EFFECT OF FLAXSEED–BASED HYDROGEL COMPOSITION ON MECHANICAL PROPERTIES OF EXTRUDED MICROSPHERS

Tanja Krunić[1], Nataša Obradović[2]

[1]University of Belgrade, Innovation Center of the Faculty of Technology and Metallurgy, Karnegijeva 4, 11000 Belgrade, Serbia, tkrunic@tmf.bg.ac.rs
[2]University of Belgrade, Faculty of Technology and Metallurgy, Karnegijeva 4, 11000 Belgrade, Serbia, ntomovic@tmf.bg.ac.rs

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Corresponding Author: Tanja Krunić, University of Belgrade, Innovation Center of the Faculty of Technology and Metallurgy, Karnegijeva 4, 11000 Belgrade, Serbia, tkrunic@tmf.bg.ac.rs

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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].

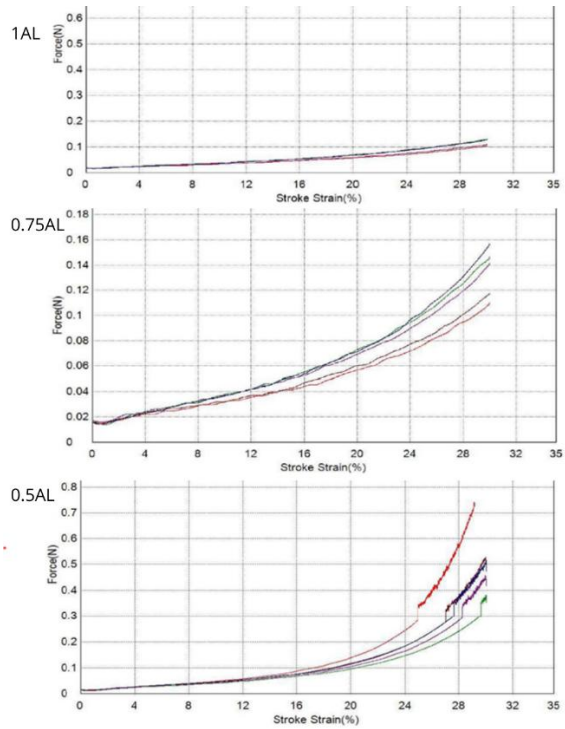


Figure 1. Graphics of the mechanical properties of carriers 1AL, 0.75AL and 0.5AL

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].

