodi sopstvenog nerazrešenog skriptnog sadržaja tako što ga, poput „vrućeg krompira“, prenese na dete [22]. U kontekstu međuetničkih odnosa, roditelj koji nije emocionalno obradio iskustvo rata, gubitka ili poniženja može nesvesno preneti na dete strah, mržnju ili obavezu osvete, pa dete „nosi“ sukob koji nije njegov.

Ovakvo tumačenje u skladu je sa socijalnopsihološkim i psihoanalitičkim analizama dugotrajnih sukoba. Volkan (1997) opisuje „izabranu traumu“, odnosno kolektivno sećanje na stradanje grupe koje se prenosi kroz generacije i postaje deo grupnog identiteta, dok Bar-Tal (2007) pokazuje kako društva u dugotrajnim sukobima razvijaju kolektivna uverenja (o sopstvenoj žrtvi, o neprijateljskoj prirodi druge strane) koja se sistematski prenose na nove generacije i otežavaju pomirenje [23], [24]. Empirijski nalazi o umerenoj sličnosti međugrupnih stavova roditelja i dece [6] ukazuju na to da porodica jeste jedan od kanala ovog prenosa, mada ne i jedini. Transakciona analiza ovim saznanjima doprinosi opisom mehanizma na nivou pojedinca: kolektivna uverenja postaju lični skript onda kada ih dete usvoji kao rane odluke i kada se ona u odraslom dobu ne preispituju.

SKRIPTNE PORUKE

Skriptne poruke predstavljaju ključni mehanizam preko kog se oblikuje životni scenario deteta, odnosno nesvesni obrasci mišljenja, emocija i ponašanja koji kasnije upravljaju njegovim životnim izborima. Reč je o verbalnim i neverbalnim porukama koje dete prima od značajnih odraslih figura, pre svega roditelja, tokom ranog razvoja, a koje imaju dubok uticaj na njegovo formiranje ličnosti i sistem uverenja [7].

Skriptne poruke se dele na dve osnovne kategorije: zabrane (injunctions) i kontrazabrane (counterinjunctions). Zabrane su negativne, često suptilne i nesvesne poruke koje osporavaju detetu pravo na osećanja, misli, ponašanje ili postojanje (npr. „Ne osećaj“, „Ne budi dete“, „Ne postoj“). One ne moraju biti izrečene direktno, već je dovoljno da su sadržane u tonu glasa, govoru tela ili emocionalnoj klimi u porodici. Na primer, roditelj koji stalno potiskuje sopstvenu tugu može detetu nesvesno preneti poruku da je izražavanje tuge nepoželjno ili zabranjeno [5]. S druge strane, kontrazabrane predstavljaju poruke koje izražavaju uslovljenu prihvaćenost, odnosno da će dete biti voljeno i prihvaćeno samo ako ispunjava određene kriterijume, poput: „Budi savršen“, „Udovolji drugima“, „Budi jak“. Iako na prvi pogled pozitivne, ove poruke stvaraju unutrašnji pritisak, jer dete internalizuje ideju da ne vredi ništa ako ne ispunjava određene uslove [5]. U transakcionoj analizi, skriptne poruke se posmatraju kao deo egzistencijalnog životnog plana, koji se razvija pre logičkog mišljenja i postaje nesvesni vodič kroz život. Njihova moć leži u tome što se kasnije retko preispituju, već bivaju ugrađene u ličnost kao „lična istina“ [4]. One mogu oblikovati stavove o sebi („Nisam dovoljno dobar“), drugima („Ljudi su opasni“) i svetu („Svet je nepravedno mesto“), te na taj način utiču i na formiranje trajnih stavova i emocionalnih obrazaca, uključujući i stavove prema drugim grupama.

Internalizovane skriptne poruke predstavljaju poruke koje je dete primilo u ranom uzrastu, a koje su vremenom postale deo njegovog unutrašnjeg psihičkog sistema, oblikujući njegove misli, emocije, ponašanja i stavove. U osnovi transakcione analize, internalizacija podrazumeva usvajanje spoljašnjih poruka (najčešće roditeljskih) kao sopstvenih uverenja i „unutrašnjih istina“, koje kasnije deluju automatski, bez svesnog preispitivanja [5]. S obzirom na to da dete tokom ranog razvoja nema razvijene kognitivne mehanizme za procenu i kritičko promišljanje, ono

apsorbuje roditeljske poruke bez filtriranja, uključujući i one koje su štetne, iracionalne ili kontradiktorne. Na primer, dete koje često dobija poruku: „Ne budi sebičan“ može internalizovati uverenje da su njegove potrebe nevažne, što se kasnije može ispoljiti kroz hronično potiskivanje ličnih želja i razvoj stavova poput: „Dobri ljudi uvek stavljaju druge na prvo mesto“. Kada se internalizovane poruke odnose na identitet, vrednost i emocije, one mogu značajno oblikovati osnovne životne stavove pojedinca. Poruke poput „Ti si glup“, „Ne možeš uspeti“, „Nisi vredan ljubavi“ lako se pretvaraju u negativna samopoimanja i pesimističke stavove o životu i drugima. Takve poruke se kasnije manifestuju kroz samosabotirajuća ponašanja, pesimizam, perfekcionizam, osećaj krivice, kao i kroz predrasude prema drugima koji „ne ispunjavaju kriterijume“ koje je osoba internalizovala. Specifičnost internalizovanih skriptnih poruka jeste što se one ne doživljavaju kao poruke spolja, već kao „sopstveni glas“, unutrašnji narativ koji oblikuje odluke, reakcije i stavove prema sebi i svetu. Osoba može biti uverena da „uvek misli tako“, ne dovodeći u pitanje poreklo takvih uverenja [10]. Isto važi i za poruke o drugim grupama: rečenica „Oni su takvi“, preuzeta od roditelja, doživljava se kao lični zaključak, a ne kao naučena poruka. Ove poruke postaju deo tzv. unutrašnjeg kritičara, čiji je uticaj često nesrazmerno veliki u odnosu na realne okolnosti. U psihoterapijskom radu, posebno u okviru transakcione analize i kognitivno-bihevioralne terapije, identifikacija i dekonstrukcija internalizovanih poruka smatra se ključnim korakom u procesu promene stavova, ponašanja i emocionalnih obrazaca. Oslobađanjem od ovih nesvesnih uticaja, osoba stiče mogućnost da uspostavi autonomne, fleksibilne i realistične stavove o sebi i svetu oko sebe.

Razumevanje vrste i sadržaja skriptnih poruka važno je ne samo u psihoterapijskom radu, već i u edukaciji i prevenciji emocionalnih i socijalnih teškoća. Prepoznavanjem, osvešćivanjem i osporavanjem tih poruka, moguće je osloboditi se skriptnih obrazaca i razviti autonomne stavove i ponašanja.

SKRIPTNA LOGIKA

Skriptna logika predstavlja specifičan način mišljenja koji proističe iz nesvesnih poruka i odluka donetih u detinjstvu, i koji oblikuje način na koji osoba tumači stvarnost, donosi zaključke i reaguje na životne situacije. Za razliku od racionalne logike, koja se oslanja na činjenice, analizu i svesnu procenu, skriptna logika potiče iz ego-stanja Dete, bazira se na emocionalnim uverenjima i sećanjima i ne podleže preispitivanju [5]. Osobe koje se ponašaju u skladu sa skriptnom logikom zapravo reaguju na sadašnjost kao da su još uvek u istim okolnostima iz detinjstva. Na primer, osoba koja je kao dete formirala uverenje „Ne mogu da uspem“ usled stalne roditeljske kritike, može kasnije u odraslom dobu izbegavati prilike za napredovanje, nesvesno sabotirajući sopstveni uspeh i „dokazujući“ sebi da to uverenje i dalje važi. Skriptna logika ima sledeće karakteristike [10]:

1. Emocionalna zasnovanost – odluke se donose na osnovu osećanja, a ne činjenica;
2. Izbegavanje racionalnog preispitivanja – osoba je uverena da „uvek tako misli“ ili da „jednostavno zna“ da je nešto tačno;
3. Samopotvrđujući mehanizam – ponašanje je usmereno ka potvrdama već postojećih uverenja, čak i kada su ona destruktivna;
4. Selektivna percepcija – osoba bira da uoči samo ono što potvrđuje skriptno uverenje, dok ignoriše informacije koje ga osporavaju.

Sve četiri karakteristike lako se prepoznaju u funkcionisanju etničkih predrasuda. Negativan događaj u kome učestvuje pripadnik druge grupe pamti se i uopštava („eto, takvi su“), dok se pozitivna iskustva pripisuju izuzecima ili okolnostima. Izbegavanje kontakta, koje je posledica predrasude, istovremeno uskraćuje osobi iskustva koja bi mogla da je opovrgnu, čime se samopotvrđujući krug zatvara.

Skriptna logika je tesno povezana sa pojmom kontaminacije Odraslog ego-stanja, gde se racionalno mišljenje „zagađuje“ sadržajima Roditeljskog ego-stanja (predrasude) i ego-stanja Dete (zablude). Kontaminacije se manifestuju kroz predrasude, iracionalna uverenja i generalizacije, koje se smatraju logičnim, iako nemaju uporište u objektivnoj stvarnosti [9]. U psihoterapijskom

radu, razotkrivanje skriptne logike podrazumeva identifikaciju neadekvatnih uverenja i obrazaca mišljenja, njihovu dekonstrukciju i zamenu autonomnim, realističnim i fleksibilnim obrascima mišljenja, što omogućava osobi veću emocionalnu slobodu i racionalnije donošenje odluka.

KONTRASKRIPT, ANTISKRIPT I AUTONOMIJA

U okviru transakcione analize, osim osnovnog životnog scenarija (skripta), postoje i alternativni obrasci ponašanja koji se mogu razumeti kroz pojmove kontraskripta i antiskripta. Ovi koncepti pomažu u razumevanju zašto spoljašnja promena ponašanja ne znači nužno i oslobađanje od skripta.

Kontraskript (counterscript) označava skup odluka koje je osoba donela u skladu sa kontrazabranama [15]. On predstavlja društveno prihvatljivu „fasadu“ skripta: osoba se trudi da bude savršena, jaka ili da ugađa drugima, i dok u tome uspeva, deluje kao da skript ne postoji. Na primer, osoba čiji skript nosi zabranu „Ne uspevaj“ može razviti kompulsivnu potrebu za postignućem, perfekcionizam i opsesivno dokazivanje uspeha, što deluje kao pobuna protiv skripta, ali zapravo potvrđuje logiku kontrazabrane: „Vredim samo ako sam savršen“ (Stewart & Joines, 2012). Kontraskript je često nestabilan i lako puca pod pritiskom emocionalnih kriza, kada osoba „pada“ nazad u primarni skript.

Antiskript se odnosi na ono ponašanje koje je svesno i direktno suprotstavljeno skriptu, odnosno osoba radi suprotno od onoga što skript propisuje, ali joj skript i dalje ostaje referentna tačka [5]. Osoba se može racionalno odlučiti da živi drugačije, da ne ponavlja obrasce koje je nasledila, ali često bez potpunog emocionalnog oslobađanja od nesvesnih poruka koje skript sadrži. Antiskript može biti krhak jer ne uključuje dubinsku rekonstrukciju unutrašnjih uverenja, već se temelji na voljnom otporu. U tom smislu, antiskript može izgledati kao oslobađanje, ali bez terapijskog procesa često ostaje površinski ili kratkotrajan [10]. U domenu međugrupnih stavova, osoba koja je odrasla uz poruku „Ne druži se s njima“ može u adolescenciji demonstrativno idealizovati drugu grupu i omalovažavati sopstvenu. Takav stav samo je obrnuti znak istog obrasca: procena drugih ljudi i dalje se zasniva na grupnoj pripadnosti, a ne na njihovim individualnim osobinama.

Autentični životni put koji osoba razvija nakon što prepozna, razume i emocionalno obradi sadržaj sopstvenog skripta transakciona analiza naziva autonomijom (Berne, 1964). Autonomija podrazumeva svesnost (awareness), spontanost i sposobnost za intimnost, odnosno stanje u kome je osoba u kontaktu sa svojim autentičnim osećanjima i svesno donosi odluke. Ona nije automatska, pošto zahteva proces dekontaminacije Odraslog ego-stanja, promenu unutrašnjih poruka i razvoj novog sistema uverenja koji nije zasnovan na strahu, krivici ili uslovnoj ljubavi [5]. Ovaj pojam treba razlikovati od episkripta, koji u TA literaturi, kako je navedeno u prethodnom poglavlju, označava skriptni sadržaj koji roditelj nesvesno prenosi na dete [22].

Razumevanje ovih pojmova pomaže kako terapeutima, tako i edukatorima i savetnicima u radu sa osobama koje pokušavaju da razbiju negativne obrasce ponašanja, jer omogućava uvid u dubinske dinamike koje nisu vidljive u svakodnevnom funkcionisanju, ali snažno određuju tok života. Kahler (1975; 1974) je identifikovao pet pokretača (drivers), odnosno kratkih, uočljivih obrazaca ponašanja koji predstavljaju jezgro kontrazabrana i koji značajno oblikuju životni stil i obrasce mišljenja osobe [25], [26]:

1. Budi savršen! – Ova poruka podrazumeva da je vrednost osobe uslovljena potpunom besprekornošću. Stavovi koji proizlaze iz nje ukazuju na to da greške nisu dozvoljene, te se svaka greška doživljava kao lični neuspeh. Osobe sa ovim uverenjem razvijaju perfekcionizam, što može dovesti do iscrpljenosti i hroničnog nezadovoljstva.
2. Budi jak! – Poruka implicira da su emocije znak slabosti i da ih ne treba pokazivati. Osobe koje usvoje ovu poruku razvijaju stavove o emocionalnoj samodovoljnosti i izbegavanju bliskosti. Takvi ljudi često potiskuju emocije, što može dovesti do emocionalne izolacije i psihosomatskih problema [10].

3. Trudi se! (Try hard) – Ova poruka vodi ka uverenju da je važno truditi se, a ne i postići cilj. Osobe koje žive pod ovim pokretačem ulažu mnogo napora, ali zadatke često ne privode kraju, a vrednost pripisuju samom ulaganju truda.
4. Ugađaj drugima! – Osoba razvija stav da je njena vrednost uslovljena time koliko može da zadovolji potrebe i očekivanja drugih, često nauštrb sopstvenih potreba. Ovo dovodi do pasivnosti, potiskivanja nezadovoljstva i gubitka autentičnosti.
5. Požuri! – Poruka da je brzina vrednost sama po sebi formira stav da je usporavanje znak lenjosti i neefikasnosti. Osobe sa ovim imperativom razvijaju užurban životni stil, što povećava stres i rizik od grešaka.

U međugrupnom kontekstu, pokretač „Budi jak!“ može se ispoljiti kao uverenje da je pokazivanje empatije prema stradanju druge grupe znak slabosti ili izdaje sopstvene, a pokretač „Ugađaj drugima!“ kao konformiranje predrasudama sopstvene grupe radi očuvanja prihvaćenosti.

Pored kontrazabrana, značajnu ulogu u formiranju stavova imaju i skriptne zabrane, tj. poruke koje direktno ili indirektno oduzimaju osobi pravo na određene aspekte ličnosti ili ponašanja. Goulding i Goulding (1976) opisuju dvanaest osnovnih zabrana: Ne postoj, Ne budi ti (uključujući: Ne budi svog pola), Ne budi dete, Ne odrastaj, Ne uspevaj, Ne radi (ništa), Ne budi važan, Ne pripadaj, Ne budi blizak, Ne budi zdrav, Ne misli i Ne osećaj [7]. Za formiranje stavova prema drugima posebno su relevantne sledeće:

1. Ne budi ti (Ne budi svog pola) – kada roditelji direktno ili simbolički negiraju detetov pol („Šteta što nisi dečak“), ono može razviti stav da je njegov pol inferioran, što može voditi ka identitetskim krizama ili preuzimanju karakteristika suprotnog pola zarad prihvatanja; ista zabrana može biti osnova rodnih stereotipa.
2. Ne misli – dete se obeshrabruje da izrazi svoje stavove ili postavlja pitanja. Kasnije razvija stav da su tuđa mišljenja važnija, što smanjuje njegovu asertivnost i samopouzdanje u donošenju odluka, a u međugrupnom kontekstu i spremnost da kritički preispita stavove svoje sredine.
3. Ne osećaj – poruke poput „Ne plači“, „Ne budi ljut“ formiraju uverenje da su određena osećanja neprihvatljiva. Osobe tada razvijaju stav da osećanja treba potiskivati, što može dovesti do emocionalne nepismenosti.
4. Ne budi blizak – roditeljske poruke koje upozoravaju dete da nikome ne veruje („Svi će te iskoristiti“) formiraju stavove duboke sumnjičavosti i otežavaju stvaranje bliskih odnosa; kada se nepoverenje usmeri na određenu grupu, ova zabrana postaje neposredna osnova socijalne distance.
5. Ne pripadaj – dete dobija poruku da nigde ne pripada ili da je pripadnost uslovljena. Može se pretpostaviti da osoba sa ovom zabranom, u traganju za sigurnošću, razvija rigidnu i isključivu identifikaciju sa sopstvenom grupom, u kojoj se pripadnost „dokazuje“ odbacivanjem drugih.

Ove poruke, kada ostanu nesvesne i nepreispitane, postaju osnova za formiranje rigidnih, često disfunkcionalnih stavova. Psihoterapijski rad usmeren je ka njihovom osvešćivanju, dekonstrukciji i zamenjivanju funkcionalnijim uverenjima koji omogućavaju emocionalnu slobodu, zdravu samoaktualizaciju i autentične odnose [27].

ŽIVOTNE POZICIJE KAO TEMELJNI STAVOVI

U okviru transakcione analize, koncept životnih pozicija predstavlja osnovnu i trajnu emocionalno-kognitivnu orijentaciju pojedinca prema sebi i drugima. To su temeljna uverenja i stavovi koje osoba formira rano u detinjstvu, najčešće pre sedme godine života, pod uticajem porodične dinamike, emocionalne klime i skriptnih poruka koje dobija. Životne pozicije oblikuju način na koji osoba procenjuje sebe, druge i svet, i utiču na sve aspekte ponašanja, odnosa i donošenja odluka [28], [5]. Berne (1962) je klasifikovao četiri osnovne životne pozicije kroz dve bipolarne dimenzije: Ja sam OK / nisam OK i Ti si OK / nisi OK [28], a Ernst (1971) ih je prikazao

u vidu matrice (engl. OK Corral) [29]. Kombinacijom tih dimenzija dobijamo četiri osnovne pozicije:

1. Ja nisam OK – Ti si OK: Ova pozicija nastaje kada dete internalizuje poruku da su drugi bolji, vredniji ili voljeniji od njega. Osobe sa ovom životnom pozicijom razvijaju stavove samoponižavanja, osećaj inferiornosti i zavisnosti od drugih. Često traže potvrdu iz spoljnog sveta i imaju sklonost ka depresiji ili pasivnosti.
2. Ja nisam OK – Ti nisi OK: Ova pozicija ukazuje na globalnu bezvrednost i sebe i drugih. Javlja se kod osoba koje su bile zanemarivane ili zlostavljane, gde su pozitivni modeli ponašanja bili odsutni. Ove osobe razvijaju stavove pesimizma, beznadežnosti, pa čak i suicidalne tendencije.
3. Ja sam OK – Ti nisi OK: Ova pozicija najčešće nastaje kao odbrambena reakcija na ranjivost. Osoba razvija stav da je vrednija od drugih, da drugi nisu pouzdani, kompetentni ili zaslužni za poštovanje. Ovaj stav se može manifestovati kroz aroganciju, manipulaciju ili antisocijalne oblike ponašanja. Na međugrupnom nivou ova pozicija odgovara obrascu „Mi smo OK – Oni nisu OK“, koji se može smatrati psihološkom osnovom etnocentrizma i predrasuda.
4. Ja sam OK – Ti si OK: Ovo je jedina konstruktivna i zdrava životna pozicija. Osoba koja je razvila ovu poziciju poseduje samopoštovanje i poštovanje prema drugima, spremna je na saradnju, konstruktivne odnose i prihvatanje različitosti. Ova pozicija se ne mora razviti spontano, već se često dostiže kroz psihološki rad i emocionalno sazrevanje.

Životne pozicije se mogu menjati, iako ih pojedinac često doživljava kao trajne i neosporne istine o sebi i drugima. Terapeutski cilj u transakcionoj analizi jeste pomoći klijentima da prepoznaju svoju početnu poziciju i razviju autonomnu životnu poziciju „Ja sam OK – Ti si OK“, jer je to temelj za zdrave stavove, emocionalnu stabilnost i zadovoljavajuće odnose [27]. Ove pozicije nisu samo unutrašnje reprezentacije, već se reflektuju i u obrascima komunikacije, stilovima rešavanja konflikata, načinu izražavanja osećanja i oblikovanju socijalnih stavova. Osobe koje se dugoročno nalaze u destruktivnim pozicijama češće usvajaju negativne ili ekstremne stavove, što dodatno potvrđuje skriptne poruke koje su usvojene u ranom razvoju.

PRIMENA TRANSAKCIONE ANALIZE U ŠIREM DRUŠTVENOM KONTEKSTU: KA FLEKSIBILNOJ I PRIHVATAJUĆOJ DRUŠTVENOJ KLIMI

Ako se predrasude delimično formiraju i održavaju kroz skriptne mehanizme, onda se pojmovi transakcione analize mogu koristiti ne samo u individualnoj psihoterapiji, već i u radu sa grupama, u obrazovanju i u oblikovanju javnog diskursa. U nastavku se izdvaja nekoliko pravaca takve primene.

Prvi pravac možemo nazvati *Od „Ja sam OK – Ti si OK“ ka „Mi smo OK – Vi ste OK“*. Prevedena na međugrupni nivo, zdrava životna pozicija ne podrazumeva odricanje od sopstvenog etničkog ili nacionalnog identiteta, već istovremeno uvažavanje sopstvene i tuđe grupe. Ovakvo shvatanje u skladu je sa nalazima da zajednički nadređeni identitet, koji ne briše postojeće pripadnosti, doprinosi međugrupnom opraštanju i manjoj socijalnoj distanci [3]. Društvena klima zasnovana na poziciji „Mi smo OK – Vi ste OK“ podrazumeva da se pripadnost sopstvenoj grupi ne dokazuje omalovažavanjem drugih.

Drugi pravac se odnosi na *dekontaminaciju u obrazovnom kontekstu*. Jednostavan model ego-stanja može se koristiti u školskom i univerzitetskom radu kao alat za kritičko mišljenje. Učenici i studenti mogu učiti da razlikuju tri izvora sopstvenih uverenja o drugim grupama: ono što su čuli od roditelja i okoline (Roditelj), ono čega se plaše ili što ih ljuti (Dete) i ono što mogu proveriti na osnovu činjenica i ličnog iskustva (Odrasli). Pitanje „Odakle znam to što mislim o njima?“ predstavlja osnovu dekontaminacije i ne zahteva terapijski kontekst, već podržavajuću i bezbednu atmosferu u grupi.

Potrebno je spomenuti i *dozvolu, zaštitu i moć*. Crossman (1966) je opisala tri uslova terapijske promene: dozvolu (permission), zaštitu (protection) i moć (potency) [30]. Na društvenom nivou, dozvole predstavljaju protivtežu skriptnim zabranama, odnosno poruke poput „Smeš da misliš svojom glavom“, „Smeš da budeš blizak i sa onima koji su drugačiji“ ili „Pripadaš, i ne moraš to dokazivati odbacivanjem drugih“. Da bi takve poruke bile delotvorne, potrebna je zaštita, odnosno bezbedni okviri u kojima osoba može da isproba novo ponašanje bez straha od odbacivanja u sopstvenoj zajednici, kao i moć, odnosno kredibilitet onih koji dozvolu daju: nastavnika, roditelja, verskih i javnih ličnosti.

Isto tako, *ekonomija priznanja* može da bude jedan od važnih elemenata primene u TA orijentisanoj na društvene promene. Steiner (1971) je opisao „ekonomiju priznanja“ (stroke economy) kao skup nepisanih pravila koja određuju za šta ljudi u nekoj sredini dobijaju pažnju i priznanje [31]. U zajednicama u kojima se priznanje dobija za lojalnost sopstvenoj grupi i distancu prema drugima, predrasude se nagrađuju i održavaju. Promena društvene klime podrazumeva i promenu onoga što se priznaje: javno vrednovanje saradnje, razumevanja i zajedničkih postignuća pripadnika različitih grupa.

Takođe, Karpman (1968) je opisao *dramski trougao*, u kome učesnici naizmenično preuzimaju uloge Progonitelja, Žrtve i Spasioca [32]. Kolektivni narativi u postkonfliktnim društvima često su organizovani upravo po ovom obrascu: sopstvena grupa se doživljava isključivo kao Žrtva, druga kao Progonitelj, a politički akteri se nude kao Spasioci, pri čemu se uloge lako zamenjuju. Choy (1990) predlaže alternativu u vidu „*pobedničkog trougla*“, u kome se uloga Žrtve zamenjuje ranjivošću koja traži rešenje, uloga Progonitelja asertivnošću, a uloga Spasioca brigom koja ne oduzima drugima odgovornost [33]. Ovaj model može biti koristan u radu sa mladima, u medijskom opismenjavanju i u programima pomirenja, jer omogućava da se stradanje prizna bez trajne podele na „dobre“ i „loše“ grupe.

Možda najvažnije i najprimenjivije tehnike primene TA za uspostalvjanje balansa u postkonflikntom društvu se oslanjaju na *povezivanje sa programima međugrupnog kontakta*. Metaanalitički nalazi pokazuju da međugrupni kontakt pouzdano doprinosi smanjenju predrasuda [34], a istraživanja u Bosni i Hercegovini potvrđuju njegovu ulogu u međugrupnom opraštanju [3]. Perspektiva transakcione analize može doprineti razumevanju zašto kontakt ponekad ne daje očekivane efekte: ako je Odraslo ego-stanje kontaminirano, a pozitivna iskustva se potcenjuju, kontakt se lako tumači kao „izuzetak“. Zato se može pretpostaviti da bi programi kontakta bili delotvorniji kada bi uključivali i reflektivni rad na poreklu sopstvenih uverenja.

