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

Suzana Knežević[1], Milena Milojević[2], Maja Došenović Marinković[1], Aleksandra Milošević[4]

[1]Academy of Applied Studies Šabac, Unit for Agricultural and Business Studies and Tourism, Vojvode Putnika 56, Šabac, Republic of Serbia, s.knezevic@akademijasabac.edu.rs, m.d.marinkovic@akademijasabac.edu.rs
[2]Independent researcher, Belgrade, Republic of Serbia, milenaminorka23@gmail.com
[3]University of Belgrade, Faculty of Law, Bulevar Kralja Aleksandra 87, Belgrade, Republic of Serbia (alexandramilosevic77@gmail.com)

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Corresponding Author: Suzana Knežević, Academy of Applied Studies Šabac, Unit for Agricultural and Business Studies and Tourism, Vojvode Putnika 56, Šabac, Republic of Serbia, s.knezevic@akademijasabac.edu.rs

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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.

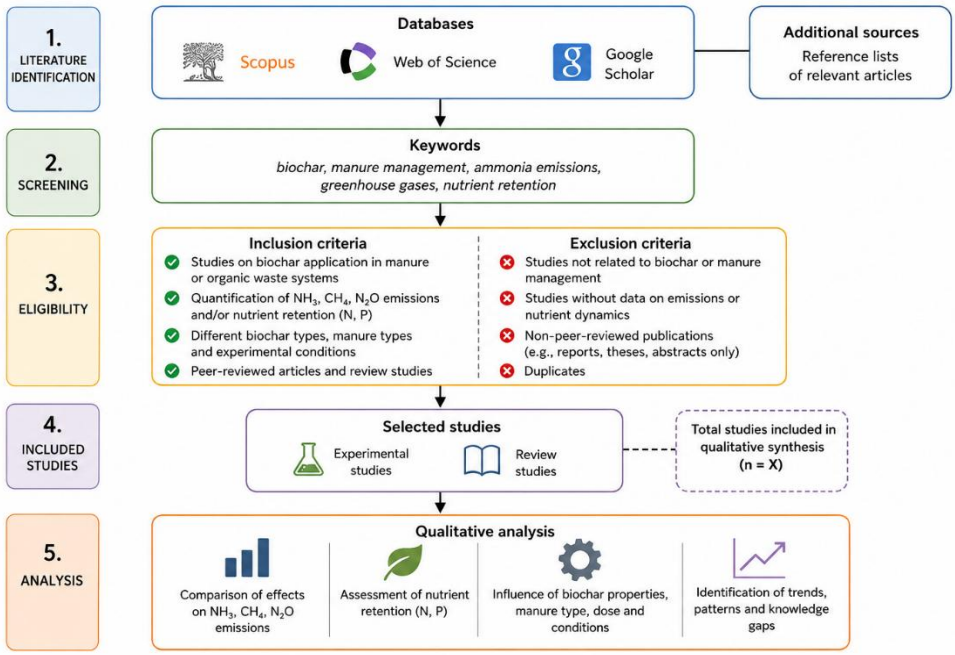


Figure 1 Methodology Flowchart (developed by the author and visually rendered with AI tools)

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].

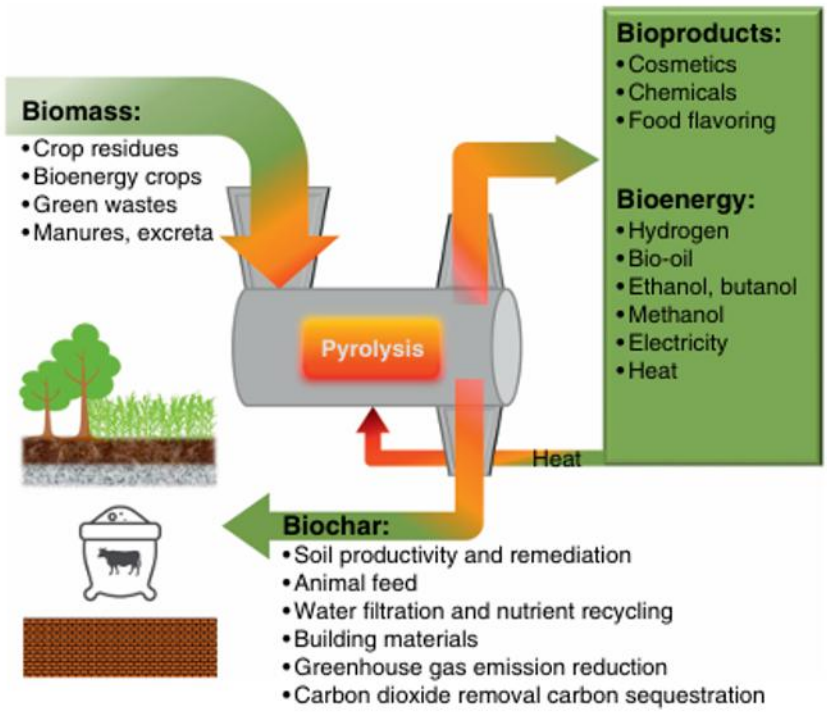


Figure 2 Structure and Flow of the Biochar System [4]

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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