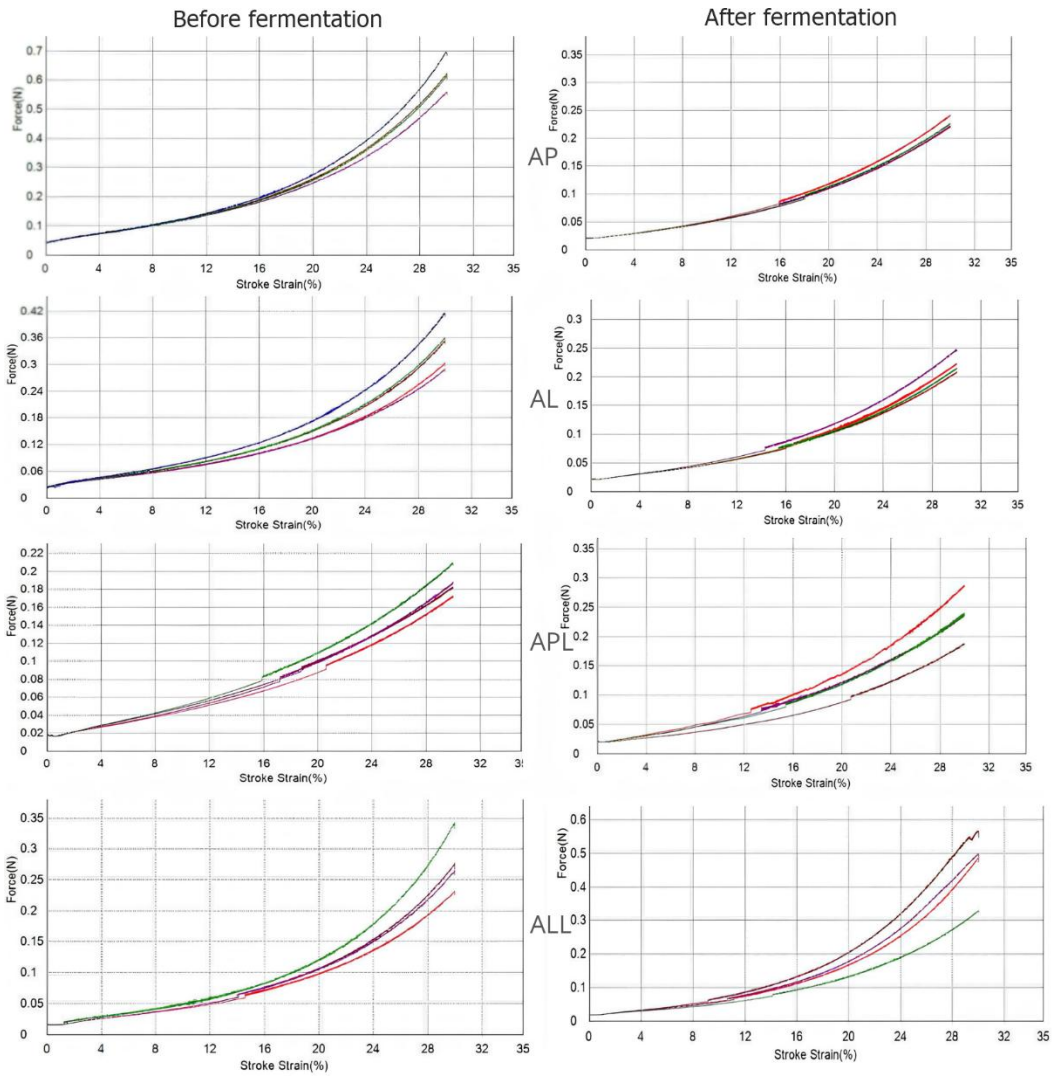


Figure 2. Graphics of the mechanical properties of carriers AP, AL, APL, ALL, before and after fermentation of coconut milk

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.

LITERATURE

1. Hill, C., Guarner, F., Reid, G., Merenstein, D. J., Pot, B., Morelli, L., Canani, R. B., Flint, H. J., Salminen, S., Calder, P. C., & Sanders, M. E. (2014). Expert consensus document: The International Scientific Association for Probiotics and Prebiotics consensus statement on the scope and appropriate use of the term probiotic. *Nature Reviews Gastroenterology & Hepatology*, 11, 506–514. https://doi.org/10.1038/nrgastro.2014.66
2. Krunic, T. Z., Bulatovic, M. L., Obradovic, N. S., Vukasinovic-Sekulic, M. S., & Rakin, M. B. (2016). Effect of immobilisation materials on viability and fermentation activity of dairy starter culture in whey-based substrate. *J. Sci. Food Agric.*, 96, 1723–1729. https://doi.org/10.1002/jsfa.7278
3. Tripathi, M. K., & Giri, S. K. (2014). Probiotic functional foods: Survival of probiotics during processing and storage. *Journal of Functional Foods,* 9, 225–241. https://doi.org/10.1016/j.jff.2014.04.030
4. Cook, M. T., Tzortzis, G., Charalampopoulos, D., & Khutoryanskiy, V. V. (2012). Microencapsulation of probiotics for gastrointestinal delivery. *Journal of Controlled Release,* 162(1), 56–67. https://doi.org/10.1016/j.jconrel.2012.06.003
5. Krunic, T. (2022) Alginate as a carrier for probiotic encapsulation: Extrusion and spray dry technique. In: Wilkerson MY (ed.) *Properties and Applications of Alginate*. New York: Nova Science Publisher, (pp. 131–150).
6. Krunic, T., Obradović, N., & Rakin, M. (2019). Application of whey protein and whey protein hydrolysate as protein based carrier for probiotic starter culture. *Food Chemistry*, 293, 74–82. https://doi.org/10.1016/j.foodchem.2019.04.062
7. Krunic, T., Rakin, M. (2022). Enriching alginate matrix used for probiotic encapsulation with whey protein concentrate or its trypsin-derived hydrolysate: Impact on antioxidant capacity and stability of fermented whey-based beverages. *Food Chemistry,* 370, 130931. https://doi.org/10.1016/j.foodchem.2021.130931
8. Krunic, T., Ilic, N., & Osmokrovic, A. (2026). Effect of Biopolymer Additives on Functional Properties of Alginate-Based Composite Hydrogels. *Gels*, 12, 266. https://doi.org/10.3390/gels12030266

9. Drozłowska, E., Łopusiewicz, Ł., Mężyńska, M., & Bartkowiak, A. (2020). Valorization of Flaxseed Oil Cake Residual from Cold-Press Oil Production as a Material for Preparation of Spray-Dried Functional Powders for Food Applications as Emulsion Stabilizers. *Biomolecules,* 10(1), 153. https://doi.org/10.3390/biom10010153
10. Kučka, M., Harenčár, Ľ., Ražná, K. et al. (2024). Great potential of flaxseed mucilage. *Eur Food Res Technol,* 250, 877–893. https://doi.org/10.1007/s00217-023-04429-0
11. Puligundla, P., & Lim, S. (2022). A Review of Extraction Techniques and Food Applications of Flaxseed Mucilage. *Foods,* 11(12), 1677. https://doi.org/10.3390/foods11121677
12. Sungatullina, A., Petrova, T., Kharina, M., Mikshina, P., & Nikitina, E. (2023). Effect of Flaxseed Mucilage on the Probiotic, Antioxidant, and Structural-Mechanical Properties of the Different Lactobacillus Cells. *Fermentation,* 9(5), 486. https://doi.org/10.3390/fermentation9050486
13. Saad, M. A., Sadik, E. R., Eldakiky, B. M. et al. (2024) Synthesis and characterization of an innovative sodium alginate/flaxseed gum green hydrogel for forward osmosis desalination. *Appl Water Sci,* 14, 20. https://doi.org/10.1007/s13201-023-02080-4