Treba naglasiti da navedeni predlozi imaju karakter teorijskih smernica. Primena koncepata TA na međugrupne odnose do sada je retko empirijski proveravana, pa bi buduća istraživanja trebalo da ispitaju, na primer, povezanost opaženih roditeljskih poruka o drugim grupama sa izraženošću etničke distance kod mladih, kao i efekte obrazovnih programa zasnovanih na modelu ego-stanja na međugrupne stavove.

OSLOBAĐANJE OD SKRIPTA

Oslobađanje od životnog skripta predstavlja jedan od osnovnih ciljeva psihoterapije u okviru transakcione analize. Skript, kao nesvesni životni plan zasnovan na ranim odlukama i roditeljskim porukama, funkcioniše kao ograničavajući okvir koji oblikuje ponašanje, emocije, očekivanja i stavove osobe tokom celog života. Iako je skript formiran u detinjstvu, on nastavlja da deluje automatski, sve dok ne postane predmet svesne analize i unutrašnje promene [4], [5]. Proces oslobađanja od skripta obuhvata više faza:

1. Svest o skriptu i prepoznavanje njegovih komponenti. Prvi korak u oslobađanju od skripta jeste osvešćivanje – identifikovanje skriptnih poruka, zabrana, ranih odluka i skriptne logike koja je utemeljena na pogrešnim uverenjima o sebi i drugima. Klijent u terapiji istražuje obrasce ponavljajućih ponašanja, emocija i stavova koji ukazuju na postojanje nesvesnog životnog plana.
2. Razotkrivanje ego-stanja i dekontaminacija Odraslog ego-stanja. Često je Odraslo ego-stanje osobe kontaminirano sadržajima Roditeljskog ego-stanja ili ego-stanja Dete, što

dovodi do iracionalnih stavova, predrasuda i emocionalno obojenih zaključaka. Dekontaminacija podrazumeva uklanjanje ovih uticaja kako bi Odraslo ego-stanje moglo racionalno i autonomno da funkcioniše [10]. Time se omogućava osobi da preispita svoje skriptne stavove i razvije nove, funkcionalnije obrasce mišljenja.

3. Donošenje novih odluka. U terapijskom procesu, klijent uz podršku terapeuta dolazi do nove životne odluke (redecision; [7](kojom menja ranije skriptne izbore. To je ključni trenutak prelaska iz pozicije „žrtve sopstvenog skripta“ u poziciju autonomnog pojedinca, koji samostalno oblikuje svoje vrednosti, stavove i izbore.
4. Razvijanje autonomije. Autonomija, u smislu transakcione analize, podrazumeva sposobnost za svesnost (awareness), spontanost i intimnost [35]. Autonomna osoba je u stanju da donosi odluke u skladu sa sopstvenim potrebama i realnošću, a ne na osnovu usvojenih skriptnih poruka. Oslobađanje od skripta znači uspostavljanje unutrašnje slobode, što dalje vodi ka razvoju konstruktivnih stavova prema sebi i drugima.
5. Zauzimanje pozicije „Ja sam OK – Ti si OK“. Jedan od znakova uspešnog oslobađanja od skripta jeste stabilno prihvatanje životne pozicije „Ja sam OK – Ti si OK“. To implicira izgradnju realističnih i samopodržavajućih stavova koji omogućavaju zdravu komunikaciju, emocionalnu stabilnost i ispunjene međuljudske odnose [27].

U konačnici, terapijski rad, bilo kroz transakcionu analizu ili druge modalitete, može voditi ka autonomnom životu, tj. životu u kojem pojedinac deluje iz slobode, odgovornosti i svesnosti, oslobođen nesvesnih ograničenja i destruktivnih skriptnih obrazaca. Zapravo, oslobađanje od skripta znači redefiniciju stavova i formiranje novih stavova koji će pojedincu omogućiti kvalitetniji život. Kada je reč o predrasudama, to znači da osoba postaje sposobna da pripadnike drugih grupa opaža kao pojedince, a ne kao nosioce skriptno usvojenih osobina.

ZAKLJUČAK

Razumevanje uticaja životnih scenarija na formiranje etničkih i nacionalnih predrasuda i stereotipa predstavlja značajan doprinos u proučavanju psiholoških i razvojnih mehanizama koji oblikuju međugrupne odnose. Transakciona analiza, kroz pojmove kao što su skript, skriptne poruke, kontaminacija Odraslog ego-stanja, potcenjivanje i životne pozicije, nudi teorijski okvir koji objašnjava kako rane porodične poruke i detetove odluke, donete u ranom razvoju, postaju osnova za kasnije formirane stavove prema sebi, drugima i svetu, uključujući i stavove prema pripadnicima drugih grupa. Analizom skriptnih zabrana i kontrazabrana uočava se da one često sadrže uslovljene poruke koje se internalizuju i postaju deo kognitivno-emocionalnog sistema ličnosti. Kada se takve poruke ukrste sa porukama o drugim grupama, nastaju skriptne generalizacije koje se održavaju kontaminacijom mišljenja, selektivnom percepcijom i potcenjivanjem iskustava koja bi ih mogla opovrgnuti.

U postkonfliktnim društvima, kakvo je društvo Bosne i Hercegovine i šireg regiona, poseban značaj ima transgeneracijski prenos predrasuda. Kroz kulturni Roditelj, porodične priče, ćutanje i episkriptni prenos nerazrešenih iskustava, deca mogu usvojiti strah i nepoverenje prema grupama sa kojima sama nisu imala negativna iskustva. Ovakvo tumačenje u skladu je sa empirijskim nalazima o sličnosti međugrupnih stavova roditelja i dece i sa analizama kolektivnih uverenja u dugotrajnim sukobima.

Psihološki razvoj pojedinca ne mora ostati determinisan skriptom. Proces osvešćivanja, dekontaminacije Odraslog ego-stanja i donošenja novih odluka pruža mogućnost za izlazak iz nesvesnog obrasca ponašanja i razvoj autonomnih, zrelih i fleksibilnih stavova. Na širem društvenom planu, pojmovi TA, kao što su životna pozicija prevedena na međugrupni nivo („Mi smo OK – Vi ste OK“), dekontaminacija kao alat kritičkog mišljenja, dozvola, zaštita i moć, ekonomija priznanja i izlazak iz dramskog trougla, mogu se koristiti u obrazovanju, radu sa mladima i javnom diskursu kao podrška fleksibilnoj, podržavajućoj i prihvatajućoj društvenoj klimi, kao i kao dopuna programima zasnovanim na međugrupnom kontaktu. Ovi predlozi zahtevaju empirijsku proveru, što predstavlja važan pravac budućih istraživanja.

Zaključno, stavovi koje pojedinac zauzima prema drugim grupama nisu uvek rezultat racionalne analize i slobodnog izbora, već često odraz nesvesnog životnog scenarija i kulturnog nasleđa. Upravo zato, razumevanje i dekonstrukcija tih nesvesnih obrazaca predstavljaju ključni zadatak kako za individualnu psihološku promenu, tako i za prevenciju rigidnih, stereotipnih i destruktivnih stavova u širem društvenom kontekstu.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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LIFE SCRIPTS AND THE FORMATION OF ETHNIC PREJUDICE AND STEREOTYPES: A TRANSACTIONAL ANALYSIS PERSPECTIVE IN A POST-CONFLICT SOCIAL CONTEXT

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ABSTRACT

This professional paper explores the role of the life script, a concept from transactional analysis (TA), in the formation and maintenance of ethnic and national prejudice and stereotypes, with particular reference to the post-conflict social context of the Western Balkans. Prejudice is understood as a specific type of attitude – a negative, emotionally charged and change-resistant attitude toward members of other groups – whose persistence cannot be fully explained by rational processes and social learning alone. The author examines how script injunctions, counterinjunctions and early decisions acquired within the family contribute to script-based generalisations about "others", and how these are maintained through contamination of the Adult ego state by Parent content, script logic and discounting. Special attention is given to the transgenerational transmission of prejudice – through the cultural Parent, family scripts and the episcript – in societies marked by armed conflict. The final part discusses how TA concepts may be applied in the wider social context (education, youth work, public discourse) to support a flexible, supportive and accepting social climate rather than rigidity, by translating the life position "I'm OK – You're OK" to the intergroup level ("We're OK – You're OK"). It is concluded that raising awareness of the script basis of prejudice may usefully complement social-psychological interventions based on intergroup contact, and that TA offers an accessible conceptual framework for preventive work aimed at reducing interethnic distance.

Keywords: life script, ethnic prejudice, stereotypes, transactional analysis, transgenerational transmission, post-conflict society.

EDUCATION
OBRAZOVANJE

UČENIČKA PERCEPCIJA PRIMJENE CAD-A U OSNOVNOŠKOLSKOM POUČAVANJU TEHNIČKOGA CRTANJA

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SAŽETAK

Tehničko crtanje sastavni je dio općeg tehničkog odgoja i obrazovanja, a time i kurikuluma predmeta Tehnička kultura u osnovnoj školi, uz preporuke za primjenu računalnih programa za crtanje i trodimenzijsko modeliranje. Time se otvara mogućnost primjene računalnog oblikovanja (CAD) u nastavi. Međutim, malo je poznato u kojoj se mjeri CAD primjenjuje u osnovnoj školi i s kojim ciljem. Stoga se u ovom radu empirijski razmatra primjena trodimenzijskoga CAD programa kao sredstva kojim učenici modeliraju i vizualiziraju tehničke tvorevine, razvijaju razumijevanje prostornih odnosa te povezuju trodimenzijski model s tehničkim crtežom u redovnoj nastavi. Istraživanje je provedeno na uzorku od 105 učenika petoga i sedmoga razreda osnovne škole koji su sudjelovali u intervenciji. Cilj je ispitati učeničku percepciju primjene CAD-a pri poučavanju tehničkoga crtanja s obzirom na razumljivost sadržaja, vlastitu uspješnost, zanimljivost nastave te opažene prednosti i poteškoće takvoga pristupa. Nalazi istraživanja upućuju na to da računalno oblikovanje može pridonijeti razvoju i koncipiranju motivirajućega i metodički prihvatljivoga pristupa učenju tehničkoga crtanja, što pridonosi pedagoškoj opravdanosti i mogućnostima primjene CAD-a u nastavi Tehničke kulture u osnovnoj školi.

Ključne riječi: CAD, tehničko crtanje, tehnički odgoj i obrazovanje, osnovna škola, učenička percepcija.

UVOD

Tehničko crtanje i nastava

Tehničko crtanje je univerzalni jezik vizualno-grafičke komunikacije koji omogućuje prijenos ideja potrebnih za izradu tehničke tvorevine neovisno o verbalnom jeziku i kulturnom kontekstu

[1], [2]. Prenoseći informacije od projektiranja i proizvodnje, preko plasmana, primjene i održavanja, pa i do zbrinjavanja, tehnički crteži predstavljaju temeljni komunikacijski medij kroz životni ciklus proizvoda [3], [4], [5]. Stoga tehničko crtanje nije samo profesionalna vještina nego i element opće tehničke pismenosti i sastavnica općeg tehničkoga odgoja i obrazovanja. U Republici Hrvatskoj učenici usvajaju ishode i sadržaje tehničkog crtanja kroz nastavu obveznog predmeta Tehnička kultura od 5. razreda osnove škole za što se predmetnim kurikulumom preporučuje primjena računalnih programa za crtanje i trodimenzijsko modeliranje [6], a postoji i obveza učitelja za uključivanjem IKT-e u nastavu kroz međupredmetne teme. Time se otvara mogućnost primjene računalnog oblikovanja (CAD) [7], ali nije poznato koliko se, na koji način i s kojim ciljem CAD koristi u nastavi Tehničke kulture. Štoviše, nekoliko je otežavajućih uvjeta za primjenu CAD-a u redovnoj nastavi Tehničke kulture poput vrlo kratkog vremena (35 sati godišnje), upitnih materijalnih uvjeta (u smislu raspoloživosti potrebnih računala i softvera) te neizostavni i neistražen uvjet stručne i metodičke pripremljenosti učitelja. Što se tiče utvrđenih preferencija učenika, istraživanja pokazuju izražen interes učenika za tehničko crtanje u 5. razredu, a zatim kroz više razrede postupno usmjeravanje interesa prema drugim područjima [8], [9] uz ustrajno izražen interes prema praktičnom radu i tehnološkim aktivnostima poput primjene IKT-a. Također, učenici cijene iskustvo tradicionalnog crtanja u smislu prenosivih vještina, osobnih postignuća i uživanja [10]. S druge strane, nerijetke su teškoće kod dijela učenika u razumijevanju i provedbi tehničkoga crtanja što je vidljivo čak i među studentima tehničkih znanosti [11], [12], [13], [14], [15]. I dok postoje brojna istraživanja s učenicima srednjih škola i studentima, manjak je istraživanja o učenju i poučavanju tehničkog crtanja s uzrastima viših razreda osnovne škole [11]. Stoga i pojedina istraživanja pozivaju na razvoj novih pedagoških metoda koje spajaju teoriju s digitalnom praksom i uvođenje tehnologija poput 3D modeliranja kao ključnih alata u modernizaciju nastave [11]. Ovakav pristup smatra se presudnim u kvalitetnoj pripremi mladih za buduće izazove na tržištu rada te kao informirane potrošače.

Sve navedeno upućuje na potrebu razmatranja didaktičkih rješenja koja povezuju aktivan rad, razumijevanje i suvremene alate poput primjene računalnog oblikovanja u osnovnoškolskom poučavanju tehničkoga crtanja kao i razmatranje učeničke percepcije te primjene.

Računalno oblikovanje i nastava

Tijekom proteklih šest desetljeća u tehničkom dokumentiranju i projektiranju gotovo je neizostavna postala primjena računalnog oblikovanja koje se potom postupno uvodilo u visokoškolsko te srednjoškolsko tehničko obrazovanje. Od kraja prošlog stoljeća nalazimo i više pokušaja uvođenja CAD-a u osnovnoškolsko obrazovanje u nekim državama svjeta [16], [17], [18] usmjerenih poticanju kreativnosti, upoznavanju učenika sa suvremenim tehnologijama dizajniranja i proizvodnje te razvoju prostornih vještina [19], uglavnom bez izričite usmjerenosti na norme i vještine tehničkoga crtanja. Uz iskazanu početnu motiviranost učenika i entuzijazam učitelja [20], [18] višestruko je prepoznata potreba za unaprijeđenjem didaktičkih pristupa i za stručnim usavršavanjem učitelja [18], [21]. Tijekom vremena je primjena CAD-a u osnovnom obrazovanju različito (ne)prihvaćana i (ne)provođena, determinirana različitim uvjetima poput (ne)navođenja u kurikularnim dokumentima, raspoloživim vremenom, osposobljenosti i spremnosti učitelja te dostupnošću računala i softvera. U rijetko provedenim istraživanjima nalazi su dosljedni: učenici iskazuju vrlo pozitivan stav prema CAD-u, visoku razinu interesa, motivacije i zadovoljstva [22] te percepcije važnosti i korisnosti za obrazovanje i buduću karijeru [10]. Nalazi također pokazuju da učitelji općeg tehničkog obrazovanja u različitim zemljama, postupno i na različite načine, a nerijetko kroz izvannastavne aktivnosti i različite projekte, primjenjuju računalno oblikovanje. No, kao relativno nov element poučavanja, malo se zna o tome što se uči i poučava kao i o svrsi koju učitelji žele postići tim poučavanjem. Saznanja ukazuju da programe za računalno oblikovanje učitelji primjenjuju uz različita ciljana postignuća u četiri kategorije: rukovanje softverom, upotreba gotovih modela, izrada i kreiranje tiskanih modela te projektiranje/modeliranje. Izrada dokumentacije, bez preciznijeg određenja, navodi se u razradi tri kategorije, a ne u kategoriji rukovanja softverom [23]. Ukratko, navedene kategorije ukazuju na poučavanje primjene CAD-a i

na poučavanje uz primjenu CAD-a te unaprjeđenje nastave što je osnova za daljnje rasprave istraživača i edukatora [23], poglavito u kontekstu poučavanja tehničkoga crtanja [24].

Uvođenje računalno oblikovanja nikako ne smije značiti zanemarivanje tradicionalnih metoda tehničkog crtanja s učenicima, jer rad s priborom i skiciranje izravno potiče kognitivni angažman, dublje razumijevanje i preciznost pridonoseći razvoju prostornih vještina i sposobnosti prenosivih i neophodnih i u digitalnom dobu [25]. Stoga se tradicionalni postupci tehničkoga crtanja skiciranjem i uporabom klasičnog pribora smatraju neizostavnim temeljom koji omogućuje brže i kvalitetnije ovladavanje digitalnim alatima te razvija disciplinu i umjetničko umijeće [10] i treba prethoditi uvođenju CAD alata u osnovnoškolskom obrazovanju. Također, inženjerski predavači naglašavaju važnost razumijevanja teorije tradicionalnog crtanja prije prelaska na CAD kako bi se osigurao kontinuitet u obrazovanju [13], te upozoravaju na potrebu primjene modernih tehnologija uz oprez, jer nedostatak baze može uzrokovati ozbiljne poteškoće u kasnijem tehničkom obrazovanju [14]. Sami učenici također podržavaju kombinaciju tradicionalnog crtanja i CAD-a [10]. Iako CAD nudi brzinu i preciznost, ručno crtanje ostaje cijenjeno zbog osjećaja osobnog postignuća i dubljeg razumijevanja tehničke komunikacije.

Slijedom evolucije CAD-a u okolnostima četvrte industrijske revolucije i iskazanog interesa za softverom kao uslugom (SaaS) [26], u proteklih desetak godina prepoznate su i prednosti primjene CAD-a u oblaku za rad s učenicima i studentima [24], [27], [28], [29]. Štoviše, zaključak je da računalno oblikovanje u oblaku trebaju prihvatiti i inženjerski edukatori [30]. Početno prepoznate pogodnosti primjene CAD-a u oblaku za obrazovanje potvrđuju se i danas. U smislu zahtjevnosti za hardver, niža je potreba za naprednom grafičkom i procesorskom snagom računala te za pohranjivanjem podataka čime je financijski veća pristupačnost institucijama i pojedinom korisniku. U smislu instalacije i ažuriranja softvera i licenciranja, instalacija ne postoji (za neke CAD programe), a ažuriranje verzija i održavanje automatski se odvija u oblaku čime izostaje potreba za održavanjem i dodatnim financijskim zahtjevima za najnovije inačice softvera. U metodičkom i didaktičkom smislu, CAD u oblaku omogućuje istodobnu suradnju više sudionika na mreži. Pritom su u parametrijskom CAD-u postupci oblikovanja i njihov slijed prikazani u stablu značajki, što svakom sudioniku omogućuje uvid u proces oblikovanja modela, a učitelju praćenje trenutačnog rada i pregled prethodnih postupaka svakog učenika. Nasuprot svemu navedenom, ključan uvjet za neometan rad u oblaku je stabilna internetska veza.

Premda malobrojna, istraživanja o primjeni CAD-a s osnovnoškolskim uzrastom donose i preporuke konkretnih softverskih rješenja. Primjerice, Brink i suradnici [23] navode Tinkercad i SketchUp kao CAD programe u oblaku prikladne za tehnološko obrazovanje u višim razredima osnovne škole. Wong i Shih [31] su izdvojili Tinkercad i Onshape pri čemu Tinkercad opisuju najprikladnijim za osnovnoškolce i početnike u učenju CAD modeliranja i stvaranju vlastitog dizajna jednostavnim koracima, dok Onshape smatraju najboljim izborom za napredne učenike i srednjoškolce jer uključuje različite napredne značajke za različite razine korisnika. Međutim, Tinkercad nema mogućnost generiranja normiranih tehničkih crteža za oblikovane modele što je u ovome istraživanju isključujući nedostatak budući da je svrha primjene CAD-a povezana upravo s izradom tehničkih crteža i primjenom normi. Također, pojedini autori preporučuju da se umjesto jednostavnijih rješenja primjenjuju napredni industrijski alati jer se njima bolje i potpunije priprema učenike kao buduće informirane potrošače i za stvarne profesionalne izazove buduće radne snage [32]. Usporedbe nekih istaknutih profesionalnih CAD alata pokazale su da Onshape ima značajno intuitivnije sučelje i bolje mogućnosti suradnje te se brže upoznaje kroz rad [28], [29], [33]. Također, Onshape omogućuje formiranje virtualnih učionica i dodjeljivanje učenika u virtualne razredne odjele i grupe, kao i neki drugi programi, ali je ipak još uvijek jedini profesionalni CAD bez instalacije na računalo [33].

Od početnih uvođenja CAD-a u osnovnoškolsku nastavu pokazalo se da je za učinkovito poučavanje ključna primjerena obuka i priprema učitelja. Ona treba biti znatno šira od osposobljavanja za rad sa softverom i upoznavanja s njegovim funkcioniranjem i mogućnostima jer samo tehničko poznavanje alata nije dovoljno za kvalitetnu nastavu. Naglasak treba biti na pedagoškim strategijama, odnosno promišljanju što, kako i s kojim ciljem približiti i predstaviti

učenicima [21]. Također, budući da učenici različitom brzinom usvajaju sadržaje, učitelj treba voditi računa i o prilagodbi tempa poučavanja. Stoga je prepoznato da konvencionalni odnos u kojem učitelj vodi, a učenik slijedi, nije održiv već demotivacijski. U takvom pristupu učenici brzo gube interes i zbog toga što nemaju mogućnosti za iskazivanje osobne kreativnosti [18], [32]. Kao optimalan model pokazala se kombinacija početnog učiteljskog vođenja kroz sučelje i specifične funkcije te slobodnijeg dijela nastave koji potiče kreativnu aktivnost učenika i istraživanje [18], [32], [34]. Važna je dostupnost fizičkih modela [34], čak i u radu sa starijim uzrastima, jer opipljivi predmeti olakšavaju razumijevanje složenih prikaza aktiviranjem vizualnih, taktilnih i prostornih osjetila učenika. Valera i sur. [35] stoga preporučuju snažnije uključivanje fizičkih nastavnih pomagala i praktičnih aktivnosti uopće u kurikulum tehničkoga obrazovanja, a osobito u poučavanju tehničkoga crtanja. Njihovi nalazi također upućuju na važnost primjene boja, koje učenicima olakšavaju određivanje orijentacije pojedinih ploha i povezivanje dvodimenzijskih prikaza s trodimenzijskim objektom. Sličnu ulogu boje mogu imati i u računalnom modelu, gdje različito obojane plohe olakšavaju uočavanje odnosa među projekcijama i prepoznavanje izgleda tijela iz različitih smjerova [19], [24], [36]. Prikaz plašteva tijela i primjena transparentnosti dodatno olakšavaju dekompoziciju objekta na osnovne dijelove i razumijevanje njegove strukture. Korisnima su se pokazali i unaprijed pripremljeni didaktički materijali koji učenicima omogućuju napredovanje vlastitim tempom i ponavljanje koraka prema potrebi. Uspješni su i pristupi koji učenike potiču na projektiranje uz izbjegavanje određenih funkcionalnosti softvera [18] te učenje kroz unaprijed izrađenu didaktičku igru [32]. Što se tiče suradničkog učenja, pokazalo se da zajednički rad u parovima i rasprava povećavaju učeničku motivaciju i kreativnost, podižu samopouzdanje te potiču dublje razumijevanje, pružajući učenicima priliku za učenje iz postupaka drugih i razmjenu ideja [32], [34], [37]. Međutim, ako je učenicima u paru dostupno samo jedno računalo, postoji mogućnost da jedan učenik dominira u interakciji sa softverom, dok drugi ostaje u pasivnoj ulozi, što može ograničiti razvoj razumijevanja i kasniju primjenu naučenoga [34]. Tijekom cjelokupnog procesa ključno je poticanje učenika na isprobavanje i prihvaćanje pogrešaka kao nužnog dijela učenja [38]. U pojedinim CAD softverima, uključujući Onshape, parametrijsko oblikovanje omogućuje jednostavne izmjene prethodno oblikovanih značajki te olakšava inoviranje i eksperimentiranje uz minimalan rizik od posljedica pogrešnih postupaka [37], [39]. Ukratko, učinkovit pristup poučavanju CAD-a u osnovnoj školi zahtijeva pažljivo balansiranje između strukturiranog vođenja i autonomije učenika, uz primjerenu pripremu učitelja, prilagodbu procesa učenja te stvaranje uvjeta za istraživanje, eksperimentiranje i suradnju.

Specifično nazivlje u računalnom oblikovanju može biti jedna od prvih prepreka u poučavanju i učenju. CAD programi obiluju naredbama i pojmovima koji su učenicima novi ili imaju ponešto drugačije značenje od prethodno poznatog, što ih može zbunjivati [38]. Među njima su izrazi poput „skica", „ravnina crtanja", „orijentacija" i „izvlačenje/ekstruzija". Možda je više od samog jezičnog značenja važno da učenici te izraze mogu smjestiti u kontekst modeliranja te da ih pokušavaju primjenjivati bez straha od pogreške. To je posebno važno za učenike koji već maju niska očekivanja od vlastite uspješnosti te ih slabije razumijevanje jezika može dodatno demotivirati. Dodatno opterećenje može imati specifično nazivlje CAD-a na engleskom jeziku.

Uz ohrabrivanje učenika na pokušaje i usmjerenost na proces rada nadovezuje se pitanje treba li u središtu vrednovanja biti proces razvoja rješenja ili samo konačno rješenje. Sudjelovanje u procesu trebalo bi imati važnu ulogu pri vrednovanju jer učenik u nastojanju da postigne što kvalitetnije rješenje promišlja i provodi višestruke iteracije modela, čime se potiče njegov daljnji razvoj [18], [37]. Pritom i neuspješni pokušaji mogu imati značajnu vrijednost za proces učenja [38]. Slijed postupaka tijekom oblikovanja modela, zabilježen u stablu značajki, učitelju omogućuje praćenje i naknadni pregled procesa učenikova rada, a time i uvid u razvoj njegova mišljenja.

Cilj i istraživačka pitanja

Slijedom prethodnih zapažanja, u ovome istraživanju CAD u nastavi nije cilj ni predmet poučavanja nego didaktičko sredstvo u funkciji poučavanja tehničkoga crtanja. Dakle, didaktička

se vrijednost primjene CAD-a promatra ponajprije kroz mogućnosti brze vizualizacije promatranih tijela, generiranja njihovih tehničkih crteža i uočavanja odnosa među plohama i projekcijama kao i susret s "profesionalnom" primjenom nazivlja i normi tehničkoga crtanja, sve uz pokušaje uvažavanja i primjene utvrđenih postavki i preporuka. Cilj ovoga rada je ispitati učeničku percepciju primjene CAD-a pri poučavanju tehničkoga crtanja s obzirom na razumljivost sadržaja, vlastitu uspješnost, zanimljivost te opažene prednosti i poteškoće takvoga pristupa. Na temelju dosadašnjih spoznaja o poučavanju tehničkoga crtanja, primjeni računalnoga oblikovanja te organizacijskim i metodičkim aspektima nastavnoga procesa, oblikovana su sljedeća istraživačka pitanja:

IP1: Kakvi su stavovi učenika prema tehničkome crtanju?
IP2: Kakvi su stavovi učenika prema primjeni računalnog oblikovanja pri poučavanju tehničkoga crtanja?
IP3: Kako učenici procjenjuju različite organizacijske i metodičke aspekte primjene računalnog oblikovanja pri poučavanju tehničkoga crtanja?

METODOLOGIJA

Uzorak

U anketnom istraživanju sudjelovalo je 105 od 125 učenika petih i sedmih razreda iz triju škola odabranih prema kriteriju dostupnosti. Uzorak je bio prigodan i obuhvatio je zatečene skupine učenika, a nastavu su izvodila dva učitelja pri čemu je jedan poučavao u jednoj, a drugi u dvije škole (Tablica 1). Anketiranje je provedeno nakon intervencije tijekom koje je u redovnoj nastavi Tehničke kulture primijenjeno računalno oblikovanje pri poučavanju sadržaja tehničkoga crtanja.

Tablica 1. Raspodjela sudionika po učitelju, razredu i spolu

Razred	Učitelj	Dječaka	Djevojčica	Ukupno
peti	Učitelj 1	13	15	28
	Učitelj 2	14	5	19
	Ukupno peti	**27**	**20**	**47**
sedmi	Učitelj 1	16	19	35
	Učitelj 2	13	10	23
	Ukupno sedmi	**29**	**29**	**58**
Ukupno		**56**	**49**	**105**

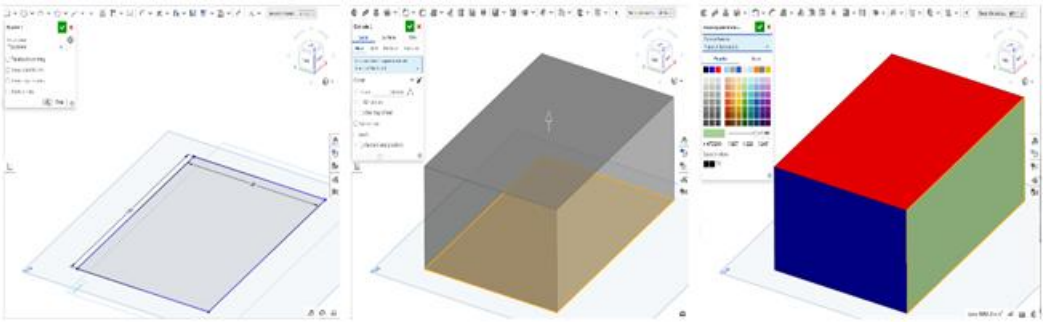
Etički aspekti istraživanja

Istraživanje je provedeno uz suglasnost školskih odbora i ravnatelja škola uključenih u provedbu. Sudjelovanje učenika bilo je dobrovoljno, uz prethodno pribavljenu informiranu privolu roditelja odnosno skrbnika. Podaci su prikupljeni i obrađeni anonimno te korišteni isključivo u istraživačke svrhe.

Intervencija

Učenici su zadane sadržaje tehničkog crtanja prvo upoznavali koristeći se tradicionalnim alatima i postupcima crtanja tijekom 5-6 nastavnih sati. Potom su te sadržaje utvrđivali i proširivali kroz aktivnosti u CAD-u tijekom 6 nastavnih sati (tri susreta po dva školska sata, 3x90'). Radili su u parovima koristeći jedno računalo i CAD Onshape odabran kao obrazovno okruženje u oblaku koje učeniku omogućuje brzu izradu i jednostavnu manipulaciju 3D modela, a učitelju omogućuje uvid u aktivnost i rad učenika u stvarnom vremenu i naknadno. Aktivnosti za učenike su osmišljene tako da slijede konceptualnu progresiju snalaženja u digitalnom radnom prostoru, od orijentacije i navigacije, preko oblikovanja jednostavnog tijela i formiranja pravokutnih i

prostornih projekcija tijela, do formiranja mreže tijela tj. plašteva (5. razred) i formiranja presjeka tijela s rupom (7. razred).



Slika 1. Koraci oblikovanja digitalnog modela kvadra

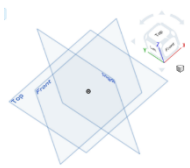
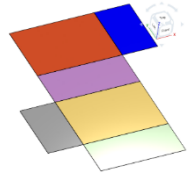
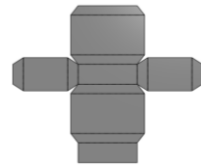
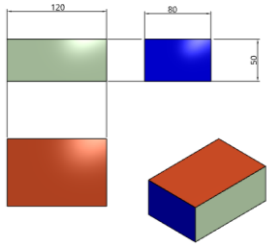
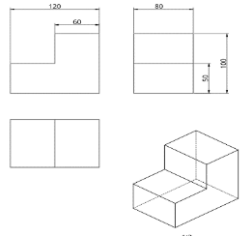
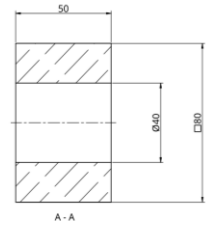
Tijekom prvog susreta, s obziron na prethodno utvrđen izostanak iskustva učenika s trodimenzionalnim modeliranjem, naglasak je za oba uzrasta na učiteljskom vođenju. Učenici su upoznavali korisničko sučelje programa i radnog prostora, kretanje tj. navigaciju radnim prostorom istovremeno usvajajući specifično nazivlje poput rotacije, pomicanja i zumiranja te uključivanje i isključivanje vidljivosti elemenata poput ortogonalnih ravnina i ishodišta. Konkretno oblikovanje prvog modela započinje crtanjem pravokutne baze zadanih dimenzija drvenog kvadra koji je učenicima fizički dostupan, zatim formiranje 3D modela tog kvadra izvlačenjem početne plohe do zadane visine nakon čega slijedi dodijeljivanje različitih boja modelu (Slika 1). Nakon promatranja modela iz različitih smjerova (i uz praćenje položaja navigacijske kocke), pristupa se izradi tj. generiranju pravokutnih projekcija modela. Pokretanjem izrade tehničkih crteža učenici se susreću s oznakama i odabirom normi poput ISO formata papira i mjerila crtanja. Pri postavljanju pravokutnih projekcija prepoznaje se definiranost njihovih uzajamnih položaja što je dodatno izraženo različitim bojama, a vidljivost boja na digitalnom tehničkom crtežu učenici mogu uključivati i isključivati. Boljem razumijevanju odnosa pravokutnih projekcija može pridonijeti postavljanje izometrijskog prikaza, poglavito uz uključivanje i isključivanje vidljivosti boja i zaklonjenih bridova. Stoga su izometrijski prikaz razmatrali i učenici 5. razreda premda je predmetnim kurikulumom zadan tek u 7. razredu. Postavljene pravokutne projekcije učenici potom kotiraju pri čemu prepoznaju primjenu normi kotiranja poput izgleda mjernica, položaj i vrijednosti kotnih brojeva te odgovarajuće vrste crta.

U drugom susretu učenici kroz ponavljanje prethodnih aktivnosti i sadržaja oblikuju novi primjer modela oblika kvadra nakon čega uz vođenje učitelja primjenjuju naredbe za formiranje mreže te samostalno odabiru izgled mreže zadanog tijela, a potom za oblikovano tijelo i odabrani izgled plašta formiraju tehničke crteže u prirodnoj veličini (učenici 5. razreda) ili odabranom mjerilu (učenici 7. razreda). Uz djelomično definirane uvjete, učenici u drugom zadatku dorađuju početni model proširivanjem ili rezanjem u formu krnjeg kvadra za kojeg također oblikuju mreže prema svom odabiru i formiraju pripadajuće tehničke crteže. Također, ovisno o brzini rada, učenici početni model proširuju dodatnim modelom oblikujući sklop dva uglata tijela za koji generiraju tehničke crteže (pravokutne i prostorne prikaze).

U trećem susretu učenici ponavljaju i proširuju prethodne vještine i znanja provodeći zadatak prema pisanim uputama i dokumentaciji kojima je djelomično definiran budući model, a dio je otvoren za slobodno oblikovanje učenika. Učenike 5. razreda zadatak usmjerava na kreativno oblikovanje tijela uz primjenu naredbe za rezanje bridova te formiranje mreže kojom bi se taj model i fizički izradio od papira. Učenike 7. razreda zadatak usmjerava prema oblikovanju tijela s provrtom za koje treba generirati puni presjek i druge tehničke crteže uz primjenu simbola za krug i kvadrat.

Struktura intervencije prikazana je na Tablici 2.

Tablica 2. Struktura intervencije po susretima i razredima

Prvi susret, 1. i 2. sat	Drugi susret, 3. i 4. sat	Treći susret,5. i 6. sat
Radno okruženje i navigacija, model kvadra i projekcije (5. i 7. r)	Mreža kvada (5. r), izometrija krnjeg kvadra (7. r)	Modeli uglatih tijela (5.r), provrti i presjeci (7.r)
		
		

Instrument

Instrument istraživanja bio je postintervencijski upitnik za učenike sastavljen od dviju skala i pojedinačnih čestica. Skalu od šest čestica činile su tvrdnje o poučavanju tehničkoga crtanja, a skalu od četiri čestice tvrdnje o primjeni računalnoga oblikovanja pri poučavanju tehničkoga crtanja. Od pojedinačnih čestica, dvije su se odnosile na postojanje prethodnog iskustva učenika s računalnim oblikovanjem izvan redovne nastave, a uz njih je otvorenom česticom prikupljen naziv programa koji su učenici naveli kao svoje prethodno iskustvo. Tri čestice odnosile su se na rad u paru na jednom računalu, četiri na organizacijske i metodičke aspekte nastave tehničkoga crtanja, a jednom česticom ispitivane su preferencije učenika rangiranjem nastavnih aktivnosti. Osim otvorene čestice i pitanja o rangiranju, sve su tvrdnje procjenjivane na petostupanjskoj Likertovoj ljestvici od 1 („uopće se ne slažem“) do 5 („u potpunosti se slažem“). Upitnik su izradili autori istraživanja na temelju relevantne literature i višegodišnjega iskustva u poučavanju tehničke kulture.

Statistička obrada podataka

Prikupljeni podaci analizirani su u programu IBM SPSS Statistics 22 primjenom deskriptivne i inferencijalne statistike. Deskriptivna statistika obuhvaćala je aritmetičku sredinu (M), standardnu devijaciju (SD), medijan (Md), frekvencije i postotke. Negativno formulirane čestice su rekodirane prije izračuna ukupnih rezultata skala. Pouzdanost skala procijenjena je Cronbachovim koeficijentom α. Normalnost distribucije rezultata skala provjerena je Shapiro–Wilkovim testom i grafičkim prikazima distribucije. Za usporedbu rezultata skala između skupina primijenjen je t-test za nezavisne uzorke, dok su razlike u odgovorima na pojedinačne Likertove čestice analizirane Mann–Whitneyjevim U testom. Povezanost dviju skala ispitana je Pearsonovim i Spearmanovim koeficijentom korelacije, a razlike u rangovima nastavnih aktivnosti Friedmanovim testom uz naknadne Wilcoxonove testove. Razina statističke značajnosti određena je na $p < 0,05$.

REZULTATI

Po pitanju stavova učenika prema tehničkom crtanju, formirana je skala od šest čestica (Tablica 3) i pokazala je zadovoljavajuću unutarnju konzistentnost (Cronbach α = 0,742).

Tablica 3. Deskriptivni pokazatelji čestica skale stavova učenika prema tehničkom crtanju

Tvrdnja	M	Md	SD	4-5(%)	1-2(%)	N
Razumijem sadržaje i namjenu tehničkoga crtanja	3,81	4	0,80	63,8	3,8	105
Tehničko crtanje nikako ne volim*	2,40	2	1,28	20,0	60,0	105
Tehničke crteže na nastavi crtam s lakoćom i brzo	3,62	4	0,89	57,1	8,6	105
Tehničke crteže crtam točno i precizno	3,69	4	1,01	54,8	9,6	104
Tehnički crtež uspješno crtam prema tekstualnom opisu	3,78	4	0,97	59,1	9,5	105
Tehničko crtanje mi nije zanimljivo, s ili bez primjene računala*	2,03	2	1,16	13,3	76,2	105
Ukupan rezultat skale	3,75	3,83	0,68	-	-	104

* Negativno formulirana čestica; niža vrijednost označava pozitivniju procjenu, za izračun ukupnog rezultata skale primjenjeno je rekodiranje.
**Postotak 4–5 označava udio odgovora „uglavnom se slažem" i „u potpunosti se slažem", a postotak 1-2 udio odgovora "uopće se ne slažem" i "uglavnom se ne slažem" među valjanim odgovorima za pojedinu česticu.

Prosječan rezultat skale iznosio je M = 3,75; SD = 0,68 i medijan Md = 3,83 što upućuje na pozitivan stav učenika prema tehničkom crtanju. Normalnost raspodjele procijenjena je primjenom Shapiro–Wilkova testa i vizualnim pregledom raspodjele (Q–Q dijagram, histogram i boxplot). Obje provjere upućivale su na prihvatljivu normalnost raspodjele (Shapiro–Wilk, p = 0,073). Jednouzoračkim t-testom utvrđeno je da se prosječna vrijednost skale statistički značajno razlikuje od neutralne vrijednosti 3, t(103) = 11,30, p <0 ,001. Dobivena vrijednost Cohenova d (d=1,11) upućuje na veliku veličinu učinka. Ukupni rezultati upućuju na izraženo pozitivno stavove ispitanika prema tehničkome crtanju.

Razlike u rezultatima skale prema dobi, spolu te prema učitelju ispitane su t-testom za nezavisne uzorke. Prosječne vrijednosti bile su vrlo slične te nijedna od utvrđenih razlika nije bila statistički značajna, uz dvije zanemarive i jednu malu veličinu učinka (Tablica 4). Malo je viša prosječna vrijednost kod učenika petoga razreda nego kod učenika sedmog razreda, a zanemarivo viša kod dječaka nego kod djevojčica te kod učenika učitelja 2 nego kod učenika učitelja 1.

Tablica 4. Rezultati t-testova za nezavisne uzorke za skalu stavova prema tehničkome crtanju

Skupina	M	SD	t(df)	p	d	N
Učenici 5. razreda	3,83	0,514	1,110(97,3)	0,270	0,21	47
Učenici 7. razreda	3,69	0,787				57
Dječaci	3,77	0,707	0,239(102)	0,812	0,05	55
Djevojčice	3,73	0,651				49
Učenici učitelja 1	3,74	0,605	0,274(102)	0,785	0,05	62
Učenici učitelja 2	3,77	0,782				42

Radi utvrđivanja razlika za pojedine čestice ove skale rezultati su također analizirani t-testom za nezavisne uzorke prema dobi, spolu i učitelju. Jedina čestica uz koju su se pokazale statistički značajne razlike je Tehničko crtanje nikako ne volim, i to s obzirom na dob (p=0,012) i s obzirom na učitelja (p=0,020). Učenici petoga razreda iskazali veće neslaganje s tvrdnjom (M=2,06, SD=1,03) od učenika sedmog razreda (M=2,67, SD=1,27), te učenici učitelja 2 (M=2,05; SD 1,17) od učenika učitelja 1 (M=2,63; SD=1,36).

Iskustvo s računalnim oblikovanjem prije primjene u nastavi (Tablica 5) iskazao je samo jedan učenik navodeći Korni, što nije CAD, već edukativni program za grafičko programiranje. Šest učenika dalo je neutralan odgovor, pri čemu su dva učenika navela Onshape, a jedan

Tinkercad, dok je 91 odgovor bio negativan. Primjenu računalnog oblikovanja u slobodno vrijeme nakon prve primjene u nastavi navela su dva učenika, dok su ostali odgovori bili negativni. Rezultati pokazuju da među ispitanim učenicima gotovo u potpunosti izostaje prethodno iskustvo s CAD-om i njegova primjena izvan nastave.

Tablica 5. Postojanje iskustva učenika s računalnim oblikovanjem izvan nastave

Tvrdnja	M	Md	SD	4-5(%)	1-2(%)	N
Imam iskustva s računalnim oblikovanjem prije nego smo ga koristili u nastavi Tehničke kulture	1,19	1	0,59	1,0	92,9	98
Nakon prvog iskustva računalnog oblikovanja na satu primjenjujem ga i u slobodno vrijeme	1,23	1	0,60	1,9	98,1	103

Skala stavova učenika prema primjeni računalnog oblikovanja u poučavanju tehničkog crtanja sastoji se od četiri čestice (Tablica 6) i pokazala je zadovoljavajuću unutarnju konzistentnost (Cronbach $\alpha = 0{,}750$).

Tablica 6. Deskriptivni pokazatelji čestica skale stavova učenika prema računalnom oblikovanju

Tvrdnja	M	Md	SD	4-5(%)	1-2(%)	N
Tehničko crtanje mi je zabavnije uz računalno oblikovanje	3,55	4	1,26	50,5	17,4	103
Oblikovanje računalom mi pomaže u razumijevanju tehničkih crteža	3,37	4	1,21	51,4	21,9	105
Računalno oblikovanje je prekomplicirano, bolje je raditi samo skice i priborom*	2,30	2	1,24	21,4	58,3	103
Želim da se tehničko crtanje uči uz primjenu računala i drugih godina.**	3,48	4	1,40	53,5	24,8	101
Ukupan rezultat skale	3,55	3,75	0,96	-	-	97

* Negativno formulirana čestica; niža vrijednost označava pozitivniju procjenu, za izračun ukupnog rezultata skale primjenjeno je rekodiranje.
** Tvrdnja je bila razvojno prilagođena dobi učenika. Učenici 5. razreda odgovarali su na tvrdnju „Želim da u višim razredima tehničko crtanje radimo uz primjenu računala", a učenici 7. razreda na tvrdnju „Volio bih/voljela bih da smo u 5. i 6. razredu koristili računalo u nastavi tehničkoga crtanja".

Prosječan rezultat skale iznosio je $M = 3{,}55$; $SD = 0{,}96$ i medijan $Md = 3{,}75$, što upućuje na pozitivne stavove učenika prema primjeni računalnog oblikovanja. Normalnost raspodjele procijenjena je Shapiro-Wilkovim testom te pregledom Q–Q dijagrama, histograma i boxplota. Iako je Shapiro–Wilkov test ukazivao na odstupanje od normalne raspodjele ($p < 0{,}05$), vizualni pregled nije pokazao izražena odstupanja. Stoga je primjenjen jednouzorački t-test koji je pokazao da je rezultat statistički značajno viši od teorijske sredine skale od 3, $t(96) = 5{,}66$, $p < 0{,}001$. Radi potvrde nalaza provedena je i dopunska neparametrijska provjera Wilcoxonovim testom za jedan uzorak koja je potvrdila odstupanje od vrijednosti 3 u pozitivnom smjeru, $p < 0{,}001$. Dobivena vrijednost Cohenova d ($d=0{,}53$) upućuje na umjerenu veličinu učinka. Rezultati upućuju na pozitivne stavove učenika prema primjeni računalnog oblikovanja pri poučavanju tehničkog crtanja.

Rezultati t-testova za nezavisne uzorke (Tablica 7) u rezultatima ove skale nisu pokazali statistički značajne razlike u stavovima učenika prema računalom oblikovanja s obzirom na dob ni spol, uz male veličine uzorka. Međutim, utvrđena je statistički značajna razlika između učenika različith učitelja pri čemu su učenici prvog učitelja iskazali pozitivnije stavove prema računalnom oblikovanja nego učenici drugog učitelja, $t(95) = 3{,}50$, $p = 0{,}001$; Cohenov $d = 0{,}74$.

Tablica 7. Rezultati t-testova za nezavisne uzorke za skalu stavova prema računalnom oblikovanju

Skupina	M	SD	t(df)	p	d	N
Učenici 5. razreda	3,68	0,83	1,07(95)	0,29	0,22	41
Učenici 7. razreda	3,47	1,05				56
Dječaci	3,49	0,98	0,73(95)	0,47	0,15	50
Djevojčice	3,63	0,95				47
Učenici učitelja 1	3,80	0,88	3,50(95)	0,001	0,74	61
Učenici učitelja 2	3,13	0,96				36

T-testom za nezavisne uzorke nisu utvrđene statistički značajne razlike u odgovorima učenika za pojedine čestice ove skale ni s obzirom na dob ni s obzirom na spol. S obziron na učitelja, statistički značajne razlike utvrđene su za sve pojedinačne tvrdnje osim za tvrdnju da računalno oblikovanje pomaže u razumijevanju tehničkih crteža. Učenici učitelja 1 iskazali su veće slaganje s tvrdnjom da je tehničko crtanje zabavnije uz računalno oblikovanje nego učenici učitelja 2 (p=0,011). Također, učenici učitelja 1 više od učenika učitelja 2 nisu se složili s tvrdnjom da je računalno oblikovanje kompliciranо (p=0,020). Čestica kojom su učenici iskazivali želju za primjenom računala tijekom drugih godina učenja tehničkoga crtanja jedina je za koju su prosječne procjene učenika dvaju učitelja bile na suprotnim stranama neutralne vrijednosti ljestvice. Učenici učitelja 1 iskazali su slaganje s tom tvrdnjom (M = 3,89; SD = 1,25), dok su učenici učitelja 2 u prosjeku iskazali neslaganje (M = 2,79; SD = 1,40; p < 0,001).

Ispitana je povezanost između skale stavova učenika prema tehničkom crtanju i skale stavova prema računalnom oblikovanju. Pearsonov koeficijent korelacije nije pokazao statistički značajnu povezanost između ovih skala ($r = -0{,}018$; $p = 0{,}864$; $N = 96$), kao ni Spearmanov koeficijent korelacije ($\rho = -0{,}037$; $p = 0{,}714$; $N = 96$).

Tri tvrdnje obuhvaćale su učeničko viđenje rada u paru na jednom računalu: preferenciju rada u paru u odnosu na samostalni rad, procjenu doprinosa suradnje učenju te procjenu vlastite aktivne uključenosti tijekom rada (Tablica 8).

Tablica 8. Stavovi učenika prema radu u paru na jednom računalu

Tvrdnja	M	Md	SD	4-5(%)	1-2(%)	N
Samostalno računalno oblilovanje je bolje nego rad u paru*	2,24	2	1,31	15,4	62,5	104
Radom u paru na računalu se nadopunjujemo i bolje napredujemo.	4,09	4	1,16	70,6	11,7	103
Radom na računalu u paru sam u ulozi promatrača dok drugi učenik radi.*	2,27	2	1,17	11,4	55,2	105

* Negativno formulirana čestica; niža vrijednost označava pozitivniju procjenu.

Od čestica o radu u paru, učenici su najpozitivnije ocijenili tvrdnju da se radom u paru međusobno nadopunjuju i bolje napreduju (M = 4,09; SD = 1,16), pri čemu je čak 70,6 % učenika tu tvrdnju podržalo. Preostale dvije negativne tvrdnje su odbačene, također od strane većina učenika. Tvrdnju da je samostalno računalno oblikovanje bolje od rada u paru je odbacilo 62,5 % učenika (M = 2,24; SD = 1,31), a tvrdnju da je tijekom rada u paru samo u ulozi promatrača je odbacilo 55,2% učenika (M = 2,27; SD = 1,17). Korelacijska analiza (Pearsonov koeficijent) pokazala je snažnu pozitivnu povezanost između stava da samostalni rad nije bolji od rada u paru i stava da se radom u paru učenici međusobno nadopunjuju i bolje napreduju (r = 0,705; p < 0,001). Tvrdnja o pasivnoj ulozi promatrača tijekom rada u paru pokazala je znatno slabiju povezanost s preostale dvije tvrdnje (r = 0,161 – 0,178) što upućuje da opisuje drukčiji aspekt iskustva rada u paru. Navedeno upućuje da većina učenika pozitivno doživljava rad u paru.

Mann–Whitneyjevim U testom nisu utvrđene statistički značajne razlike u odgovorima učenika na tri tvrdnje o radu u paru ni s obzirom na spol ni s obzirom na učitelja ($p > 0,05$). S obzirom na dob, statistički značajna razlika utvrđena je samo za tvrdnju o ulozi promatrača tijekom rada u paru ($p = 0,044$) pri čemu su učenici sedmog razreda iskazali veće neslaganje s tom tvdnjom nego učenici petog razreda.

Kroz četiri čestice upitnika su ispitivana učenička viđenja različitih aspekata poučavanja tehničkoga crtanja i računalnog oblikovanja. Tvrdnje i rezultati su u Tablici 9.

Tablica 9. Stavovi učenika prema različitim aspektima poučavanja tehničkog crtanja i računalnog oblikovanja.

Tvrdnja	M	Md	SD	4-5(%)	1-2(%)	N
Lakše mi je izraditi crtež predmeta ako predmet imam ispred sebe	4,25	5	0,99	78,1	5,7	105
Računalno oblikovanje treba biti prije crtanja rukom i priborom	2,83	3	1,16	26,2	38,8	103
Računalno oblikovanje bolje prema napisanim uputama nego učiteljevim pokazivanjem.	3,16	3	1,23	35,9	28,2	103
Računalne naredbe na engleskom jeziku mi otežavaju rad	2,19	2	1,29	13,3	61,9	105

Korelacijska analiza nije pokazala statistički značajne povezanosti između navedenih tvrdnji (Pearsonov $r = -0,073$ do $0,166$; $p > 0,05$), što upućuje da one predstavljaju međusobno različite aspekte poučavanja tehničkoga crtanja i računalnog oblikovanja.

Najizraženije pozitivan stav prema jednoj tvrdnju u cijelom upitniku učenici su iskazali prema tome da im je lakše izraditi tehnički crtež ako tijekom crtanja promatraju stvarni predmet ($M = 4,25$; $SD = 0,99$). Tu tvrdnju je podržalo čak 78,1 % učenika, dok ju je samo 5,7 % odbacilo.

Tvrdnja da računalno oblikovanje treba poučavati prije tehničkoga crtanja rukom i priborom procijenjena je ispod neutralne vrijednosti ($M = 2,83$; $SD = 1,16$). S navedenim redoslijedom poučavanja nije se složilo 38,8 % učenika, 35% zauzelo je neutralan stav, a nešto više od četvrtine učenika (26,2 %) iskazalo je slaganje.

Također, učenici nisu iskazali jasno opredjeljenje za tvrdnju da je računalno oblikovanje bolje učiti pomoću pisanih uputa nego praćenjem uputa koje pokazuje učitelj ($M = 3,16$; $SD = 1,32$). Odgovori su bili jednako podijeljeni između neslaganja s tvrdnjom (35,9 %) i neutralnosti (35,9 %), a nešto manje učenika (28,2 %) se složilo s tvrdnjom.

Korištenje engleskih naziva naredbi u programu nije se pokazalo značajnom preprekom za učenike ($M = 2,19$; $SD = 1,29$). Više od tri petine učenika (61,9 %) nije se složilo s tvrdnjom da im engleski nazivi predstavljaju značajnu poteškoću, dok je samo 13,3 % iskazalo suprotno mišljenje.

Mann–Whitneyjevim U testom nisu utvrđene statistički značajne razlike u odgovorima učenika na četiri pojedinačne čestice ni s obzirom na spol ni s obzirom na učitelja ($p > 0,05$). S obzirom na dob, statistički značajna razlika utvrđena je samo za tvrdnju da engleski nazivi otežavaju ($p = 0,015$), pri čemu su učenici sedmog razreda iskazali veće neslaganje s tom tvrdnjom nego učenici petog razreda.

Jednom česticom upitnika tražilo se da učenici prema osobnim preferencijama u nastavi rangiraju teorijsku nastavu, tehničko crtanje i praktične radove (1 = najpoželjniji, 3 = najmanje poželjan). Razlike u rangiranju praktičnog rada, tehničkoga crtanja i teorijskih sadržaja analizirane su Friedmanovim testom jer je svaki učenik rangirao sva tri nastavna sadržaja. Friedmanov test pokazao je statistički značajne razlike u rangiranju, $\chi^2(2) = 73,666$, $p < 0,001$. Najpoželjnijim je ocijenjen praktični rad (Mean Rank = 1,38), zatim tehničko crtanje (Mean Rank = 2,02), dok je teorijska nastava bila najmanje preferirana (Mean Rank = 2,60). Naknadne usporedbe Wilcoxonovim testom pokazale su da su sve parne razlike bile statistički značajne ($p < 0,001$), pri čemu je praktični rad bio značajno preferiraniji od tehničkoga crtanja i teorijske nastave, a tehničko crtanje značajno preferiranije od teorijske nastave. Zbog triju parnih usporedbi primijenjena je Bonferronijeva korekcija ($\alpha = 0,017$). Sve usporedbe ostale su statistički značajne ($p < 0,001$).

RASPRAVA

Rezultati istraživanja pokazuju da učenici imaju pozitivno viđenje tehničkoga crtanja te pozitivno procjenjuju primjenu računalnog oblikovanja u nastavi. To je u skladu s nalazima koje su iznijeli Purković i suradnici [8], [9] te McLaren [10] za tehničko crtanje, a Huang i Wang [22] te Kimbell i suradnici [18] za računalno oblikovanje. Obje skale su ostvarile prosječne vrijednosti statistički značajno više od neutralne vrijednosti, uz zadovoljavajuću unutarnju konzistentnost i srednje do velike veličine učinka. Takvi rezultati upućuju na to da učenici računalno oblikovanje doživljavaju kao prihvatljiv i koristan način učenja tehničkoga crtanja. Podatak prema kojem gotovo nitko od učenika nije imao prethodno iskustvo s primjenom CAD-a upućuje na to da je pozitivna percepcija ponajprije proizašla iz iskustva stečenoga tijekom provedbe nastavne intervencije.

Posebno je značajno da računalno oblikovanje učenici nisu procijenili kao prezahtjevno niti su ga smatrali preprekom učenju. Naprotiv, više od polovice učenika procijenilo je da računalno oblikovanje pridonosi razumijevanju tehničkih crteža te da bi trebalo biti redoviti dio nastave tehničke kulture. Takvi su rezultati u skladu s prethodnim istraživanjima koja ističu da CAD može povećati motivaciju učenika, olakšati razumijevanje prostornih odnosa i povezivanje trodimenzionalnog modela s dvodimenzionalnim tehničkim crtežom [18], [20], [22]. Međutim, izostanak statistički značajne povezanosti između stavova prema tehničkom crtanju i primjeni računalnog oblikovanja upućuje na to da računalno oblikovanje učenici procjenjuju neovisno o svojem odnosu prema tehničkom crtanju. Drugim riječima, učenici koji pozitivnije procjenjuju računalno oblikovanje ne procjenjuju nužno pozitivnije i tehničko crtanje. Štoviše, učenici nisu iskazali sklonost uvođenju računalnog oblikovanja prije upoznavanja s tradicionalnim tehničkim crtanjem. Iz toga proizlazi da, iako učenici CAD procjenjuju korisnim i zanimljivim, ne doživljavaju ga kao zamjenu za tradicionalne postupke rada, već kao njihovu nadopunu u procesu usvajanja sadržaja tehničkoga crtanja. Time i sami učenici daju prednost redoslijedu na koji upućuju prethodna istraživanja, prema kojima tradicionalni postupci tehničkoga crtanja predstavljaju temelj za razvoj prostornih i drugih relevantnih sposobnosti te trebaju prethoditi primjeni digitalnih alata [10], [13], [14], [25]. Prema odgovorima učenika, rad u paru na jednom računalu uglavnom je pozitivno doživljen, osobito u pogledu međusobnoga nadopunjavanja i napredovanja u radu. Takav je nalaz u skladu s prethodnim istraživanjima koja ističu prednosti suradničkoga učenja u početnim fazama računalnoga oblikovanja [32], [34], [37]. Iako je većina učenika odbacila tvrdnju da tijekom rada u paru ostaje u ulozi promatrača, mogućnost pasivne uloge jednoga člana ne treba zanemariti te je pri organizaciji rada važno osigurati aktivno sudjelovanje obaju učenika.

Učenici nisu iskazali jasnu prednost pisanim uputama u odnosu na praćenje uputa učitelja, što upućuje na to da oba pristupa imaju svoju vrijednost tijekom početnoga usvajanja rada u CAD okruženju. Njihovim kombiniranjem može se učenicima omogućiti samostalnije napredovanje vlastitim tempom uz ponavljanje pojedinih koraka prema potrebi, što je u skladu s preporukama prethodnih istraživanja [32], [34].

Izrazito pozitivno učenici su procijenili mogućnost promatranja fizičkoga modela tijekom izrade tehničkoga crteža. Time se podupiru preporuke o uključivanju fizičkih modela i drugih praktičnih nastavnih sredstava u poučavanje tehničkoga crtanja te primjeni CAD-a u kombinaciji s konkretnim nastavnim sredstvima, a ne kao potpuno samostalnog oblika rada [34], [35]. Važnost praktičnoga pristupa dodatno potvrđuju rezultati rangiranja nastavnih aktivnosti, prema kojima učenici prednost daju praktičnom radu u odnosu na teorijske sadržaje. Takva je sklonost u skladu i s prethodno utvrđenim izrazito pozitivnim stavovima učenika prema praktičnom radu u nastavi Tehničke kulture [9]. Pozitivna procjena rada uz fizički model i izražena sklonost praktičnim aktivnostima zajedno upućuju na važnost nastavnih pristupa koji objedinjuju praktično iskustvo, vizualizaciju prostornih odnosa i aktivno sudjelovanje učenika u procesu učenja.

Stručno nazivlje, koje se oslanja na engleski jezik u označavanju naredbi i funkcija u programu, uglavnom se nije pokazalo kao značajnija teškoća učenicima. Takav nalaz može biti

ohrabrujući nastavnicima koji oklijevaju s uvođenjem CAD-a zbog pretpostavljene zahtjevnosti stručnoga nazivlja i engleskoga jezika. Nalaz pritom nije u skladu sa zapažanjima Winn [38] o bogatom nazivlju kao jednoj od prvih potencijalnih prepreka učenju uz CAD. Međutim, ovo odstupanje valja promatrati u kontekstu načina provedbe intervencije. Tijekom rada primjenjivan je samo minimalan broj potrebnih naredbi, i to na primjerima prethodno upoznatih normi tehničkoga crtanja. Stoga rezultati prije upućuju na to da stručno nazivlje ne mora predstavljati značajniju prepreku ako se CAD uvodi postupno i sadržajno primjereno učenicima. Time se dodatno naglašava važnost poštivanja načela postupnosti i primjerenosti te izbjegavanja predstavljanja velikog broja mogućnosti programa u početnim fazama rada.

Usporedbe prema uzrastu i spolu nisu pokazale statistički značajne razlike u ukupnom viđenju tehničkoga crtanja ni računalnoga oblikovanja, što upućuje na relativno ujednačenu percepciju ovakvog pristupa među različitim skupinama učenika. Ipak, analiza pojedinačnih čestica pokazala je nekoliko statistički značajnih razlika. Tako su učenici petoga razreda iskazali veće neslaganje s tvrdnjom da nikako ne vole tehničko crtanje, što je u skladu s ranijim istraživanjima koja upućuju na veći interes za tehničko crtanje mlađih nego starijih učenika [8], [9]. U viđenjima primjene računalnog oblikovanja su učenici petoga razreda u većoj mjeri od učenika sedmoga razreda procjenjivali da englesko nazivlje predstavlja poteškoću, što je razumljivo s obzirom na njihovu dob i kraće iskustvo u učenju engleskoga jezika, te dodatno potvrđuje važnost postupnoga uvođenja CAD-a u nastavu. Također, učenici petoga razreda nešto su češće procjenjivali da jedan član para može ostati pasivan promatrač, što može upućivati na veću samostalnost starijih učenika u zajedničkom radu, no takvo bi tumačenje trebalo dodatno istražiti. Ovaj nalaz ipak dodatno upućuje na potrebu pažljivoga planiranja rada u paru, osobito s mlađim učenicima.

Dok usporedbe prema uzrastu i spolu nisu pokazale statistički značajne razlike u ukupnim procjenama skala, usporedba prema učitelju pokazala je statistički značajnu razliku u procjeni računalnoga oblikovanja. Budući da istraživanje nije bilo usmjereno na analizu čimbenika koji bi mogli objasniti takvu razliku, nije moguće zaključiti koji su njezini uzroci. Ona bi mogla biti povezana s razlikama u metodičkoj provedbi nastavne intervencije, komunikaciji s učenicima kao i obilježjima pojedinih razrednih odjela ili drugim okolnostima nastavnog procesa, što predstavlja moguće polazište za buduća istraživanja.

Rezultate istraživanja potrebno je promatrati i u svjetlu njegovih ograničenja. Istraživanje je provedeno na ograničenom uzorku učenika uključenih u nastavu dvaju učitelja, a procjene se temelje na samoprocjeni učenika nakon provedene nastavne intervencije. Buduća istraživanja mogla bi uključiti veći broj škola i učitelja te detaljnije ispitati čimbenike koji utječu na prihvaćanje računalnog oblikovanja u nastavi tehničkoga crtanja, kao i povezanost učeničkih stavova s objektivnim pokazateljima uspješnosti učenja i razvoja prostornih sposobnosti.

ZAKLJUČAK

Poticaj za ovo istraživanje proizašao je iz nedostatka spoznaja o primjeni CAD-a s učenicima osnovne škole, osobito o njegovoj ulozi kao didaktičkoga sredstva u poučavanju tehničkoga crtanja. Stoga je cilj bio ispitati učeničku percepciju takvoga pristupa te organizacijske i metodičke aspekte njegove primjene. Dosadašnja saznanja i dobiveni nalazi upućuju na zaključak da CAD ima svoje mjesto u osnovnoškolskom poučavanju tehničkoga crtanja, ali ne kao zamjena za tradicionalne postupke niti kao zaseban sadržaj usmjeren ovladavanju softverom. Naprotiv, primjena CAD-a i mogućnosti digitalne vizualizacije trebaju se nadovezati na upoznavanje s tradicionalnim postupcima tehničkoga crtanja te pridonijeti utvrđivanju i proširivanju stečenih znanja. Pritom didaktička vrijednost CAD-a nije u samoj uporabi digitalne tehnologije, nego u načinu na koji se ona uključuje u nastavni proces. Njegova primjena treba biti metodički osmišljena i usmjerena na odabir onih funkcija i naredbi koje pridonose razumijevanju i primjeni sadržaja tehničkoga crtanja, uz postupno uvođenje te povezivanje s fizičkim modelima i praktičnim aktivnostima. Vođenje učenika treba kombinirati s mogućnostima samostalnoga napredovanja i suradničkoga rada te pritom osigurati aktivno sudjelovanje svakog učenika.

Ove zaključke potrebno je razmatrati u okviru ograničenoga uzorka, nastave dvaju učitelja i oslanjanja na učeničke samoprocjene nakon nastavne intervencije. Daljnjim bi istraživanjima trebalo obuhvatiti veći broj škola i učitelja te učeničke procjene povezati s objektivnim pokazateljima uspješnosti učenja i razvoja prostornih sposobnosti. Time bi se, uz neizostavno osiguravanje odgovarajućih tehničkih i organizacijskih uvjeta te metodičke pripremljenosti učitelja, stvorila pouzdanija osnova za širu i svrhovitu primjenu CAD-a u osnovnoj školi.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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PRIMARY SCHOOL STUDENTS' PERCEPTIONS OF USING CAD IN TECHNICAL DRAWING INSTRUCTION

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ABSTRACT

Technical drawing is an integral part of general technology education and, consequently, of the Technical Culture curriculum in primary schools, with recommendations for the use of computer programs for drawing and three-dimensional modelling. This creates opportunities for the implementation of computer-aided design (CAD) in teaching. However, little is known about the extent to which CAD is used in primary schools and for what purposes. Therefore, this paper empirically examines the use of three-dimensional CAD software as a means through which students model and visualise technical creations, develop an understanding of spatial relationships, and connect a three-dimensional model with a technical drawing in regular classroom instruction. The research was conducted on a sample of 105 fifth- and seventh-grade primary school students who participated in the intervention. The aim was to examine students' perceptions of using CAD in teaching technical drawing with regard to content comprehensibility, self-perceived achievement, instructional interest, and the perceived advantages and difficulties of such an approach. The findings indicate that computer-aided design can contribute to the development and conceptualisation of a motivating and methodologically appropriate approach to learning technical drawing, thereby supporting the pedagogical justification and possibilities of applying CAD in the Technical Culture subject in primary schools.

Keywords: computer-aided design (CAD), technical drawing, technology education, primary school, student perceptions.

DIGITALIZATION OF EDUCATION: ADVANTAGES AND CHALLENGES

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ABSTRACT

In recent years, the digitalization of education has significantly transformed the organization of teaching and the overall approach to the learning process. The use of digital technologies has enabled faster access to information, greater availability of educational content, and the implementation of various forms of online learning. The aim of this paper is to present the main advantages and challenges of the digitalization of education, with a particular focus on the application of e-learning platforms and learning management systems in contemporary teaching. The paper analyzes the positive aspects of digital education, such as flexibility in teaching organization, opportunities for distance learning, and easier access to educational materials, as well as the challenges encountered in practice, including insufficient technical equipment, the digital divide, reduced motivation, and issues related to the quality of online teaching. The research is based on the analysis of relevant scientific and professional literature, as well as the examination of examples of the implementation of digital tools in educational institutions. The results indicate that digitalization has significant potential to improve the educational process. However, its successful implementation depends on adequate technical support, the development of digital competencies, and the adaptation of teaching methods to modern working conditions. The findings suggest that achieving a high-quality and inclusive education system requires sustained investment in digital infrastructure alongside the continuous adoption of innovative teaching practices.

Keywords: digitalization of education, online learning, e-learning, learning management systems, digital divide.

INTRODUCTION

The digital transformation of modern society has significantly influenced the way people communicate, work, and acquire knowledge, making education one of the fields in which these changes have been particularly evident. Advances in information and communication technologies

have transformed learning environments by enabling educational activities to take place beyond the limitations of time and location through the use of digital platforms, electronic learning resources, and interactive technologies [1]. These developments have contributed to the emergence of contemporary teaching models characterized by greater flexibility, improved accessibility of educational content, and more active student participation in the learning process.

The digitalization of education encompasses far more than the introduction of computers and the Internet into classrooms. It encompasses the comprehensive transformation of the educational process by incorporating digital technologies, enhancing instructional practices, and fostering new forms of interaction between teachers and students [2]. In the contemporary educational environment, digital tools have become an important support for planning, delivering, and assessing instruction, enabling more efficient management of the educational process and greater adaptation to students' individual needs. In addition, the development of e-learning systems and learning management platforms has considerably expanded the possibilities for organizing instruction and has enabled various forms of distance and blended learning [3].

Although the digitalization of education offers numerous opportunities to enhance the quality of teaching, its implementation also raises issues related to access to technology, digital literacy, student motivation, data protection, and the preservation of educational quality. For this reason, it is essential to examine the digitalization of education from multiple perspectives and to analyze both its positive effects and the challenges associated with its implementation in contemporary educational systems.

Based on these considerations, the aim of this paper is to examine the digitalization of education as a contemporary educational concept, with particular emphasis on its key advantages, challenges, and future development prospects. Particular emphasis is placed on examining how digital technologies can enhance the teaching process and on identifying the conditions that support their effective and sustainable integration into educational practice.

DIGITALIZATION OF EDUCATION AS A CONTEMPORARY EDUCATIONAL CONCEPT

Digitalization is one of the most significant processes shaping modern society, transforming the way people work, communicate, access information, and acquire new knowledge. The rapid development of information and communication technologies has brought about numerous changes across various aspects of life, with education emerging as one of the fields most profoundly affected by these transformations [4]. Contemporary educational systems are increasingly moving away from traditional teaching models based solely on face-to-face classroom interaction and are integrating digital technologies as an essential component of the educational process. As a result, not only has the way teaching is delivered changed, but so have the roles of teachers, students, educational content, and the learning process itself.

The digitalization of education is a complex process that involves the transformation of the entire educational system through the integration of digital technologies into the planning, organization, implementation, and evaluation of the teaching process [5]. Furthermore, digitalization includes the development of new pedagogical approaches that promote greater flexibility in learning, more effective communication among all participants in the educational process, and easier access to educational content [6]. In this context, technology is not an end in itself but rather a means of improving the quality of education and enhancing the achievement of learning outcomes.

The development of the digitalization of education is the result of simultaneous advances in information technologies and changes in societal needs. The expansion of the Internet, mobile devices, cloud computing, and various digital platforms has enabled educational institutions to significantly broaden the possibilities for organizing teaching and learning activities [7]. Educational content has become available in electronic formats, communication between teachers and students is no longer confined to the classroom, and the learning process can take place regardless of geographical location or time constraints [8]. Consequently, education has become more accessible to diverse groups of learners, including students who are unable to attend traditional classes regularly due to work commitments, health conditions, or geographical distance.

One of the most significant characteristics of the digitalization of education is the changing role of teachers and students. Traditional education was based on the teacher serving as the primary source of knowledge, while students generally assumed a passive role in the learning process. Through the application of digital technologies, students are given the opportunity to independently explore various sources of information, participate in interactive learning activities, collaborate with their peers, and develop problem-solving skills [9]. At the same time, the teacher's role has evolved toward that of an organizer, mentor, and facilitator of learning, guiding students, fostering critical thinking, and helping them transform information into meaningful and applicable knowledge [10].

The digitalization of education also involves the application of various digital tools that enable more efficient planning, organization, and implementation of the teaching process. Learning management systems occupy a particularly important position, as they facilitate the distribution of learning materials, the organization of educational activities, the monitoring of students' progress, the administration of assessments, and continuous communication between teachers and students [11]. In addition, video conferencing platforms, digital libraries, interactive educational resources, multimedia materials, and various collaborative learning tools are being increasingly adopted in educational practice [12]. Their common characteristic is the creation of a more dynamic and flexible learning environment that can be adapted to students' diverse needs and abilities.

The contemporary concept of the digitalization of education is closely associated with the development of digital competencies. The effective implementation of digital technologies depends not only on the availability of technical equipment but also on the ability of teachers and students to use these technologies responsibly, safely, and purposefully. Digital competencies encompass far more than basic computer and Internet skills. They include the ability to locate, evaluate, and critically assess information, use digital tools for communication and collaboration, protect privacy and ensure safe behavior in digital environments, as well as foster creativity and innovation through the application of modern technologies in the learning process [13].

In addition to transforming the teaching process, digitalization has also had a significant impact on the organization and management of educational institutions. Electronic information systems facilitate more efficient administrative management, digital record-keeping, data exchange, timetable organization, and the monitoring of educational outcomes [14]. In this way, digital technologies contribute to improving the operational efficiency of educational institutions while supporting evidence-based decision-making through the availability of reliable data.

ADVANTAGES OF THE DIGITALIZATION OF EDUCATION

The digitalization of education has brought about numerous changes that have influenced the organization of the teaching process, access to educational content, and communication between teachers and students. The integration of digital technologies has enabled the development of more flexible learning models that overcome the limitations of traditional instruction and create conditions for more effective knowledge acquisition. Contemporary educational systems are increasingly adopting digital tools to enhance the quality of teaching, improve access to education, and encourage more active student participation in the learning process [33]. Although the successful implementation of these technologies depends on various factors, current evidence suggests that digitalization can contribute to the improvement of multiple aspects of the educational process [15].

One of the most significant advantages of the digitalization of education is the increased accessibility of educational content. Unlike the traditional model of instruction, in which physical classroom attendance was often a prerequisite for learning, digital technologies provide access to educational materials at any time and from various Internet-connected devices [16]. This allows pupils and students to organize their learning according to their own needs and pace, which is particularly beneficial for individuals who are unable to attend classes regularly due to geographical, health-related, or professional circumstances. Furthermore, digital educational resources facilitate the continuous updating of instructional materials and their efficient distribution to a large number of users.

An additional benefit of the digitalization of education is the increased flexibility it brings to the teaching process. Digital platforms support the delivery of face-to-face, distance, and various forms of blended learning, enabling educational institutions to adapt instructional organization to the diverse needs of both students and teachers [17]. This flexibility extends beyond the location of learning to include the timing, pace, and structure of educational activities. Students are able to revisit learning materials, review previously covered topics, and progress at their own pace, while teachers can adapt instructional content to different levels of knowledge and students' interests.

The digitalization of education also contributes to improving the quality of the teaching process through the use of diverse multimedia and interactive resources. The application of videos, animations, simulations, virtual laboratories, and interactive exercises facilitates the understanding of complex concepts and encourages greater student engagement during instruction [18]. Visual and interactive elements often help bridge theoretical knowledge with practical applications, thereby enhancing the effectiveness of learning. Moreover, the integration of text, images, audio, and video provides a more diverse presentation of educational content and accommodates different learning styles.

A particularly valuable feature of digitalization is the possibility of individualizing and personalizing education. Contemporary digital systems make it possible to monitor students' progress, identify areas in which they encounter difficulties, and adapt learning activities to the individual needs of each learner [19]. Based on students' performance, teachers can provide additional assignments, supplementary materials, or activities of varying levels of complexity. Such an approach promotes more effective knowledge acquisition, increases learner autonomy, and ensures that the learning process is tailored to students' actual needs and abilities.

Digitalization also significantly enhances communication and collaboration among all participants in the educational process. Digital platforms enable faster information exchange between teachers and students, facilitate the distribution of learning materials, support the electronic submission of assignments, and provide timely feedback. Beyond enhancing communication between teachers and students, digital technologies also promote collaborative learning by supporting group projects, teamwork, and interactive online discussions [20]. As a result, students develop teamwork, communication, and collaborative problem-solving skills, all of which are essential competencies in contemporary society and the labor market.

Another important advantage of digitalization is the opportunity for continuous monitoring and assessment of students' academic achievement. Digital systems allow the automated processing of assessment results, monitoring of students' learning activities, and real-time tracking of their progress [21]. Based on the available data, teachers can more easily identify areas in which students experience difficulties and adjust instructional activities accordingly. At the same time, students receive prompt feedback on their performance, which enhances motivation and enables them to monitor their own learning progress more effectively.

The use of digital technologies also contributes to the development of digital competencies, which are considered one of the key competencies required in contemporary society. Through the use of various digital tools, students develop skills related to locating, analyzing, and critically evaluating information, communicating safely in digital environments, solving problems, and using technology responsibly [22]. In addition, teachers strengthen their professional competencies through the adoption of innovative teaching methods, the use of contemporary educational platforms, and continuous professional development [23]. Consequently, the digitalization of education contributes not only to the acquisition of academic knowledge but also to the development of competencies necessary for successful participation in a digital society.

Finally, digitalization has a positive impact on the operational efficiency of educational institutions. The implementation of information systems facilitates the management of the teaching process, electronic administration, timetable organization, digital attendance records, and more efficient management of educational documentation [24]. As a result, the administrative workload of teachers and educational staff is reduced, while the availability of relevant information is improved, supporting more efficient and evidence-based decision-making.

CHALLENGES OF THE DIGITALIZATION OF EDUCATION

Although the digitalization of education offers numerous opportunities to enhance the teaching process, its implementation also presents a range of challenges that may affect the quality and effectiveness of education. The integration of digital technologies requires appropriate infrastructure, well-developed digital competencies, adequate institutional support, and careful planning of the implementation process. If these conditions are not met, digitalization may deepen existing inequalities among students, complicate the delivery of instruction, and reduce the overall quality of education.

One of the most significant challenges is unequal access to digital technologies, commonly referred to in the literature as the digital divide [25]. Differences in access to computers, mobile devices, reliable Internet connections, and modern digital resources can substantially affect students' opportunities to participate equally in the educational process [26]. This issue is particularly evident in areas with underdeveloped infrastructure or among families with limited financial resources, where students often lack access to appropriate equipment or must share a single device with other household members. Such circumstances may lead to reduced participation in learning activities, difficulties in completing academic tasks, and increased educational inequalities.

In addition to access to technology, the successful digitalization of education largely depends on the digital competencies of both teachers and students. Although younger generations have grown up surrounded by digital technologies, this does not necessarily mean that they possess the skills required to use these technologies effectively and responsibly in educational settings. Digital literacy extends far beyond the basic use of computers or mobile devices and includes the ability to critically evaluate information, use digital tools safely, solve problems, and behave responsibly in digital environments. At the same time, teachers face the need for continuous professional development in order to keep pace with rapid technological advancements and successfully integrate digital tools into the teaching process. A lack of appropriate knowledge and skills may result in the superficial use of technology, with digital tools serving merely as substitutes for traditional teaching resources rather than genuinely enhancing the learning process [27].

Maintaining the quality of teaching in digital environments also represents a considerable challenge. Although digital platforms facilitate various forms of communication and the exchange of educational materials, they cannot fully replace direct interaction between teachers and students. Online instruction is often associated with reduced social interaction, fewer opportunities for spontaneous discussion, and greater difficulty in monitoring student engagement. Teachers may find it more challenging to identify students' learning difficulties, while students may experience a weaker sense of connection to both the learning process and the educational community [28]. Therefore, maintaining active student participation and effective communication remains one of the primary challenges of digitally delivered education.

Student motivation represents another important challenge associated with the digitalization of education. Learning in digital environments requires a high level of independence, responsibility, and effective time management. In the absence of direct teacher supervision and regular face-to-face interaction with peers, some students may demonstrate lower motivation, procrastinate in completing academic tasks, or experience reduced concentration during learning activities [29]. In addition, the abundance of digital content may serve as a source of distraction, making it more difficult for students to remain focused on educational tasks. Consequently, the effective implementation of digital education requires strategies that encourage active student engagement, self-regulated learning, and continuous monitoring of learning progress.

As digital education continues to expand, increasing attention has been given to issues related to data security, privacy protection, and the ethical use of digital technologies. The use of various educational platforms involves the collection and processing of large amounts of data concerning students and teachers, making it essential to ensure an appropriate level of personal data protection and prevent potential misuse [30]. Furthermore, the rapid development of generative artificial intelligence and the widespread availability of digital tools have introduced new concerns regarding academic integrity. The growing accessibility of technologies capable of generating texts, solving assignments, or producing different types of educational content requires the

reconsideration of assessment methods, as well as the development of ethical guidelines that support the responsible use of emerging technologies in education.

The challenges of the digitalization of education also include organizational and financial aspects of its implementation. Establishing a high-quality digital infrastructure requires substantial investment in technical equipment, software solutions, information system maintenance, and the continuous training of educational staff. Beyond the initial investment, educational institutions must ensure regular equipment upgrades, technical support, and the adaptation of new technologies to evolving curricula [31]. Under conditions of limited financial resources, particularly in less developed regions, maintaining a modern digital learning environment can become a significant challenge.

Special attention should also be paid to the potential consequences of excessive use of digital technologies. Extended exposure to computers and other digital devices may contribute to fatigue, lower levels of physical activity, and visual discomfort, while an overreliance on digital resources can have adverse effects on face-to-face communication and students' social interactions [32]. Although digital technologies provide numerous opportunities to improve education, their implementation should remain aligned with pedagogical objectives and students' developmental needs in order to preserve an appropriate balance between digital and traditional forms of learning.

RESULTS AND DISCUSSION

The effects of educational digitalization cannot be assessed solely through the availability of technology. Digital tools provide greater flexibility, broader access to learning materials, and opportunities to adapt instruction to individual learning needs. Personalization systems can support the selection and organization of content according to students' characteristics and progress, thereby creating more responsive learning environments [19]. These advantages do not arise automatically from the introduction of platforms or devices, as their educational value depends primarily on the pedagogical purpose for which they are used and the manner in which they are incorporated into teaching activities.

Interaction remains a central factor in digitally mediated education. Gherghel et al. (2023) found that interaction during online classes was positively related to student engagement and self-directed study [28]. The quality of digital learning consequently depends on opportunities for active communication rather than merely on access to online content. This relationship helps explain why identical technologies may produce different outcomes across educational institutions. Digital tools incorporated into collaborative and well-structured activities can strengthen participation and support independent learning. When their use is limited to distributing materials and assignments, their contribution to educational quality may remain modest.

Accessibility represents both a principal advantage and an important contradiction of digital education. Online learning can overcome geographical and temporal barriers, but unequal access to devices, reliable Internet connections, and digital skills may reproduce or deepen existing educational inequalities. Miras et al. (2023) confirmed that the digital divide affects participation in e-learning and the implementation of information and communication technologies [26]. Expanding digital education therefore requires measures that address material access, user competencies, and institutional support. Providing digital content without resolving these underlying inequalities cannot ensure equal participation or comparable learning opportunities.

Effective digitalization also requires comprehensive organizational change. Pettersson (2021) demonstrates that educational digitalization is shaped by how institutions understand, plan, and implement technological change [5]. The process cannot be reduced to the acquisition of equipment or the introduction of new software. Its effectiveness depends on coordinated development across four interconnected dimensions: technological infrastructure, pedagogical design, human competencies, and institutional governance. These dimensions form an analytical framework for understanding why some digital initiatives achieve sustainable educational improvements, while others remain limited to temporary or superficial technological changes.

Successful digitalization should therefore be balanced and pedagogically oriented. Educational institutions need to combine investment in infrastructure with teacher development, inclusive access policies, interactive teaching strategies, and responsible data practices. Under

these conditions, digital technologies can improve accessibility, instructional flexibility, and student participation while preserving the social and pedagogical functions of education.

CONCLUSION

The digitalization of education represents one of the most significant processes transforming contemporary educational systems, reshaping the organization of teaching, access to educational content, and the roles of all participants in the learning process. The development of information and communication technologies has created opportunities to make education more accessible, flexible, and responsive to the diverse needs of both students and teachers, thereby opening new possibilities for improving the quality of teaching and learning. Moreover, digital technologies contribute to the development of innovative teaching methods, encourage more active student engagement, and facilitate more efficient knowledge sharing and information exchange.

However, the digitalization of education should not be viewed merely as a technological advancement but rather as a complex process that requires the alignment of technological capabilities with pedagogical principles and educational objectives. Its successful implementation depends on well-developed digital infrastructure, the continuous enhancement of teachers' and students' digital competencies, and the willingness of educational institutions to adapt existing teaching models to contemporary educational demands. In addition, particular attention should be devoted to addressing challenges related to the digital divide, maintaining educational quality, protecting privacy, and ensuring the responsible use of digital technologies in educational settings.

Contemporary educational systems are faced with the task of achieving an appropriate balance between traditional pedagogical values and the opportunities offered by digital technologies. Their application should not replace the role of teachers or diminish the importance of direct interaction in the learning process; rather, it should serve as a means of supporting higher-quality, more effective, and more inclusive education. In this regard, the digitalization of education should remain focused on enhancing learning processes and fostering the development of competencies that enable individuals to function successfully in modern society.

It can be concluded that the future development of digital education will largely depend on continuous investment in technology, human resources, and educational policies that promote innovation and the responsible implementation of digital solutions. Only a systematic approach, based on the collaboration of educational institutions, teachers, students, and policymakers, can ensure the sustainable development of education and enable digital technologies to realize their full potential in improving the quality and accessibility of education.

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DESIGN METHODOLOGY FOR FUZZY LOGIC CONTROLLERS

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ABSTRACT

The paper presents an insight into the mathematical basis of fuzzy linguistic modeling and discusses the sensitivity of fuzzy rule-based systems with respect to membership function parameters, rule structure, and inference mechanisms. Examples with different inference models are analyzed and compared in order to illustrate their influence on the behavior and performance of fuzzy systems. Particular attention is devoted to the effects of parameter variations on system stability, robustness, accuracy, and interpretability. The study highlights the importance of sensitivity analysis in the design of reliable fuzzy controllers.

Keywords: Fuzzy logic, linguistic variable, inference, controller.

INTRODUCTION

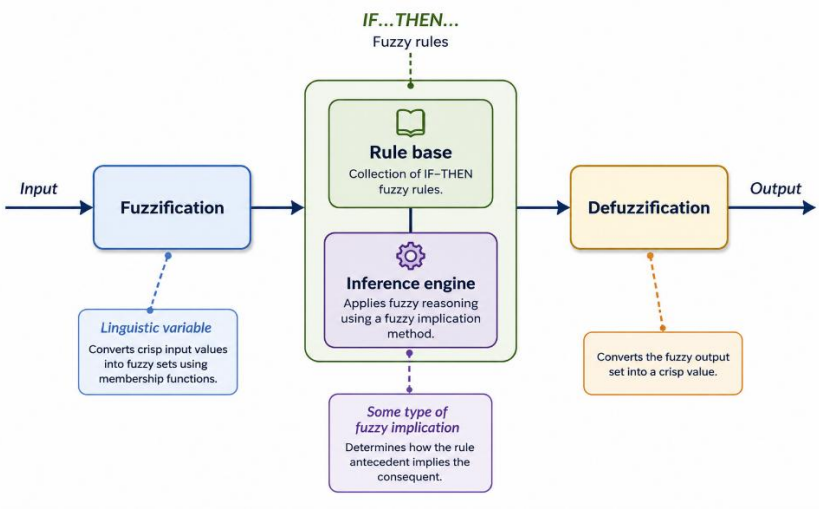
Fuzzy sets were introduced by Lotfi Zadeh in 1965 as a way to overcome the imprecision and uncertainty that arise in certain aspects and domains of human reasoning [1]. The source of imprecision is considered to be the lack of clear criteria, as well as the subjectivity and uncertainty present in many problems. Such problems frequently occur when dealing with classes of objects in the real world, which is why fuzzy sets have found applications in many fields such as psychology, sociology, economics, and other scientific disciplines [2], [3], [4], [1].

Classical two-valued (bivalent) logic is a formal mathematical discipline focused on examining the principles and techniques of reasoning, where new conclusions are generated from established propositions. In classical logic, it is assumed that every proposition has exactly one of two truth values: true or false, typically denoted by 1 for true and 0 for false. Fuzzy logic serves as a natural expansion and generalization of traditional logic, permitting propositions to hold a degree of truth instead of being strictly true or false. As a result, the truth value of a proposition is no longer limited to the binary set $\{0,1\}$, but can assume any value from a wider range, typically the real interval $[0,1]$. In this way, fuzzy logic presents the idea of graded truth, thus offering a mathematical structure for depicting the vagueness and uncertainty intrinsic to human reasoning and natural language. This generalization facilitates approximate reasoning, which involves

generating graded conclusions (fuzzy propositions) based on a set of vague or partially accurate premises. In contrast to traditional logical systems that demand exactness, fuzzy logic is intentionally formulated to represent reasoning in contexts marked by vagueness, partial information, and unpredictability.

The main goal of fuzzy logic is to create a strong theoretical base for approximate reasoning with vague statements, using fuzzy set theory as its core mathematical instrument and key analytical resource. A fuzzy controller is a control system that uses a collection of linguistic IF-THEN rules to regulate a system's behavior based on the current values of its input variables. Fuzzy systems, including fuzzy controllers, were first practically applied in 1975, when Ebrahim Mamdani developed a fuzzy controller for controlling a steam engine. His work demonstrated that complex control tasks could be successfully performed using linguistic IF–THEN rules instead of precise mathematical models. This achievement marked the beginning of fuzzy control as a practical engineering discipline and inspired numerous applications in industrial automation, robotics, automotive systems, and consumer electronics [5].

Fuzzy logic, rather than exact mathematical functions, is used to describe the relationships between variables. Fuzzification, a rule base, an inference mechanism, and defuzzification are the four primary parts of a fuzzy control system. Fuzzy sets with linguistic labels like “low,” “medium,” or “high” are created from crisp numerical inputs during the fuzzification stage. In the form of IF-THEN rules that specify the control strategy, the rule base comprises expert knowledge. These rules are assessed and combined by the inference mechanism to provide a fuzzy output. The combined fuzzy output is finally transformed into a single clear control action that can be implemented during the defuzzification stage. Also, fuzzy logic follows an approach that resembles human reasoning and is relatively simple to understand. It has been widely applied in various fields and has proven effective in solving numerous problems. Based on set theory, fuzzy logic employs fuzzy models and algorithms to reduce the differences between formal and natural languages. Nevertheless, fuzzy logic also has some limitations, including the lack of precisely defined rules, possible imprecision in reasoning, the necessity of extensive hardware testing for fuzzy systems, and longer data processing times in comparison with some classical approaches [6], [7], [4], [8], [9].



Picture 1. Parts of fuzzy control system.

BASIC CONCEPTS, FUZZY IF-THEN RULES

First, we will give an overview of the basic concepts and results of the fuzzy logic theory. Let X be the set we call the universe. The fuzzy set A is defined as a set of ordered pairs

$A = \{(x, \mu_A(x)) | x \in X\}$,

where

$\mu_A: X \to [0,1]$

is a membership function that assigns each element of the universe X some value from the interval $[0,1]$.

Various types of membership function can be used to describe these fuzzy sets: linear, triangular, trapezoidal, bell and Gaussian functions. A fuzzy set A on the discrete universe $X = \{x_1, x_2, \dots, x_n\}$ can be represented as

$$A = \frac{\mu_A(x_1)}{x_1} + \frac{\mu_A(x_2)}{x_2} + \cdots + \frac{\mu_A(x_n)}{x_n},$$

that is

$$A = \sum_{x \in X} \frac{\mu_A(x)}{x}.$$

The intersection of the fuzzy sets A and B is the fuzzy set C whose membership function is given by

$\mu_C(x) = \mu_A(x) \wedge \mu_B(x), x \in X.$

The union of fuzzy sets A and B is a fuzzy set C whose membership function is given by

$\mu_C(x) = \mu_A(x) \vee \mu_B(x), x \in X.$

The complement of the fuzzy set A is the fuzzy set A' whose membership function is given by

$\mu_{A'}(x) = 1 - \mu_A(x), x \in X.$

A binary fuzzy relation, denoted by $\mathcal{R}$, is a fuzzy set defined on the Cartesian product of non-empty sets $X_1 \times X_2$. The mapping $\mu_R: X_1 \times X_2 \to [0,1]$, where $\mu_R(x_1, x_2)$ represents the degree to which the element (x_1, x_2) belongs to the relation $\mathcal{R}$ is called the membership function of the set $\mathcal{R}$

$\mathcal{R} = \{((x_1, x_2), \mu_R(x_1, x_2)) | (x_1, x_2) \in X_1 \times X_2, \mu_R(x_1, x_2) \in [0,1]\}.$

Fuzzy relations have many uses and are an extension of classical relations. In contrast to classical relations, which show whether or not things are related, fuzzy relations let elements to be somewhat related.

A fuzzy IF-THEN rule is a rule of the form: IF p THEN q, where p and q are corresponding propositions. In classical logic, the following property holds

$p \Rightarrow q \equiv \neg p \vee q.$

In fuzzy logic, the expression IF p THEN q is represented by a membership function $\mu: U_1 \times U_2 \to [0,1]$ defined by

$\mu(p, q) = \neg p \vee q,$

for $p \in U_1, q \in U_2$. Depending on which operator is used to model the complement and which operator is used to model the fuzzy union, various different fuzzy implications are obtained

$\mu_Z(x, y) = \max(\min(\mu_{p1}(x), \mu_{p2}(y)), 1 - u_{p1}(x))$ – Zadeh implication,

$\mu_L(x, y) = \min(1, 1 - \mu_{p1}(x) + \mu_{p2}(y))$ – Lukasiewicz implication,

$\mu_D(x, y) = \max(1 - \mu_{p1}(x), \mu_{p2}(y))$ – Dienes-Rescher implication,

$\mu_{MP}(x, y) = (\mu_{p1}(x)\mu_{p2}(y))$ – Mamdani 2 implication.

We extend the fundamental rules of inference from classical logic. **Modus ponens**: If p is true and $p \Rightarrow q$ is true, then q is also true, i.e.

$(p \wedge (p \Rightarrow q)) \Rightarrow q.$

Intuitively, modus ponens means

Premise 1: x is equal A;

Premise 2: IF x is equal A, THEN y is equal B;

Conclusion: y is equal B.

Generalization of modus ponens: If the proposition "x is equal to A'" holds, and the proposition "if x is equal to A, then y is equal to B" holds, then the proposition "y is equal to B'" also holds, in the sense that the closer A' is to A, the closer B' is to B.

Generalization of modus ponens means

Premise 1: x is equal A';

Premise 2: IF x is equal A, THEN y is equal B;

Conclusion: y is equal B'.

For given fuzzy set $A': U \to [0,1]$, which represents premise "x is equal A'", and fuzzy relation $A \to B \in \mathcal{R}(U,V)$, which represents premise "IF x is equal A, THEN y is equal B", fuzzy set $B': V \to [0,1]$, which represents conclusion "y is equal B'", we represent as

$$\mu_{B'} = \sup_{x \in U}(\mu_{A'}(x), \mu_{A \to B}(x,y)).$$

Triangular norm (t-norm) is a binary operation used in fuzzy logic and fuzzy set theory to model the intersection and union of fuzzy sets. T-norm is function $T: [0,1]^2 \to [0,1]$ that for $a, b, c \in [0,1]$ is valid

boundary condition $T(a,1) = a$;

commutativity $T(a,b) = T(b,a)$;

monotonicity, if $b_1 \leq b_2$ then $T(a,b_1) \leq T(a,b_2)$;

associativity $T(a,T(b,c)) = T(T(a,b),c)$.

EXAMPLE

Consider the sets $U = \{x_1, x_2, x_3\}$ and $V = \{y_1, y_2\}$. The fuzzy sets are given as follows:

$$A = \frac{0.5}{x_1} + \frac{1}{x_2} + \frac{0.6}{x_3}, \quad A' = \frac{0.6}{x_1} + \frac{0.9}{x_2} + \frac{0.7}{x_3}, \quad B = \frac{1}{y_1} + \frac{0.4}{y_2}.$$

Using the generalized Modus ponens rule, determine B assuming that the t-norm is the minimum, and that the implication representing the statement $A \to B$ is given as follows

Zadeh implication;

1. Lukasiewicz implication;
2. Dienes-Rescher implication;
3. Mamdani 2 implication.

SOLUTION

Since the generalized Modus ponens rule is applied, the membership function is defined as follows

$$B'(y) = \sup_{x \in U} t[\mu_{A'}(x), \mu_{A \to B}(x,y)],$$

t-norm is minimum, then we have

$$B'(y) = \sup_{x \in U} \min[\mu_{A'}(x), \mu_{A \to B}(x,y)].$$

1. Using Zadeh's implication, we have

$$B'(y) = \sup_{x \in U} \min[\mu_{A'}(x), \max[\min[A(x), A(y)], 1 - A(x)]].$$

- For $y = y_1$ is valid

$$B'(y_1) = \sup_{x \in U} \min[\mu_{A'}(x), \max[\min[A(x), \mu_B(y_1)], 1 - A(x)]]$$

$$= \sup \begin{cases} \min[0.6, \max[\min[0.5,1], 1 - 0.5]], & x = x_1, \\ \min[0.9, \max[\min[1,1], 1 - 1]], & x = x_2, \\ \min[0.7, \max[\min[0.6,1], 1 - 0.6]], & x = x_3 \end{cases}$$

$$= \sup \begin{cases} 0.5, & x = x_1, \\ 0.9, & x = x_2, \\ 0.6, & x = x_3 \end{cases}$$

$$= 0.9.$$

- For $y = y_2$ is valid

$$B'(y_2) = \sup_{x \in U} \min[\mu_{A'}(x), \max[\min[A(x), \mu_B(y_2)], 1 - A(x)]]$$

$$= \sup \begin{cases} \min[0.6, \max[\min[0.5, 0.4], 1 - 0.5]], & x = x_1, \\ \min[0.9, \max[\min[1, 0.4], 1 - 1]], & x = x_2, \\ \min[0.7, \max[\min[0.6, 0.4], 1 - 0.6]], & x = x_3 \end{cases}$$

$$= \sup \begin{cases} 0.5, & x = x_1, \\ 0.4, & x = x_2, \\ 0.4, & x = x_3 \end{cases}$$

$$= 0.5.$$

- Finally, we have that $B'(y_1) = 0.9$ and $B'(y_2) = 0.5$.

2. Using the Lukasiewicz implication, we have

$$B'(y) = \sup_{x \in U} \min[A'(x), \min[1, 1 - A(x) + B(y)]].$$

- For $y = y_1$ is valid

$$B'(y_1) = \sup_{x \in U} \min[A'(x), \min[1, 1 - A(x) + B(y_1)]]$$

$$= \sup \begin{cases} \min[0.6, \min[1, 1 - 0.5 + 1]], & x = x_1, \\ \min[0.9, \min[1, 1 - 1 + 1]], & x = x_2, \\ \min[0.7, \min[1, 1 - 0.6 + 1]], & x = x_3 \end{cases}$$

$$= \sup \begin{cases} 0.6, & x = x_1, \\ 0.9, & x = x_2, \\ 0.7, & x = x_3 \end{cases}$$

$$= 0.9.$$

- For $y = y_2$ is valid

$$B'(y_2) = \sup_{x \in U} \min[A'(x), \min[1, 1 - A(x) + B(y_2)]]$$

$$= \sup \begin{cases} \min[0.6, \min[1, 1 - 0.5 + 0.4]], & x = x_1, \\ \min[0.9, \min[1, 1 - 1 + 0.4]], & x = x_2, \\ \min[0.7, \min[1, 1 - 0.6 + 0.4]], & x = x_3 \end{cases}$$

$$= \sup \begin{cases} 0.6, & x = x_1, \\ 0.4, & x = x_2, \\ 0.7, & x = x_3 \end{cases}$$

$$= 0.7.$$

- Finally, we have that $B'(y_1) = 0.9$ and $B'(y_2) = 0.7$.

3. Using Dienes-Rescher implication, we have

$$B'(y) = \sup_{x \in U} \min[\mu_{A'}(x), \max[1 - A(x), B(y)]].$$

- For $y = y_1$ is valid

$$B'(y_1) = \sup_{x \in U} \min[\mu_{A'}(x), \max[1 - A(x), B(y_1)]]$$

$$= \sup \begin{cases} \min[0.6, \max[1 - 0.5, 1]], & x = x_1, \\ \min[0.9, \max[1 - 1, 1]], & x = x_2, \\ \min[0.7, \max[1 - 0.6, 1]], & x = x_3 \end{cases}$$

$$= \sup \begin{cases} 0.6, & x = x_1, \\ 0.9, & x = x_2, \\ 0.7, & x = x_3 \end{cases}$$

$$= 0.9.$$

- For $y = y_2$ is valid

$$B'(y_2) = \sup_{x \in U} \min[\mu_{A'}(x), \max[1 - A(x), B(y_2)]]$$
$$= \sup \begin{cases} \min[0.6, \max[1-0.5, 0.4]], & x = x_1, \\ \min[0.9, \max[1-1, 0.4]], & x = x_2, \\ \min[0.7, \max[1-0.6, 0.4]], & x = x_3 \end{cases}$$
$$= \sup \begin{cases} 0.5, & x = x_1, \\ 0.4, & x = x_2, \\ 0.4, & x = x_3 \end{cases}$$
$$= 0.5.$$

- Finally, we have that $B'(y_1) = 0.9$ and $B'(y_2) = 0.5$.

4. Using the Mamdani 2 implication, we have

$$B'(y) = \sup_{x \in U} \min[\mu_{A'}(x), A(x)B(y)].$$

- For $y = y_1$ is valid

$$B'(y_1) = \sup_{x \in U} \min[\mu_{A'}(x), A(x)B(y_1)]$$
$$= \sup \begin{cases} \min[0.6, 0.5 \cdot 1], & x = x_1, \\ \min[0.9, 1 \cdot 1], & x = x_2, \\ \min[0.7, 0.6 \cdot 1], & x = x_3 \end{cases}$$
$$= \sup \begin{cases} 0.5, & x = x_1, \\ 0.9, & x = x_2, \\ 0.6, & x = x_3 \end{cases}$$
$$= 0.9.$$

- For $y = y_2$ is valid

$$B'(y_2) = \sup_{x \in U} \min[\mu_{A'}(x), A(x)B(y_2)]$$
$$= \sup \begin{cases} \min[0.6, 0.5 \cdot 0.4], & x = x_1, \\ \min[0.9, 1 \cdot 0.4], & x = x_2, \\ \min[0.7, 0.6 \cdot 0.4], & x = x_3 \end{cases}$$
$$= \sup \begin{cases} 0.2, & x = x_1, \\ 0.4, & x = x_2, \\ 0.24, & x = x_3 \end{cases}$$
$$= 0.4.$$

- Finally, we have that $B'(y_1) = 0.9$ and $B'(y_2) = 0.4$.

CONCLUSION

The presented example demonstrates that the generalized modus ponens can be successfully applied using different fuzzy implication operators. Although the same fuzzy sets and the same inference procedure were used in all cases, the resulting fuzzy conclusions were not identical. This confirms that the selected implication operator has a significant influence on the outcome of the inference process. The comparison also shows that different implication models preserve and propagate uncertainty in different ways. Therefore, the choice of a fuzzy implication should be made according to the requirements of the specific application, since it directly affects the behavior, accuracy, and interpretability of the resulting fuzzy controller.

The proposed methodology establishes a systematic approach to the design and implementation of fuzzy controllers for systems involving uncertainty and imprecise information. Their capability to represent human expertise through linguistic rules, together with their flexibility and transparency, makes fuzzy controllers a valuable solution for a wide range of control applications. Future research may focus on improving controller performance through the optimization of membership functions, the automatic generation of fuzzy rules, and the combination of fuzzy logic with adaptive and machine learning methods.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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OTHER TOPICS

OSTALE TEME

DIGITAL TOURISM AND TOURISM 4.0 AS A CONCEPT OF THE FUTURE

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ABSTRACT

Tourism 4.0 encompasses the integration of the most advanced digital technologies, including artificial intelligence (AI), the Internet of Things (IoT), virtual reality (VR), augmented reality (AR), blockchain technology, and advanced data analytics. These innovations facilitate a comprehensive transformation within the tourism industry, aimed at improving the user experience, optimizing operational efficiency, and promoting sustainable practices. Through a systematic literature review, meta-analysis, and thematic analysis, this study identifies key themes concerning service personalization, economic contributions to local communities, and challenges associated with digitalization. The research questions deal with the main advantages and obstacles presented by digital technologies, their role in sustainable development, their impact on service quality, and their contributions to local communities. The results indicate the transformative potential of digital technologies for the future of tourism, while also highlighting the challenges related to data security and privacy. This document provides a framework and practical recommendations for the advancement of Tourism 4.0 as an emerging field of study.

Key words: tourism 4.0, AI, IoT, VR, AR, future tourist experience, impact on local communities

INTRODUCTION

Digitalization, which includes a wide range of technologies from artificial intelligence to blockchain, is the foundation of the fourth industrial revolution and has a deep impact on the tourism industry [1]. The process of digital transformation is fundamentally changing the way consumers plan, book, and engage in their trips. Innovations like artificial intelligence and the Internet of Things make it easier to personalize experiences and optimize operational processes, creating opportunities for economic and environmental sustainability. This paper examines the impact of Tourism 4.0 on the future landscape of the tourism industry and explores the role of

digital innovations in promoting economic sustainability and helping destinations adapt to emerging market trends. The research questions were designed to clarify the main benefits and challenges associated with this evolution, assess its impact on sustainability and service quality, and evaluate its contribution to the economic development of local communities.

Formulating research questions is key to clarifying the fundamental aspects of Tourism 4.0:

- What are the advantages and what are the obstacles associated with the implementation of digital technologies in the tourism sector?
- What is the impact of Tourism 4.0 on the sustainability of tourist destinations?
- How do digital technologies affect the customer experience?
- How does digitalization benefit local communities?

The introduction provides an overview of the concept of Tourism 4.0 and explains why it is important for the development of the sector in tourism, key research questions are outlined. The theoretical framework explains the main technologies of the Fourth Industrial Revolution that enable Tourism 4.0, including the application of smart technologies in tourist destinations and their impact on sustainability. The research methodology explains the process of data collection, literature analysis, and the use of meta-analysis and thematic analysis to identify key themes. The research results show the analysis results organized according to main themes, which are economic sustainability, personalization of the user experience, and sustainable development of tourist destinations. In the discussion, the challenges and opportunities related to the implementation of Tourism 4.0 are analyzed, as well as its impact on local communities. The conclusion presents the key results and highlights recommendations for future development and research, focusing on long-term sustainability and data security.

THEORETICAL FRAMEWORK OF THE RESEARCH

The theoretical framework of this paper focuses on analyzing the transformative role of digital technologies in tourism, specifically on the concept of Tourism 4.0, which arises from the Fourth Industrial Revolution. The mentioned revolution represents a new era of applying digital innovations in nearly all industries, including the tourism sector, transforming traditional business models and creating new opportunities for personalizing customer services, increasing sustainability, and managing resources more efficiently [2]. Tourism 4.0 relies on technologies like artificial intelligence, the Internet of Things, blockchain, virtual reality, and augmented reality, which together make it possible to tailor experiences to the needs of modern users, improve business, and support sustainable development of destinations. Technological infrastructure and its use in tourism have the potential to enhance user experiences, reduce costs, empower local communities, and provide security and transparency for transactions in the tourism sector [3].

The Fourth Industrial Revolution and Its Technologies

The Fourth Industrial Revolution marks an era of integrating advanced digital technologies into almost every aspect of modern life, from business processes and social interactions to individual user experiences. The revolution is transforming various sectors, including tourism, which is going through deep changes in how services are delivered, how customers are reached, and how resources are managed [2]. The main drivers of this revolution include a wide range of technologies that enable personalization, optimization, and security, as well as new opportunities for sustainable development. Tourism 4.0 uses these same technologies to improve services and enhance the user experience, making them personalized, dynamic, and secure. One of the key technologies enabling Tourism 4.0 is artificial intelligence (AI). This technology allows understanding and analyzing user preferences and adjusting services based on collected data, which increases user satisfaction and loyalty [3]. Artificial intelligence algorithms in tourism can predict user needs, offer personalized recommendations, and tailor travel experiences to their specific interests. For example, AI-based hotel systems can analyze previous user choices to customize the offering of accommodation, services, and entertainment activities. Another important technology is the Internet of Things (IoT), which connects physical devices like sensors,

smart devices, and other tech solutions, allowing for real-time data collection and analysis. Through IoT, tourist destinations can monitor resource consumption, like energy and water, which helps optimize resource use and reduce their impact on the environment [1]. IoT also allows for a better understanding of user behavior patterns, which makes it easier to customize offerings and improve operational efficiency. For example, hotels can use IoT to control room temperature based on the number of guests, thus reducing unnecessary energy consumption. Blockchain technology also plays an important role in Tourism 4.0, increasing the security and transparency of transactions. Blockchain creates a decentralized network where data is stored in secure blocks, allowing for a high level of security and reducing the need for intermediaries in financial transactions [4]. The use of blockchain technology in tourism allows guests and service providers to make safer bookings, conduct direct financial transactions, and even set up personalized loyalty programs without needing complex intermediary systems. Finally, virtual reality (VR) and augmented reality (AR) technologies let tourists 'experience' destinations before they actually arrive. VR offers a fully virtual experience of a tourist spot, while AR enhances the real world with digital information and enriched content. The use of these technologies in tourism allows visitors to virtually get to know places, reducing the chance of dissatisfaction while increasing their interest and engagement [5]. AR also helps in interpreting cultural sites by providing interactive information about historical events, cultural heritage, and local attractions, which helps preserve the destination's identity and promotes cultural tourism. All these technologies form the foundation of Tourism 4.0 and make it possible to build new service models that are tailored to the needs of today's users and focused on sustainable development. Integrating these advanced technologies into tourism not only improves the quality of customer service but also optimizes resource management, providing long-term benefits to local communities and the environment.

Smart Tourism and Smart Destinations

Smart tourism has emerged as a concept based on using advanced digital technologies to optimize resources and enhance tourist experiences. As an example of this concept, smart destinations use IoT sensors and data analytics to manage resources like energy, water, and space in an eco-friendly way [3]. By using these technologies, destinations can track visitors' movements and behavior and provide personalized recommendations, which enhances user satisfaction. Smart tourism is the foundation of a sustainable model that considers the needs of local communities and the environment. For example, cities that adopt smart technologies can monitor tourist flow to reduce congestion in the most visited areas, making for a better experience for tourists and a more comfortable life for local residents. Besides that, the collected data allows destinations to predict resource consumption needs and plan necessary interventions in advance, which reduces negative impacts on the environment and improves long-term sustainability.

Sustainable Development in Tourism

Sustainable development is becoming a key aspect of Tourism 4.0 as more and more destinations use digital technologies to support environmental, economic, and social sustainability goals. By using IoT technologies, destinations can reduce resource consumption like energy and water, helping to protect the environment and lower their ecological footprint [2]. Sustainable development also includes economic aspects, with blockchain technology allowing transparent tracking of financial transactions, which encourages local development by supporting small entrepreneurs and local producers [4]. Social sustainability, an important part of Tourism 4.0, refers to preserving cultural heritage and promoting local identity. Technologies like augmented reality allow visitors to interact with historical and cultural landmarks, which increases understanding and respect for local culture [5]. For example, augmented reality apps can allow tourists to learn about local history and customs through interactive guides, helping preserve cultural identity and promote local heritage. By putting sustainability at the center of their strategies, Tourism 4.0 aims to create a balance between economic benefits and ecological priorities, making destinations more resilient and appealing to visitors who increasingly value sustainability.

RESEARCH METHODOLOGY

To analyze the effects of digital transformation and Tourism 4.0, this paper uses a systematic methodological approach based on reviewing relevant literature and using qualitative research methods like meta-analysis and thematic analysis. The goal of this systematic approach is to provide a comprehensive overview of the existing literature to identify key themes, patterns, and trends related to the use of advanced technologies in tourism, with a special focus on personalization, sustainability, and economic benefits for local communities.

Data Collection and Literature Selection

Data collection was carried out using articles from relevant academic databases like Google Scholar, by selecting articles related to Tourism 4.0, digital technologies, sustainable development, and smart directions in tourism development. In the selection process, special attention is given to works that provide empirical and theoretical knowledge on the application of digital technologies, which allows for a comprehensive analysis of the impact of Tourism 4.0 on the tourism industry.

Meta-analysis

Meta-analysis is used to combine results from different studies on Tourism 4.0 to assess the overall impact of digital technologies on the tourism industry. This method helps organize data on the effects of digitalization on aspects like personalizing the customer experience, transaction security, resource sustainability, and economic benefits. A meta-analysis involves showing the results of research from multiple sources to get an idea of the overall direction of development and the impact of digitalization on the tourism industry.

Thematic Analysis

Thematic analysis was applied to identify the main themes and patterns in the existing literature on Tourism 4.0. This method allows for the identification of key aspects and trends in the use of digital technologies in tourism, such as increased personalization, sustainability, and economic benefits for local communities. The analysis involves picking out and interpreting patterns in the data, which gives a deeper understanding of how digital technologies are transforming the tourism sector and laying the groundwork for sustainable development.

RESEARCH RESULTS

This chapter presents the results derived from the meta-analysis and thematic analysis of the collected literature, with a particular focus on the impact of Tourism 4.0 on tourist destinations. The analysis focuses on three key areas: economic sustainability, personalization of user experiences, and sustainable development.

Economic Sustainability

An extensive meta-analysis covering various studies on the implementation of blockchain technology indicates that Tourism 4.0 plays a significant role in improving the economic sustainability of destinations. This improvement is primarily achieved through enhanced transparency of financial transactions, reduced operational costs, and greater direct market access for local entrepreneurs [4], [6].

Using blockchain technology allows for safer and more efficient transactions, which reduces the reliance on intermediaries, thereby lowering associated costs and increasing the security of financial data. The results support the idea that blockchain technology can promote economic stability and boost revenue in the tourism sector, bringing benefits to both destinations and local communities [7]. The thematic analysis revealed noticeable patterns that highlight the importance of Internet of Things (IoT) technology in improving resource optimization and helping reduce costs. For example, destinations that use IoT sensors to monitor energy and water consumption experience a decrease in operating costs and an improvement in efficiency [1]. The analysis shows that tourist destinations using IoT systems have better control over their resources and show increased operational efficiency, which leads to lower costs and greater economic sustainability

[1]. The results highlight the potential of IoT to reduce environmental impact while also boosting economic profitability.

Personalizing User Experiences

A meta-analysis of existing literature on implementing artificial intelligence (AI) technologies in the tourism sector shows that digital innovations make it easier to achieve a high level of personalization, which in turn boosts user satisfaction and encourages customer loyalty [8], [3], [9]. Empirical studies suggest that artificial intelligence algorithms, by analyzing large datasets related to user behavior, are able to customize offers to match the different interests of individual visitors. For example, it has been shown that providing personalized itineraries and tailored recommendations increases overall tourist satisfaction, which in turn boosts the likelihood of them returning to the destination. A meta-analysis confirms the claim that the principles of Tourism 4.0 give destinations a competitive edge through personalization, a phenomenon that also reflects on their economic success. The thematic analysis revealed noticeable patterns that show the capabilities of Internet of Things (IoT) sensors and data analytics tools in enabling a personalized user experience in real time. For example, IoT sensors placed in hotel environments can autonomously adjust temperature and lighting settings based on individual guest preferences, enhancing both the overall experience and comfort during their stay [3], [5]. The identified patterns show that IoT technology can be used to continuously adjust service offerings according to the development of tourist preferences. This adaptability not only boosts customer satisfaction but also contributes to the overall success of tourism businesses.

Sustainable Development

A meta-analysis of existing literature on sustainable development shows that Internet of Things (IoT) technology significantly contributes to reducing the ecological footprint of tourist destinations. By using IoT sensors to monitor resource consumption in real time, these destinations can improve energy and water management efficiency, thereby mitigating negative environmental impacts and promoting sustainability [3], [5]. Meta-analysis findings show that destinations implementing IoT technologies achieve significant reductions in greenhouse gas emissions, reinforcing the idea that Tourism 4.0 can be both sustainable and environmentally responsible. The results of the thematic analysis highlight the significant role of augmented reality (AR) technology in promoting sustainability by preserving and showcasing cultural heritage. A review of existing literature on the use of AR in the tourism sector shows that AR makes it easier for tourists to access information about local culture, which helps preserve cultural resources, while also encouraging responsible behavior among visitors [3], [1]. Furthermore, AR applications offer opportunities for virtual tours and deliver interactive content related to historical events, traditions, and cultural landmarks, which not only increase visitor engagement but also support the preservation of cultural identity. Tourism 4.0 represents a transformative paradigm that integrates key technologies linked to the Fourth Industrial Revolution, reshaping the tourism industry. The integration of technologies like blockchain, artificial intelligence (AI), the Internet of Things (IoT), and augmented reality (AR) is revolutionizing the processes through which tourist destinations are developed, resources are managed, and visitors are provided with personalized experiences [1]. The synthesis of results highlights the interconnected effects of Tourism 4.0 on economic sustainability, tailoring customer experiences, and the sustainable development of tourist destinations. A key part of Tourism 4.0 is its role in boosting the economic sustainability of tourist spots, especially through innovative technologies like blockchain and Internet of Things (IoT) systems. Findings from the meta-analysis show that blockchain technology is crucial for increasing transparency and security in financial transactions. By cutting out middlemen, blockchain helps reduce costs and allows direct transactions between tourists and service providers, which boosts market competitiveness and gives local businesses more direct access to potential customers. Additionally, IoT technologies contribute to this sustainability by allowing tourist facilities to optimize operational costs through monitoring and managing resources, including energy and water consumption. As a result, by minimizing resource use and streamlining expenses, tourist

destinations can establish a stable financial framework that supports their long-term economic sustainability. A critical aspect of Tourism 4.0 is about personalizing user experiences, which is made easier by sophisticated analytics tools and artificial intelligence (AI) technologies. Findings from the thematic analysis show that integrating AI and the Internet of Things (IoT) promotes a significant level of customization, boosting user satisfaction. By using data on past behaviors and preferences, AI systems can offer personalized suggestions for travel plans, activities, and accommodations that match the unique needs of each traveler. Additionally, IoT technology further enhances this personalization by using sensors that adjust environmental conditions in real time, ensuring optimal comfort for visitors and providing experiences that meet the high expectations of modern travelers. Such a high level of personalization not only boosts customer satisfaction and loyalty but also gives destinations a competitive edge in attracting and keeping visitors. The sustainable development of tourist destinations in the context of Tourism 4.0 is increasingly enabled by the use of advanced technologies, like the Internet of Things (IoT) and augmented reality (AR). These technologies help make resource use more efficient while promoting the preservation of cultural heritage. IoT sensors are key to improving environmental sustainability by allowing precise monitoring of resource consumption, which helps reduce the ecological footprint of tourist destinations. During the peak tourist season, IoT systems can effectively manage the flow of visitors, directing tourists and regulating their distribution across different locations, which helps protect the environment and reduces pressure on infrastructure. Additionally, augmented reality contributes to social sustainability by providing tourists with interactive and informative ways to engage with a destination's cultural resources. AR apps offer additional insights into the historical significance and relevance of various landmarks, fostering a sense of responsibility and encouraging contributions to the preservation of cultural heritage. Tourism 4.0 isn't just about technological progress; it's a fundamental shift in how destinations operate and interact with their resources, visitors, and local communities. Using advanced technologies makes it easier to develop the tourism sector sustainably and responsibly, giving destinations a framework that boosts economic resilience, increases visitor satisfaction, promotes environmental goals, and offers a holistic approach to tourism development that considers economic, social, and environmental factors, creating conditions for long-term sustainable tourism that benefits not only visitors but also local communities and the environment.

DISCUSSION

This part of the paper examines the research findings in relation to the research questions posed, followed by discussions on the study's recommendations and limitations. The analysis highlights the main challenges and opportunities that Tourism 4.0 presents for the tourism sector, with a particular focus on the involvement of local communities and the long-term implications for the development of this paradigm. Empirical evidence shows that Tourism 4.0 offers a host of benefits within the tourism industry, including improved economic sustainability, tailored customer experiences, and greater commitment to environmental care [4], [6]. Implementing technologies like blockchain boosts transaction security and transparency of financial info, which in turn helps lower operational costs and gives local entrepreneurs direct access to the market. Using Internet of Things (IoT) sensors guides resource usage, helping cut costs and improve environmental efficiency [1]. On the other hand, adopting digital technologies in the tourism sector comes with several challenges, with data security and user privacy being the most important issues. Extensive collection of user data requires the implementation of strong data protection measures to prevent privacy breaches [3]. The use of augmented reality (AR) gives tourists access to information about local culture and history, promoting responsible behavior and the preservation of cultural resources [5]. Tourism 4.0 serves as a foundational framework for encouraging long-term sustainability in the tourism industry. How do digital technologies impact the user experience? The findings show that digital technologies, including artificial intelligence (AI) and the Internet of Things (IoT), play a key role in improving customer experiences by making service personalization easier. Artificial intelligence algorithms are used to analyze user preferences, providing tailor-made recommendations that not only boost tourist satisfaction but also encourage

loyalty to the destination [8]. IoT sensors allow real-time modifications of environmental conditions, such as temperature and lighting in hotel accommodations, which contributes to a better overall experience and greater comfort for users [3]. While implementing personalized services increases the competitiveness of tourist destinations, it also presents significant challenges related to data privacy. Delivering tailored experiences involves collecting and processing users' personal data, which requires strict compliance with privacy regulations.

The digitization of tourism services offers significant benefits to local communities by increasing job opportunities, improving the transparency of financial transactions, and encouraging economic development. Implementing blockchain technology allows local entrepreneurs to directly participate in the global market, which helps boost economic growth and smooth out seasonal income fluctuations [4]. Furthermore, integrating Internet of Things (IoT) and augmented reality (AR) technologies provides innovative ways to promote local culture and heritage, which in turn supports the preservation of community identity and increases visitors' appreciation of the intrinsic value of local resources [3]. It's essential to involve local communities in shaping tourism initiatives and offer them education on using digital technologies. This approach allows them to actively participate and helps achieve the best benefits from Tourism 4.0. Based on the research conducted, recommendations are proposed for a more successful implementation of Tourism 4.0. It's crucial to establish data protection standards, which include well-defined protocols that regulate the collection and use of personal data to protect user privacy. There's also a need for support in developing Internet of Things (IoT) and augmented reality (AR) technologies that facilitate optimized resource use, minimize environmental impact, and help preserve cultural heritage. It is recommended to carry out further research on the impact of digital technologies on sustainability, environmental preservation, and the protection of cultural resources to ensure alignment with sustainable development goals. Promoting education in local communities is important so that they can fully take advantage of Tourism 4.0; it's key to implement educational initiatives focused on digital technologies and their associated benefits. The research was conducted by reviewing available literature, which may limit the breadth of information and the geographic context considered. Future studies should include empirical research carried out in specific tourist destinations to get more accurate data on the actual effects of Tourism 4.0. Further research should focus on longitudinal studies exploring the implications of digital technologies on social sustainability, especially regarding the preservation of cultural resources and their impact on local communities. The emergence of Tourism 4.0 marks a potential shift in the paradigm within the tourism industry; however, it also presents challenges that require further research to ensure alignment with sustainable development goals and to optimize benefits for all stakeholders involved.

CONCLUSION

The research results highlight the potential of Tourism 4.0 to significantly enhance the sustainable development of the tourism industry. This improvement is primarily made possible through personalized user experiences, resource optimization, and promoting economic benefits for local communities. The integration of advanced technologies, including artificial intelligence (AI), the Internet of Things (IoT), and blockchain, allows tourist destinations to strengthen operational efficiency, minimize costs, and increase market accessibility for local entrepreneurs. Technological progress contributes to the stability and sustainability of the local economy. At the same time, the opportunities offered by personalization help enrich the user experience, increasing visitor satisfaction and encouraging loyalty to the destination. Despite this, there are still significant challenges in protecting privacy and ensuring data security, especially regarding the extensive collection and analysis of user data. Effective implementation of Tourism 4.0 requires setting strict data protection standards and complying with relevant regulations.

A key component involves getting local communities involved in digital initiatives, which makes it easier to fairly share benefits and promote social sustainability in tourism development. Future research efforts should focus on exploring the long-term implications of digitalization,

especially when it comes to adapting technologies in different tourism settings. The goal of this approach is to make sure that the benefits linked to Tourism 4.0 are available and useful to all stakeholders and communities. It's recommended to carry out further research on the effects of Tourism 4.0 on preserving cultural heritage and natural resources. Such studies would help establish Tourism 4.0 not just as a basis for economic progress, but also for a holistic improvement of sustainability within the tourism sector.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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КОГНИТИВНИ МЕХАНИЗМИ КОНЦЕПТУАЛНЕ МЕТАФОРЕ У ПОЛИТИЧКОЈ КОМУНИКАЦИЈИ У ПОСЉЕДЊОЈ ПРЕДСЈЕДНИЧКОЈ КАМПАЊИ У САД

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АПСТРАКТ

Једна од дисциплина која проучава ментално функционисање појединца је когнитивна лингвистика. Предмет овог рада је анализа феномена метафоре као средства доживљавања и разумијевања апстрактних искустава. Стога је предмет овог истраживачког пројекта истраживање метафоре не као стилске фигуре говора, већ као когнитивног механизма. Подаци за ову студију су корпус неколико различитих концептуалних метафора изведених из говора двају америчка политичких кандидата на предсједничким изборима 2024. године. Циљ студије је да опише и класификује, а затим интерпретира и објасни најчешће типове метафора и њихову заступљеност у политичком дискурсу. Посебна пажња је усмјерена на равнотежу између два модела анализе корпуса: квалитативног и квантитативног. Након што смо корпус анализирали и резултате упоредили, могли смо закључити да политички дискурс обилује различитим метафоричко-лингвистичким изразима. Штавише, закључено је да су изворни домени РАТА и ПУТОВАЊА најпродуктивније категорије. Ово доказује кључну улогу структурне метафоре, кроз коју се разумијевање апстрактног концепта структурира коришћењем конкретнијег.

Кључне ријечи: когнитивна лингвистика, концептуална метафора, апстрактни домен, конкретни домен, структурна метафора

УВОД

Гледано из наше људске перспективе, можемо рећи да се догађаји попут појаве мисли и говора сматрају преломним и у биолошкој и у културној еволуцији човјека. Говорење је немогуће одвојити од мишљења о чему свједочи низ биохемијских можданих процеса који тек путем говорења доспијевају у човјеку до прага свјеснога. Језик је средство изражавања,

преношења и обликовања мисли. Мисао кроз језик добија своју форму постајући одраз наше личности, нашег идентитета. Језик је инструмент креативности и моћи; средство социјалне кохезије и сепарације. Припадници неке друштвене заједнице постају свјесни свог положаја помоћу језика који је у стању да прикаже најбоље и најгоре људске особине, испољавајући тако своју моралну вриједност. Сваки од наведених процеса могуће је разматрати из угла посебне диспциплине познате под називом когнитивна лингвистика, која објашњава да у нашем појмовном систему постоје сложени когнитивни процеси које с лакоћом обављамо а чије сложености нисмо свјесни.

Такве когнитивне функције бивају обликоване кроз језик, односно метафору. У литератури се помињу различите дефиниције метафоре, од традиционалне стилске фигуре па до когнитивне теоријске концепције.

Традиционалном схватању супротставила се когнитивна лингвистика са тумачењем да је метафора прије свега нешто што „does not just expresses previously undiscovered analogies and suggest new possible relationships; metaphor as a speech act performs certain functions; it has illocutionary force“ [1]. Исто тако, Лејкоф и Џонсон [2] уочавају да је суштина метафоре „in understanding and experiencing one kind of thing in terms of another“. Дефинише се као разумијевање једног апстрактнијег феномена (политика, љубав, вријеме и сл.), помоћу другог, конкретнијег физичког искуства. Према наведеним ауторима, метафора представља повезивање ових двају домена нашег знања при којем долази до скупа пресликавања из конкретног у апстрактни домен. Бит такве метафоре јесте разумијевање једне појаве помоћу карактеристика неке друге појаве. Они подвлаче да је метафора ствар мишљења, и да је као таква далеко од традиционалног, уобичајеног језичког израза.

У овом раду, као што се да наслутити из самог назива, бавићемо се метафорама, тачније врстама концептуалних метафора у политичким говорима. Другим ријечима, предмет овог рада јесте истраживање метафоре не као стилске фигуре, него као когнитивно-лингвистичког феномена. Концептулна метафора је, како истиче Ковечес, један од когнитивних конструисања значења на темељу којег повезујемо два концептуална домена: *изворни* (енгл. *source domain*) и *циљни* (енгл. *target domain*) [3].

Концептуалне метафоре могуће је класификовати према функцији коју обављају, њиховој утемељености на тјелесном, друштвеном и културном искуству и нивоу општости. У оквиру когнитивно-лингвистичког приступа, издвојићемо *структурне метафоре*. Њихова улога јесте омогућити говорнику разумијевање апстрактног, циљног домена кроз структуру конкретног, изворног домена. И најзад, поред поменутих категорија и функција, наше истраживање укључиваће и прагматични ниво реализације метафоре гдје ћемо кроз примјере показати сврху појављивања оваквих метафора у политичким говорима. На тај начин ћемо, узимајући у обзир њену сложену функцију и различите видове испољавања, проблему метафоре прићи постепено.

МЕТОДОЛОГИЈА

Наше истраживање ће се темељити на два модела анализе корпуса: квалитативног и квантитативног. Кроз квалитативну фазу настојаћемо идентификовати, интерпретирати и класификовати сакупљене податке, а све у циљу задовољења основних принципа дефинисања метафоре. На основу ове херменеутичке анализе, утврдиће се основна квалитативна својства, суштине, услови, узроци и класификације метафоре. Исто тако, позабавићемо се и другим моделом анализе, квантитативним, на темељу којег ћемо процијенти заступљеност метафоричко-лингвистичких израза и концептуалних метафора у корпусу.

Сврха овог истраживачког пројекта јесте да квалитативним и квантитативним проучавањем извршимо систематски преглед и анализу метафора и метафоричко-лингвистичких израза, како би дошло до квалитетнијег сагледавања поменутог феномена са становишта когнитивне лингвистике. Кроз студиј релевантне литературе, кренућемо у испитивање начина на који наш мозак функционише и његове повезаности са језиком.

Упоређујући податке добијене бројчаном анализом корпуса, покушаћемо открити до којег степена су метафоре сличне или различите. Изношењем главних теоријских поставки, у којима се политички говор ослања на неколико универзалних домена, циљ нам је идентификовати када и како се метафорички арсенал појављује и који су услови његовог формирања. Кренули смо од основне хипотезе да метафора није присутна само у оквиру књижевно-умјетничког текста, те да присуство метафоре у корпусу нема функцију да код читаоца изазове само стилистички ефекат. Таквој претпоставци доприноси когнитивно-лингвистички приступ Лејкофа и Џонсона, који метафору смјешта у мисаони процес који се рефлектује у свакодневном језику. Тако је политика представљена кроз ратну терминологију, гдје су политички противници непријатељи, а изборне кампање ратиште. Даље, политички процеси су попут путања које имају своје успоне и падове. И најзад, политика је структура која се гради, руши и обнавља своје темеље.

Исто тако, циљ нам је да појаснимо прагматичну продуктивност метафора и да утврдимо могући значај таквих метафора у обликовању политичког дискурса. У политичком дискурсу, метафоре чине моћна средства убјеђивања и манипулације. У стању су да открију и прикрију одређене аспекте проблема изазивајући снажне емоционалне реакције јавности. Употребом метафоре, политички кандидати мудро обликују политички дискурс и мијењају перцепцију јавности без нужности за рационалним аргументима.

Наше претпоставке су да у политичким говорима неће доћи до већих колебања када су у питању конкретни домени метафоре и да ће мисли наших говорника највише бити реализоване кроз концепт путовања. То подразумијева да оба говорника користе мање-више исте метафоричко-лингвистичке изразе. Једине разлике могле би се огледати у степену заступљености тих метафоричко-лингвистичких израза. И најзад, претпостављамо да ће корпус сачињен од примјера из говора демократског политичког кандидата бити богатији у односу на говоре републиканског кандидата.

РЕЗУЛТАТИ

Корпус за ово истраживање представљају говори двају америчких политичара: Доналда Трампа, кандидата Демократске странке на предсједничким изборима 2024. године и Камале Харис, кандидата Републиканске странке. Корпус чине два говора о прихватању предсједничке номинације објављена на интернету 18. јула 2024. (енг. *Donald Trump's Presidential Nomination Acceptance Speech*) и 22. августа 2024. године (енг. *Kamala Harris' Presidential Nomination Acceptance Speech*).

Како научни метод претпоставља образлагање оног што је мање познато оним што је познатије, истраживањем дискурса наших двају политичких кандидата дошли смо до закључка да оба говорника користе мање-више исте метафоричко-лингвистичке изразе, барем када је концептуална метафора у питању.

Истраживањем метафоре као когнитивног феномена, највећи број метафоричко-лингвистичких израза смо пронашли везаних за структурну категорију метафоре па смо се тако опредијелили да, због њихове обимности, највећи дио наше пажње усмјеримо ка њима. И напосљетку, оправдано смо претпоставили да су структурне метафоре легло разних језичких израза. У прилог томе иде и чињеница да је у 2 говора пронађено 42 примјера метафоричко-лингвистичких израза од којих се: 25 односи на изворни домен рата, док се 16 односи на изворни домен путовања.

За поменуте изворне домене које ћемо обрадити у овом раду, наводимо по четири карактеристична примјера (два из корпуса Доналда Трампа и два из корпуса Камале Харис).

Такође смо претпоставили да ће корпус Доналда Трампа бити богатији и потпунији и да ће као такав задовољити категорије битне за разумијевање свих врста метафора. Исто тако је видљиво да су изворни домени корпуса Камале Харис остварени мањим бројем примјера, што не умањује њихову валидност.

Као што се из Табеле 1. види, постоји осцилација у броју примјера унутар сваке категорије.

Табела 1. Преглед изворних домена

ИЗВОРНИ ДОМЕНИ	МЕТАФОРИЧКО-ЛИНГВИСТИЧКИ ИЗРАЗИ	
ГОВОРНИЦИ	ДОНАЛД ТРАМП	КАМАЛА ХАРИС
РАТ	25	2
ПУТОВАЊЕ	7	8
УКУПНО	32	10

ДИСКУСИЈА

Видјели смо да метафора прожима наш цјелокупни концептуални систем. Због великог броја апстрактних појмова са којима се свакоднево сусрећемо и који нису јасно дефинисани у нашем искуству (емоције, идеје, вријеме и сл.), потребно је ухватити корак са другим појмовима који су јаснији, конкретнији (предмети, просторне оријентације и сл.). Концептуалне метафоре су постале плодно тло за изучавање различитих сфера људског живота. Стога, ако су наша друштвена искуства организована у смислу метафора онда политика, као дио друштвеног домена, такође бива метафорички доживљена.

Да је метафора важна и у прагматичком домену, показује нам и Чартерис-Блек: „A metaphor is an incongruous linguistic representation that has the underlying purpose of influencing opinions and judgements by persuasion; this purpose is often covert and reflects speaker intentions within particular context of use“ [4]. Према томе, политички говор кроз метафору има потенцијал да слушаоца убиједи у вриједност апстрактних друштвених идеја (нпр. мир, просперитет, правда), а све то у смислу да придобије, привуче слушаоца. Ковечес и Чартерис-Блек су нас научили да се когнитивни и прагматични ниво надограђују, међусобно преплићу и да су, као такви, врло битан дио анализе политичког дискурса. Да је метафора у политичком говору не само жива него и витална упућује и њена способност да се комбинује са различитим ентитетима и да тако на сложеније начине организује наш појмовни систем.

Према мишљењу Бугарског, метафора је присутна у разним областима људског дјеловања, у којима се јавља импулсивно без свијести о логичким односима између представе и појма који се представља, чинећи централну улогу у креирању друштвене реалности [5]. Истраживања су показала да политички говори наших двају кандидата обилују разним метафоричко-лингвистичким изразима, и то највише оним чији се изворни домени односе на *путовање* и *рат*. Метафоре ће бити класификоване према когнитивној функцији коју обављају, а наша пажња ће највећим дијелом бити усмјерена ка структурним, будући да су најзаступљеније у корпусу који смо истраживали.

Изворни домен ове врсте метафоре пружа богату структуру знања циљном домену. То заправо подразумијева да ће човјек разумјети циљни домен само кроз структуру изворног, па се такав начин разумијевања с правом може назвати метафора.

Прелазимо на преглед свих категорија које су пронађене у оба политичка говора. Почнимо са метафором рата која нас одводи у било коју област људске активности и искуства.

Метафоре рата (енгл. WAR METAPHORS)

Метафоре из домена рата прве су по заступљености у политичком говору Доналда Трампа, док су у говору Камале Харис риједак примјер. Избор овог домена није нимало наиван. Знање које посједујемо о датој области одлучује „whether odd language should be taken as a mistake or as an intentional metaphor [1]“.

Ради илустрације послужићемо се примјерима из корпуса који су већ постали класични примјери концептуалне метафоре помоћу које разумијевамо појам политике, а која гласи POLITICS IS WAR:

(1) And everything I have to give with all of the energy and *fight* in my heart and soul, I pledge to our nation tonight (*Donald Trump's Presidential Nomination Acceptance Speech*, July 18, 2024).

(2) The Democratic party should immediately stop *weaponizing* the justice system and labeling their political *oponent* as an *enemy* of democrats (*Donald Trump's Presidential Nomination Acceptance Speech*, July 18, 2024).

(3) No one should be made *to fight* alone (*Kamala Harris' Presidential Nomination Acceptance Speech,* August 22, 2024).

(4) The future is always worth *fighting for*. And that's *the fight* we are in right now – *a fight* for America's future (*Kamala Harris' Presidential Nomination Acceptance Speech,* August 22, 2024).

Концептуална метафора која обједињује ове изразе је POLITICS IS WAR, што би се могло разложити на концептуални кључ Чартерис-Блека LIFE IS A STRUGGLE FOR SURVIVAL [4]. Сценарио везан за рат огледа се у сценарију политике. Метафоре рата одражавају циљеве.

Метафора POLITICS IS WAR припада групи структурних метафора у којима је апстрактни концепт, као што је политика, структуриран кроз конкретнији концепт, као што је рат. Наше разумијевање овога заснива се на аналогији између друштва и појединца и њихове борбе за опстанак. Кореспонденције које чине метафору POLITICS IS WAR пресликавају сценарио рата на сценарио политике.

ИЗВОРНИ ДОМЕН: РАТ
ЦИЉНИ ДОМЕН: ПОЛИТИКА

Домен рата је снажан, конкретан, високо интелектуалан. Он је набијен емоцијама, напада из прикрајка, одсликава личну пожртвованост ради остварења апстрактних друштвених циљева. Из свега реченог, можемо рећи да се наша два говорника борећи за опстанак на предсједничким изборима врло вјешто служе концептуализацијом и стварањем утиска да су наши друштвени проблеми разумљивији и прихватљивији када су приказани као лични. Кроз примјере које смо навели и Трамп и Харис примјењују оно што је познато и већ доживљено на оно што је релативно ново, страно, а све у циљу да покажу како обоје рационално размишљају о проблемима политике коју заговарају. Начин на који говоре, кроз метафоре рата, заправо обликује начин њиховог дјеловања.

Метафоре путовања (енгл. JOURNEY METAPHORS)

Метафоре путовања у когнитивну лингвистику су уведене од стране Лејкофа и Џонсона осамдесетих година прошлог вијека. Метафоре из домена путовања прве су по заступљености у политичком говору Камале Харис, док су у говору Доналда Трампа нешто рјеђе заступљене.

Погледајмо наведени пар примјера ексцерпираних из политичких говора наших двају предсједничких кандидата:

(5) I see a nation that is ready *to move forward*, ready for *the next step* in *the incredible journey* that is America (*Kamala Harris' Presidential Nomination Acceptance Speech*, August 22, 2024).

(6) When I think about *the path* that we *have traveled* together, I am filled with gratitude (*Kamala Harris' Presidential Nomination Acceptance Speech*, August 22, 2024).

(7) No matter what danger comes our *way,* no matter what *obstacles* lie in our *path*, we will keep *striving forward* our glorious destiny (*Donald Trump's Presidential Nomination Acceptance Speech*, July 18, 2024).

(8) On this *journey*, I am deeply honored to be joined by my amazing wife, Melania (*Donald Trump's Presidential Nomination Acceptance Speech*, July 18, 2024).

Наведени примјери заправо говоре о политичкој кампањи. Пошто је политика, а самим тим и политичка кампања, апстрактна појава, закључујемо да је ово циљна област. Наведени примјери су метафорични јер говоре о политици као путовању.

Путовање, као конкретан концепт, представља снажан и динамичан изворни домен који се састоји од сљедећих елемената: путници, одредиште и правац. Према Чартерис-Блеку наведени примјери би се могли свести на једну универзалну метафору: POLITICS IS A JOURNEY [6]. Кореспонденције које чине метафору POLITICS IS A JOURNEY пресликавају сценарио путовања на сценарио политике.

ИЗВОРНИ ДОМЕН: ПУТОВАЊЕ
ЦИЉНИ ДОМЕН: ПОЛИТИКА

Према томе, свако путовање има своју почетну тачку и своје одредиште што би значило да и политичар, користећи се метафором, жели проћи наведене фазе путовања и реализовати предодређени циљ. Исто тако, овакви обрасци логичког закључивања и разумијевања једног појма помоћу другог за нас имају смисла само зато што их можемо повезати са нашим уобичајеним тјелесним искуствима. Овакво метафоричко разумијевање ситуације функционише у два дијела: прво; постоји скуп метафора које структурирају начин на који поимамо свијет око себе; друго, постоји скуп метафоричких дефиниција које нам омогућавају да такву метафору примијенимо на одређену ситацију [7]. Наша два говорника, Доналд Трамп и Камала Харис, су свјесни да је метафора путовања приступачна и лако разумљива па је стога и користе у циљу ефикаснијег убјеђивања. Она је попут сценарија, па се и Трамп и Харис представљају као водичи нације, њихове политике су мапе, а њихови сљедбеници су сапутници.

ЗАКЉУЧАК

Проучавањем концептуалне метафоре и њене употребе у политичком дискурсу сачинили смо систематски преглед метафоре на когнитивно-лингвистичком нивоу. Реализација концептуалних метафора у корпусу који је анализиран показује степен њихове учесталости у политичкој комуникацији. Концептуалну метафору смо дефинисали као један од спознајних процеса конструисања значења на темељу којег повезујемо изворни и циљни домен путем пресликавања. Прилог овој тврдњи је чињеница да су оба контрастирана корпуса дали примјере метафоре које су далеко од књижевно-умјетничког доживљаја што потврђује и хипотезу коју смо навели на самом почетку истраживања. Овакве нумеричке односе оправдава динамичност концептуалних метафора које су говорницима искуствено ближе а самим тим и учинковитије у остварењу персуазивне функције језика.

Наиме, изворни домени попут путовања и рата својтсвени су свакој реторици и начину њиховог поимања су у суштини исти. Изворни домени путовања и рата чине најбројније категорије у оба корпуса. Динамичност концептуалних метафора у два различита политичка корпуса наводи нас на закључак да је ситуација слична и у осталим јавним комуникацијама.

Реализација концептуалних метафора у анализираном корпусу показује степен њихове учесталости у политичкој комуникацији. Концептуалну метафору смо дефинисали као један од когнитивних процеса конструисања значења на основу којег повезујемо изворни и циљни домен кроз мапирање. Домени попут рата и путовања су инхерентни свакој реторици и начину њиховог разумијевања у оба дискурса су у суштини исти. Домен рата је био доминантнији у говору Доналда Трампа, а домен путовања је био истакнутији у дискурсу Камале Харис. Ово потврђује улогу коју концептуализација има у политичкој интеракцији. С обзиром на то да активирају емоције, метафоре у политичком дискурсу имају снажан реторички и убједљивачки потенцијал. Свака концептуализација у дискурсу открива један аспект стварности уз истовремено скривање другог. Са становишта теоријских и аналитичких импликација овог истраживања, очигледно је да су ови изворни домени бројни и далекосежни – они су дио обичног језика и не могу се замијенити ниједним другим.

Концептулана метафора није језичка игра, него инструмент моћи. Онај ко контролише метафору, често контролише и политичку агенду.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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COGNITIVE MECHANISM OF CONCEPTUAL METAPHOR IN POLITICAL COMMUNICATION DURING THE LAST PRESIDENTIAL CAMPAIGN IN THE USA

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ABSTRACT

One of the disciplines that studies the mental functioning of an individual is cognitive linguistics. The subject of this paper is to analyse the phenomenon of metaphor as a means of experiencing and understanding abstract experiences. Therefore, the subject of this research project is to explore the metaphor not as a figure of speech but as a cognitive mechanism. The data for this study is a corpus of several different conceptual metaphors excerpted from the speeches of two American political candidates in the 2024 presidential election. The aim of the study is to describe and classify, and then interpret and explain the the most frequent types of metaphors and their representation in political discourse. Special attention was focused on the balance between the two models of corpus analysis: qualitative and quantitative. After the corpus has been analysed and the results compared, it can be concluded that the political discourse abounds in various metaphorical-linguistic expressions. Furthermore, it was concluded that the source domains of WAR and JOURNEY are the most productive categories. This proves the key role of structural metaphor, through which the understanding of an abstract concept is structured using a more concrete one.

Keywords: cognitive linguistics, conceptual metaphor, abstract domain, concrete domain, structural metaphor.

XSTUDIO: TRANSFORMING STUDIO PEDAGOGY THROUGH POP-UP-LIVE LEARNING ENVIRONMENTS

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ABSTRACT

Contemporary architectural education increasingly faces the challenge of reconciling academic studio models with the complex realities of spatial practice, which require collaboration, adaptability, and direct engagement with diverse societal actors. Conventional design studios, typically centred on hypothetical briefs and representational outcomes, only partially address the social, material, ecological, and institutional conditions that shape the built environment.

This paper investigates how the architectural design studio can be transformed into a Pop-Up Live Learning Environment through the longitudinal development of xSTUDIO, an experimental teaching line established within APLE Lab Banja Luka. Drawing on a sequence of studio implementations conducted between 2022 and 2026, the study examines the gradual evolution of the pedagogical model across different spatial scales, thematic contexts, and forms of stakeholder collaboration. The analysis is based on a qualitative examination of successive studio iterations, focusing on their organisational structure, learning processes, implementation strategies, and educational outcomes.

The findings reveal a progressive shift from conventional design-based teaching towards an experiential and constructivist model that integrates research, collaborative design, material experimentation, full-scale implementation, and critical reflection within real spatial contexts. Across successive iterations, the studio expanded from experimental interior interventions and small-scale urban actions to institutional environments, territorial landscapes, and living ecological systems, while simultaneously strengthening collaboration with public institutions, cultural organisations, local communities, and private-sector partners.

Rather than proposing a fixed teaching methodology, the paper identifies a set of transferable pedagogical principles through which live learning environments can expand architectural studio education. These include process-oriented learning, collective authorship, stakeholder engagement, implementation literacy, embodied spatial experience, and socially responsible spatial action. The paper argues that such principles provide a robust framework for rethinking contemporary studio pedagogy and offer a transferable model for architectural schools seeking to strengthen the relationship between education, professional practice, and society.

Keywords: architectural education; studio pedagogy; live learning environments; constructivism; experiential learning; socially responsive practice.

INTRODUCTION: FROM DESIGN STUDIO TO LIVE LEARNING ENVIRONMENTS

Contemporary architectural practice increasingly unfolds through collaborative, interdisciplinary, ecological, and socially engaged processes that challenge conventional models of architectural education [1], [2]. While professional practice requires architects to negotiate complex relationships among multiple stakeholders, institutions, material systems, and environmental conditions, architectural education continues to rely predominantly on studio models centred on hypothetical briefs, individual authorship, and representational outcomes. Although the architectural design studio remains the pedagogical core of architectural education, its traditional format has been increasingly questioned regarding its capacity to prepare students for the complexity of contemporary practice [3], [4].

The architectural design studio nevertheless continues to represent a unique environment for learning through experimentation, dialogue, and reflective action. Throughout the twentieth century, particularly following the pedagogical reforms introduced by the Bauhaus ([5] Gropius, 1938), studio education developed around the integration of conceptual thinking, material exploration, and learning by doing [5], [6]. Later, Schön's concept of the *reflective practicum* further established the studio as a setting in which professional knowledge is constructed through iterative cycles of action, reflection, and critique rather than through the transmission of predefined solutions [3]. Recent pedagogical discourse has increasingly emphasized that the studio should be understood not merely as a physical space but as a distinctive pedagogical culture that enables collaborative knowledge construction through situated and practice-based learning [6], [7], [8], [4].

Building upon these foundations, contemporary pedagogical discourse has increasingly drawn on constructivist learning theory, experiential learning, and stakeholder engagement to reconceptualise architectural education. Rather than treating design as the production of architectural objects alone, these perspectives shift attention towards the design of learning processes in which knowledge emerges through collaboration, experimentation, implementation, and critical reflection [9], [3], [7]. Consequently, live studios, design-build programmes, community-based projects, and practice-oriented laboratories have emerged as educational formats that reconnect architectural learning with real contexts, real actors, and real consequences. Their educational value has been demonstrated through enhanced material understanding, collaborative competencies, and stronger links between academic learning and professional practice.

These developments also resonate with recent European initiatives seeking to redefine the relationship between education, sustainability, and society [10]. The New European Bauhaus (NEB) promotes an integrated approach that combines sustainability, inclusivity, aesthetics, and interdisciplinary collaboration through experimental spatial practices [10]. Within this broader framework, the Erasmus+ project *Architecture Pop-Up Lab Exchange (APLE)* ([11] introduced Architectural Pop-Up Laboratories as flexible educational infrastructures designed to connect universities with public institutions, local communities, cultural organisations, and professional practice through experimental, context-based learning.

Against this background, the paper analyses investigate how the architectural design studio can evolve into a Pop-Up Live Learning Environment through the longitudinal development of xSTUDIO, an experimental line established within APLE Lab Banja Luka. The study analyses a

sequence of studio implementations conducted between 2022 and 2026, analysing how successive experiments gradually expanded the pedagogical framework across different spatial scales, thematic contexts, implementation formats, and modes of stakeholder collaboration.

Through the xSTUDIO case study, the paper identifies the transferable pedagogical principles that emerged through its continuous evolution. By analysing this process through the perspectives of contemporary studio pedagogy, constructivist learning, and experiential education, the paper argues that Pop-Up Live Learning Environments provide an adaptable framework for reconnecting architectural education with reflective practice, embodied spatial experience, collaborative knowledge production, and socially responsible spatial action.

THEORETICAL BACKGROUND: FROM STUDIO PEDAGOGY TO LIVE LEARNING ENVIRONMENTS

The Architectural Design Studio as a Learning Environment

The architectural design studio has long occupied a distinctive position within higher education, functioning simultaneously as a site of creative inquiry, technical instruction, critical reflection, and professional socialisation. Since the pedagogical reforms introduced by the Bauhaus, architectural education has increasingly recognised the studio as more than a place for design production, establishing it as a workshop in which knowledge is generated through experimentation, making, and collaboration [5]. This conception fundamentally transformed architectural education by integrating art, craft, and technology within a unified learning environment.

Despite its central role, the contemporary design studio has increasingly been criticised for its limited capacity to address the complexity of present-day architectural practice. Traditional studio formats often remain centred on hypothetical briefs, individual authorship, and representational outputs, while professional practice increasingly demands collaboration across disciplines, engagement with multiple stakeholders, negotiation of institutional frameworks, and responsiveness to ecological and social challenges. As Till [1] argues, architecture is inherently contingent upon external forces that extend beyond disciplinary autonomy, requiring architects to operate within conditions of uncertainty rather than predetermined design problems.

Schön's concept of the *reflective practitioner* further reframed studio education by understanding professional knowledge as emerging through iterative cycles of action, reflection, and adaptation rather than through the application of fixed disciplinary knowledge [3]. From this perspective, the architectural studio becomes not simply a place where projects are produced, but a pedagogical environment in which learning develops through engagement with uncertain situations, critical dialogue, and reflective experimentation.

Constructivist and Experiential Learning in Architectural Education

Contemporary discussions on studio pedagogy increasingly draw upon constructivist and experiential theories of learning, which regard knowledge as actively constructed through experience, social interaction, and critical reflection. Dewey [6] argued that meaningful learning emerges from inquiry situated within authentic situations, while Kolb [9] conceptualised learning as a continuous cycle of concrete experience, reflective observation, conceptualisation, and active experimentation. Together, these perspectives shift educational emphasis from knowledge transmission towards knowledge construction through action.

The social dimension of learning has been further elaborated through Vygotsky's [7] constructivist theory, which positions learning as an inherently collaborative process mediated through dialogue, interaction, and shared problem solving. Building upon these foundations, Jonassen [8] proposed constructivist learning environments characterised by authentic tasks, contextual learning, multiple perspectives, and collaborative knowledge construction. These theoretical positions closely align with architectural education, where design knowledge emerges through continuous interaction between spatial context, material conditions, users, institutions, and environmental systems.

Within architectural education, such perspectives have increasingly encouraged a shift beyond speculative design exercises towards situated, practice-oriented learning environments. Salama [4] argues that contemporary architectural education should extend beyond conventional studio culture by integrating experiential learning, real-world engagement, and interdisciplinary collaboration into the educational process. Rather than treating architecture primarily as the production of formal solutions, these approaches emphasize learning as an evolving process of inquiry, negotiation, implementation, and reflection.

Live Learning Environments and Pop-Up Pedagogies

These theoretical developments have contributed to the emergence of live studios, design-build programmes, community-engaged projects, and practice-based laboratories as alternative models of architectural education. Although differing in format and institutional organisation, these approaches share a common pedagogical premise: architectural knowledge develops most effectively through direct engagement with real places, real actors, and real consequences. Learning therefore becomes inseparable from implementation, collaboration, material experimentation, and societal engagement [2].

Recent European initiatives have further reinforced this educational direction. The New European Bauhaus [10] advocates experimental spatial practices that integrate sustainability, inclusivity, aesthetics, and interdisciplinarity through collaboration between academia, professional practice, public institutions, and civil society. Within this broader framework, the Erasmus+ project *Architecture Pop-Up Lab Exchange (APLE)* [11] introduced Architectural Pop-Up Laboratories as flexible pedagogical infrastructures capable of connecting architectural education with diverse spatial contexts and societal actors through temporary, adaptive, and collaborative learning environments.

Together, these theoretical perspectives suggest that architectural learning is most effective when knowledge is constructed through authentic action, collaborative inquiry, critical reflection, and engagement with real spatial conditions. This conceptual synthesis provides the theoretical foundation for analysing the evolution of xSTUDIO as a Pop-Up Live Learning Environment and for identifying transferable pedagogical principles relevant to contemporary architectural education.

METHODOLOGY

This research investigates how an architectural design studio can evolve into a Pop-Up Live Learning Environment through the longitudinal development of xSTUDIO, an experimental teaching line established within APLE Lab Banja Luka. Rather than documenting individual educational projects, the study examines the gradual transformation of a pedagogical model implemented through successive studio iterations between 2022 and 2026. The primary objective is to identify the pedagogical principles that emerged throughout this evolutionary process and to evaluate their transferability to broader contexts of architectural education.

The study adopts a qualitative longitudinal case-study approach grounded in constructivist and experiential educational theory. A longitudinal perspective was selected because the research focuses not on isolated studio projects but on the continuous evolution of a single pedagogical framework across multiple implementations. This approach enables the identification of recurring patterns, gradual transformations, and emerging educational principles that would remain less visible through the analysis of individual studio projects.

Methodologically, the research combines comparative case-study analysis, reflective pedagogical inquiry, research-through-design, and qualitative process evaluation. Rather than evaluating architectural proposals primarily through formal or aesthetic criteria, the analysis focuses on learning processes, organisational structures, stakeholder relationships, implementation strategies, and competency development.

The empirical basis of the research consists of four successive xSTUDIO implementations realised between 2022 and 2026 within APLE Lab Banja Luka. These studio iterations are

interpreted not as independent educational projects but as consecutive developmental phases of a single pedagogical model.

The analysis draws upon multiple sources of qualitative evidence, including studio briefs, project documentation, design outputs, implementation records, workshop documentation, public exhibitions, photographic archives, pedagogical observations, participant reflection forms, stakeholder feedback, and documentation of realised spatial interventions. The triangulation of these materials enables a comprehensive interpretation of both the pedagogical process and its evolving organisational structure.

To ensure systematic comparison across successive studio iterations, the research applies a common analytical framework organised around four interrelated dimensions:

1. Learning environment – organisation of the studio process, educational methods, learning activities, and the relationship between academic and real-world contexts;
2. Spatial and material engagement – interaction with real sites, material experimentation, prototyping, construction processes, and full-scale implementation;
3. Stakeholder integration – forms of collaboration among students, educators, public institutions, cultural organisations, local communities, and private-sector partners;
4. Learning outcomes – development of competencies related to collaborative practice, implementation literacy, communication, reflective thinking, embodied spatial understanding, and socially responsible spatial action.

Applying this analytical framework across all four studio iterations enables the study to interpret pedagogical development as an evolutionary process rather than as a collection of isolated educational activities. Consequently, the research shifts attention from individual projects towards the identification of transferable pedagogical principles that characterise Pop-Up Live Learning Environments as an emerging model of contemporary architectural education.

XSTUDIO AS A POP-UP LIVE LEARNING ENVIRONMENT

The pedagogical model examined in this study did not emerge as a predefined educational methodology. Rather, it evolved progressively through a sequence of experimental studio implementations that gradually expanded the relationship between architectural education, spatial practice, and societal engagement. Instead of being designed according to a fixed pedagogical framework, the model developed iteratively, with each studio implementation introducing new forms of collaboration, spatial engagement, material experimentation, and public interaction. Consequently, the evolution of xSTUDIO is understood not as a succession of independent educational projects but as the continuous development of a single pedagogical framework.

This evolution accelerated within the Erasmus+ Architecture Pop-Up Lab Exchange (APLE) project, where Architectural Pop-Up Laboratories were conceived as flexible educational infrastructures capable of operating across institutional, disciplinary, and spatial boundaries [11]. Within this broader framework, xSTUDIO became the pedagogical platform through which Live Learning Environments were systematically explored and tested at the University of Banja Luka. Rather than functioning as a conventional design studio, it positioned architectural education within authentic spatial situations where research, design, implementation, collaboration, and reflection formed an integrated learning process.

Although formally established through APLE, several methodological principles that later became characteristic of xSTUDIO had already emerged in earlier experimental studio teaching at the Faculty of Architecture, Civil Engineering and Geodesy [12]. A particularly important precursor was the *Studio Project 6* course (2022/23), developed in collaboration with the Museum of Contemporary Art of Republika Srpska. Structured around the concepts of architectural elements, atmosphere, and embodied spatial experience, the course encouraged students to investigate architecture not primarily as the production of form but as the orchestration of material presence, sensory perception, and spatial relationships. Drawing upon Rem Koolhaas' *Elements of Architecture* and Peter Zumthor's *Atmospheres* [13], students explored thresholds, light, sound,

tactility, intimacy, and embodied spatial experience [14] as operative design instruments within an existing institutional setting.

Beyond its thematic focus, this studio introduced several pedagogical characteristics that would later become fundamental components of xSTUDIO. Collaboration with a cultural institution replaced the conventional hypothetical design brief; external experts participated throughout the design process; projects were publicly presented and discussed beyond the academic environment; and architectural proposals were understood as open processes rather than closed design products. Although implementation at full scale had not yet become a central educational objective, the studio established an important methodological transition from autonomous design towards context-based, collaborative, and experience-oriented learning.

Subsequent studio iterations progressively expanded this pedagogical foundation. Rather than concentrating exclusively on interior space, later implementations extended towards public space, institutional environments, territorial landscapes, and living ecological systems. At the same time, the scope of learning evolved from conceptual design towards material experimentation, prototyping, construction, and full-scale implementation. The role of external stakeholders also gradually changed, shifting from occasional reviewers to active collaborators involved in defining problems, co-developing projects, facilitating implementation, and evaluating outcomes.

This gradual transformation was accompanied by a parallel shift in the educational objectives of the studio. Whereas early iterations primarily explored spatial experience and architectural atmosphere, later phases increasingly addressed collaboration, implementation, social responsibility, institutional negotiation, and ecological awareness. Consequently, the focus of learning moved beyond the production of architectural proposals towards the development of competencies required for contemporary architectural practice, including collaborative authorship, stakeholder communication, implementation literacy, reflective practice, and socially engaged spatial action.

From this perspective, the significance of xSTUDIO lies not in any individual studio project but in the cumulative evolution of its pedagogical structure. The successive studio implementations demonstrate how relatively small methodological adjustments—expanding the range of stakeholders, increasing engagement with real contexts, introducing material experimentation, or extending the scale of intervention—collectively transformed the conventional architectural design studio into a Pop-Up Live Learning Environment. The following section analyses this evolution through four successive studio iterations, identifying the pedagogical transformations that emerged across different spatial contexts, implementation formats, and collaborative configurations.

RESULTS: EVOLUTION OF THE PEDAGOGICAL FRAMEWORK

The longitudinal analysis reveals that xSTUDIO did not evolve through a series of independent educational projects but through the gradual transformation of a single pedagogical framework. Across successive implementations, the studio continuously expanded its learning environment, spatial scope, forms of stakeholder collaboration, and implementation strategies while maintaining a consistent commitment to constructivist learning, experiential education, and socially embedded architectural practice.

From Interior Pedagogy to Live Laboratories

The first formal implementation of xSTUDIO, conducted during the spring semester of 2024, represented a methodological transition from experimental interior pedagogy towards a live learning environment situated in public space. Integrating the courses *Studio Project 6* and *Small-Scale Design*, the studio used the immediate surroundings of the newly completed Faculty of Architecture, Civil Engineering and Geodesy as its learning environment.

Rather than treating the site as a hypothetical design exercise, students worked within an occupied and continuously used public setting, collaborating with building users, project

architects, industry representatives, and invited critics [15]. Six proposals for small-scale spatial interventions were developed to improve circulation, social interaction, and the everyday use of the faculty environment. The emphasis was placed on feasibility, implementation readiness, and material testing rather than on purely representational design outcomes.

Pedagogically, this phase established several principles that would remain characteristic throughout subsequent iterations: learning through authentic spatial situations, collaboration with external actors, iterative design development, and the integration of research, design, and implementation within a unified educational process. The principal pedagogical shift therefore moved the studio beyond the production of architectural proposals towards collaborative engagement with real spatial conditions.

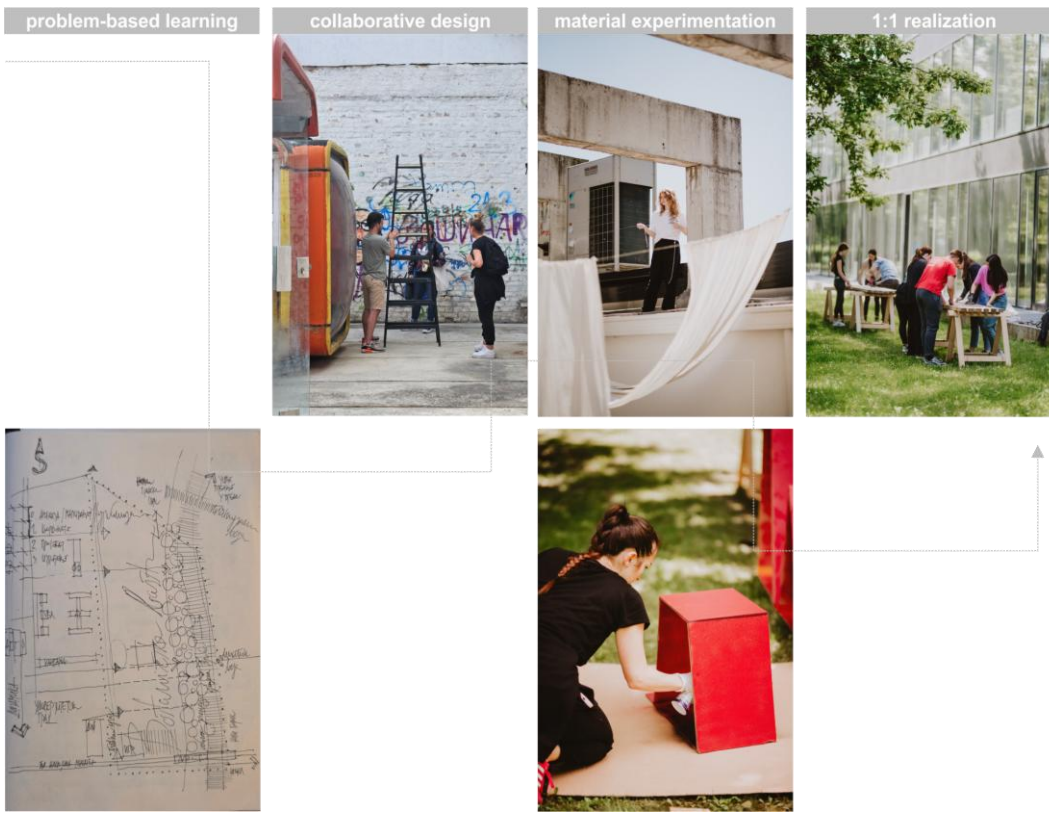

Figure 1. Learning phases during the course 2024/25.

Institutional and Collaborative Complexity

The second implementation, carried out between February and June 2025 within the *Studio Project 6* course, substantially increased the organisational and pedagogical complexity of the model. The focus shifted from the public space surrounding the faculty to the interior of the building itself, which was approached as an evolving institutional environment shaped by multiple users, overlapping activities, and changing spatial requirements.

More than fifty students participated in collaborative teams involving faculty staff, administrative personnel, industry partners, building users, and external reviewers. Fourteen design proposals were organised into thematic clusters addressing exhibition spaces, learning environments, social interaction, and performative interior programmes.

Unlike the previous phase, students were required to negotiate simultaneously with spatial, technical, organisational, and safety-related constraints inherent to an occupied institutional

building. Consequently, architectural design became inseparable from communication, coordination, and decision-making among multiple actors. The pedagogical emphasis shifted from stakeholder participation towards stakeholder negotiation, reinforcing the studio's role as a platform for collaborative problem-solving under real institutional conditions.

Landscape, Ecology, and Living Systems

The third phase extended the pedagogical framework beyond individual buildings towards territorial landscapes. Implemented between March and October 2025 within the master's programme, the studio investigated the Olympic mountains of Bosnia and Herzegovina as complex socio-ecological systems where questions of landscape resilience, cultural heritage, tourism, and environmental sustainability intersect.

Although the spatial scale expanded considerably, the educational logic remained consistent. Students continued to work through collaborative research, field investigations, stakeholder dialogue, and context-specific design development. Public institutions, cultural organisations, and academic partners became active participants throughout the process, broadening both the disciplinary and institutional scope of learning.

This phase marked a significant conceptual transformation. Rather than understanding architecture primarily through individual objects or sites, students engaged with territorial relationships, environmental processes, and long-term spatial strategies. Consequently, the pedagogical focus expanded from architectural intervention towards systems thinking, reinforcing architecture as a practice operating across ecological, cultural, and institutional networks.

From Territory to Living Systems

The fourth phase, initiated during the 2025/26 academic year, represented the broadest conceptual expansion of the pedagogical framework. Located within the Botanical Garden of the University of Banja Luka, the studio investigated the relationship between interior architecture, atmosphere, and living ecological environments through the central question: *Can an interior exist without a ceiling?*

This pedagogical experiment transferred analytical tools traditionally associated with interior architecture into an open landscape characterised by vegetation, seasonal change, humidity, light, shadow, sound, and constantly evolving ecological conditions. Students designed reversible "urban rooms" that generated spatial identity through thresholds, atmosphere, and embodied perception rather than permanent enclosure. The proposed interventions were conceived as temporary, reversible, and ecologically sensitive structures integrated into the living system of the garden.

Compared with previous phases, architecture was no longer understood primarily as the organisation of physical space but as the mediation of relationships between environmental processes, human perception, and ecological dynamics. The pedagogical framework therefore expanded from territorial thinking towards learning through living systems, introducing ecological responsiveness as an integral component of architectural education.

Together, these case studies demonstrate a gradual expansion of pedagogical complexity—from interior experimentation and small-scale urban interventions toward institutional systems, territorial landscapes, and living ecological environments—while maintaining methodological consistency grounded in collaboration, material experimentation, and experiential learning.

Longitudinal Transformation of the Pedagogical Model

Viewed collectively, the four studio implementations reveal a continuous evolution rather than a sequence of unrelated educational experiments. Across successive phases, the learning environment progressively expanded from interior space to public space, institutional systems, territorial landscapes, and living ecological environments. Simultaneously, the pedagogical emphasis shifted from conceptual exploration towards implementation, stakeholder negotiation, systems thinking, and ecological engagement.

Importantly, this expansion did not replace the original educational principles but continuously built upon them. Each new iteration retained the core characteristics established during earlier phases—experiential learning, collaborative inquiry, material engagement, reflective practice, and authentic spatial action—while introducing additional layers of complexity through new spatial scales, stakeholder configurations, and implementation contexts.

Consequently, the evolution of xSTUDIO demonstrates that the transformation of architectural studio pedagogy does not depend on a single methodological innovation but on the cumulative integration of multiple pedagogical shifts over time. The longitudinal development documented in this study therefore provides the empirical foundation for identifying the transferable pedagogical principles discussed in the following section.

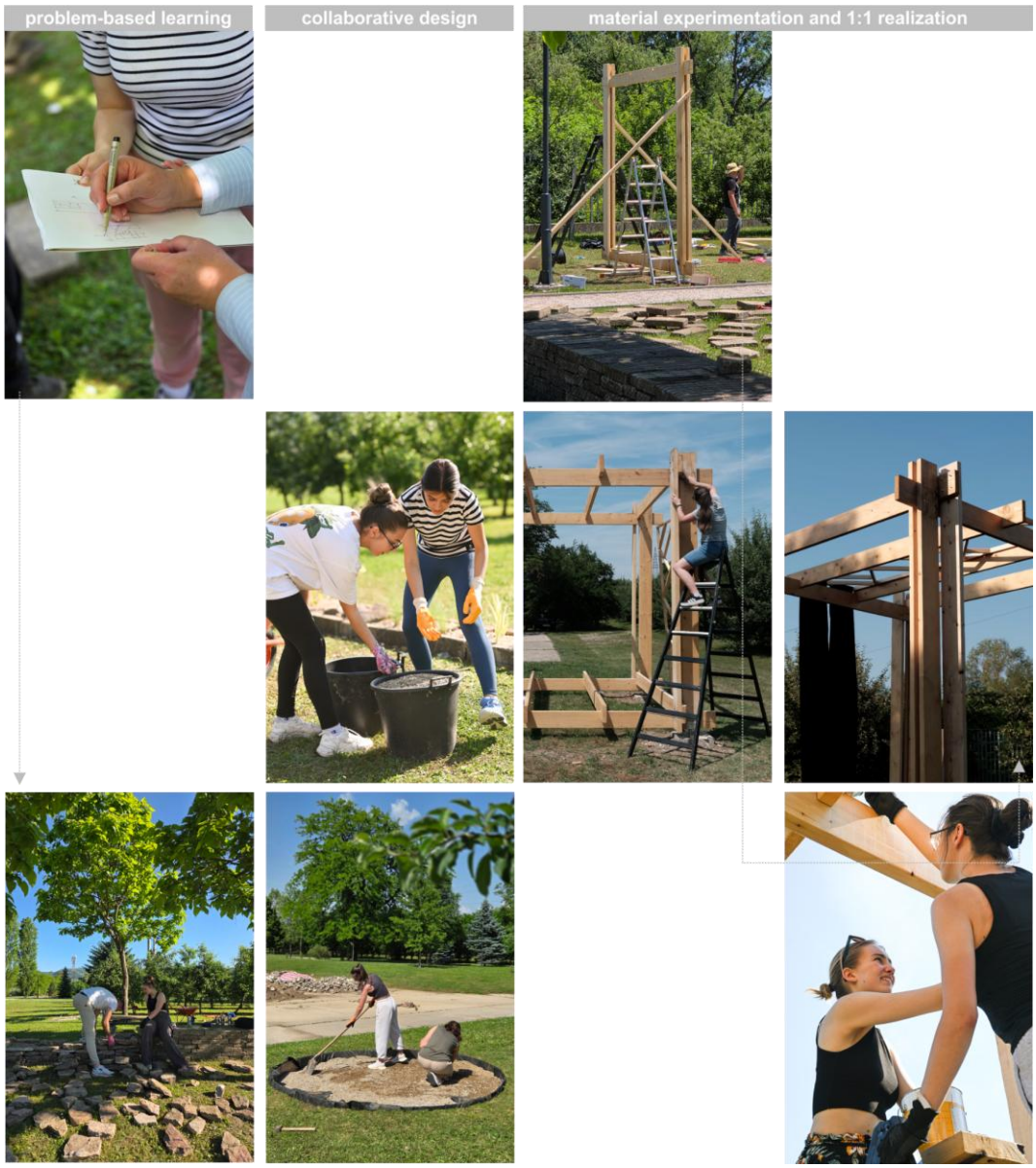

Figure 2. Learning phases during the course 2025/26.

Table 1. Longitudinal analysis graph

Phase	Learning environment	Spatial scale	Stakeholders	Implementation	Pedagogical shift
Origins (2022/23)	Museum	Interior	Cultural institution	Conceptual interventions	Spatial experience
Phase I	Faculty surroundings	Public space	Users, architects, industry	Feasibility	From design to collaboration
Phase II	Faculty building	Institutional system	Multi-actor	Technical & organisational constraints	From collaboration to negotiation
Phase III	Olympic mountains	Territory	Public institutions	Landscape strategies	From buildings to systems
Phase IV	Botanical Garden	Living landscape	Ecological actors	Reversible interventions	From territory to living systems

DISCUSION: EMERGING PEDAGOGICAL PRINCIPLES

The longitudinal analysis suggests that the transformation of the architectural design studio cannot be attributed to a single methodological innovation. Rather, it emerged through the cumulative integration of multiple pedagogical shifts that progressively redefined the learning environment, the role of educators and stakeholders, and the object of architectural learning itself. Across successive studio implementations, xSTUDIO evolved from an experimental educational initiative into a flexible pedagogical framework capable of integrating constructivist learning, experiential education, stakeholder collaboration, and implementation-oriented architectural practice.

Learning Through Authentic Contexts. Perhaps the most significant pedagogical transformation concerned the relocation of learning from hypothetical design scenarios towards authentic spatial situations. Throughout all studio iterations, students worked within existing institutional, urban, territorial, or ecological contexts, engaging directly with the spatial, organisational, and social conditions that shaped each design task. In this sense, learning emerged through situated inquiry rather than through the simulation of professional practice, closely reflecting Dewey's concept of experiential education [6] and Schön's reflective practice [3]. Real contexts became active educational resources rather than merely project locations.

Learning Through Collaboration. A second defining characteristic of the pedagogical model was the gradual expansion of collaboration beyond the academic studio. Public institutions, cultural organisations, industry representatives, local communities, and building users participated throughout the design process, contributing to problem definition, project development, implementation, and evaluation. Consequently, authorship evolved from an individual design activity towards a collaborative process of negotiation and shared responsibility. This transformation closely corresponds to constructivist understandings of knowledge as socially constructed through interaction and dialogue [7], [8].

Learning Through Implementation. Across successive studio iterations, implementation increasingly became an integral component of learning rather than a final stage following design. Material testing, prototyping, construction logistics, feasibility assessment, and reversible interventions enabled students to understand architecture as a process of making rather than solely of representation. Such experiences substantially expanded students' awareness of materials,

construction processes, technical constraints, and implementation strategies, reinforcing Kolb's experiential learning cycle through the continuous interaction between action and reflection [9].

Learning Through Negotiation and Uncertainty. As the complexity of studio environments increased, architectural design progressively became an exercise in negotiation rather than optimisation. Students were required to reconcile institutional requirements, technical regulations, financial limitations, organisational procedures, ecological considerations, and diverse stakeholder expectations. Rather than limiting creativity, these constraints became productive components of the learning process, supporting Till's understanding of architecture as a discipline fundamentally shaped by contingency and external relationships [1]. Within this framework, uncertainty worked not as an obstacle but as an educational resource.

Learning Through Reflection. Reflection remained a continuous component throughout all phases of the pedagogical process. Public presentations, exhibitions, workshops, stakeholder discussions, and structured reflection sessions transformed evaluation from a final assessment into an iterative process of collective learning. Simultaneously, the educator's role gradually shifted from that of an authoritative design critic towards facilitator, coordinator, and mediator of collaborative learning processes, consistent with Schön's understanding of reflective studio pedagogy [3].

Learning Through Ecological Engagement. The final phase of xSTUDIO expanded architectural learning beyond buildings and public spaces towards living ecological systems. By investigating atmosphere, vegetation, seasonality, biodiversity, and environmental processes within the Botanical Garden, students engaged with architecture as a dynamic relationship between spatial intervention and ecological change. This evolution introduced ecological responsiveness as a pedagogical principle rather than solely as a design objective, closely aligning the studio with the values promoted by the New European Bauhaus initiative [10].

Subsection: Writing Introductions

An internal survey was conducted among fourth-year (final-year) students of the Architecture Study Programme at the Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka, during the 2025/26 academic year, with the aim of analysing students' perceptions of contemporary approaches to architectural education and identifying learning activities that complement traditional studio-based teaching.

The survey was conducted electronically using Google Forms between 9 and 22 February 2026. The questionnaire was distributed via email to all fourth-year students based on the official student registry provided by the Student Services Office, with a total population of 60 students. A total of 36 valid responses were collected, representing a response rate of 60%.

Analysis of the open-ended responses revealed a strong preference among students for experiential and practice-oriented forms of architectural education (Table 2). The most frequently mentioned activity was site visits to construction sites and relevant buildings (69.2%), followed by workshops involving practitioners and professionals from the field (42.3%). Approximately one quarter of respondents emphasized the importance of architectural competitions (23.1%) and interdisciplinary collaboration (23.1%) as valuable learning opportunities. Other identified activities included material testing and experimentation (19.2%), small-scale design-build projects (11.5%), and mentorship by practicing architects (7.7%).

Collectively, these findings indicate that students perceive direct engagement with professional practice, stakeholders, materials, and the built environment as an essential complement to conventional studio-based education. The results highlight the importance of learning environments that extend beyond the boundaries of the academic setting, enabling students to develop practical knowledge, collaborative skills, and a deeper understanding of the processes involved in architectural production. In this context, the findings support the pedagogical principles underpinning the xSTUDIO Pop-Up Live Learning Environment, which promotes situated, experiential, and practice-based approaches to architectural education.

Rather than introducing new findings independent of the case study, these student perspectives reinforce the pedagogical principles identified through the longitudinal analysis. The strongest educational expectations expressed by students—direct engagement with professional practice, collaboration with external actors, material experimentation, implementation, and experiential learning—closely correspond to the defining characteristics of the xSTUDIO framework. This convergence suggests that the pedagogical transformations documented in this study are not only internally

Table 2. Student perspective

Identified Student Need	Responses (n = 26)	Share of Respondents	Corresponding xSTUDIO Pedagogical Principle
Site visits to construction sites and exemplary buildings	18	69.2%	Embodied spatial experience
Workshops with practitioners and industry experts	11	42.3%	Stakeholder engagement
Participation in architectural competitions	6	23.1%	Real-world implementation
Interdisciplinary collaboration (e.g., with civil engineering students)	6	23.1%	Collective authorship
Material and structural testing	5	19.2%	Material experimentation
Small-scale design-build projects and prototyping	3	11.5%	Learning by making
Mentorship by practicing architects	2	7.7%	Implementation literacy

CONCLUSION

This paper analysed how an architectural design studio can evolve into a Pop-Up Live Learning Environment through the longitudinal development of xSTUDIO within APLE Lab Banja Luka. By examining successive studio implementations between 2022 and 2026, the research demonstrated how architectural education can progressively expand from speculative design towards authentic, collaborative, implementation-oriented, and socially embedded learning.

The longitudinal analysis identified a set of transferable pedagogical principles that characterised this evolution, including learning through authentic contexts, stakeholder collaboration, material engagement, implementation, reflection, and ecological responsiveness. Together, these principles reposition the architectural design studio as a flexible learning environment in which knowledge is constructed through direct engagement with real spatial situations, societal actors, and material processes rather than through hypothetical design exercises alone.

Importantly, the findings do not advocate replacing the conventional architectural design studio. Instead, they demonstrate that Pop-Up Live Learning Environments extend its pedagogical capacity by integrating dimensions of contemporary architectural practice that remain difficult to address within traditional studio teaching, including collaborative authorship, stakeholder negotiation, implementation literacy, and socially responsible spatial action. At the same time, the study indicates that the successful adoption of such approaches depends not only on pedagogical innovation but also on institutional flexibility, interdisciplinary collaboration, and sustained partnerships with actors beyond academia.

Although the research is grounded in a single institutional case, its primary contribution lies in identifying pedagogical principles that are potentially transferable across different architectural schools and educational contexts. Rather than proposing a fixed teaching model, the study argues that the scalability of Pop-Up Live Learning Environments resides in the adaptability of their underlying principles to different institutional, cultural, and spatial settings. Further research should examine these principles through comparative studies involving different universities and educational environments, contributing to a broader understanding of how architectural studio pedagogy can respond to the evolving professional, societal, and ecological challenges of contemporary practice.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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