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Review Article

The role of postbiotics in food packaging and their challenges: A mini review on current status

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Abstract

Postbiotics are metabolites derived from probiotics and other beneficial microorganisms that due to containing organic acids, bacteriocins, and bioactive peptides possess antimicrobial and antioxidant properties. In recent years, the use of postbiotics as a functional agent for food packaging systems has increased in popularity among researchers. However, although the postbiotics-packaging system has increased gradually, there are some obstacles that challenge it such as the safety and stability of novel beneficial microorganisms like mold as a next generation of postbiotics sources, parameters optimization of preparation and treatments of postbiotics, safety and performance of postbiotic carrier polymer and the sensorial effect of postbiotics on packaged foods. In addition, to ensure the consumption of packaged food with postbiotic-containing polymers, its safety needs to be thoroughly investigated, as research has shown that the postbiotic administration can have negative effects such as gastrointestinal complications, and allergies on the consumer body's health. Finally, for the entry of postbiotics as functional compounds into the food packaging market, the collaboration between academia and industry, clear labeling of packaged food and increasing consumer awareness about postbiotics are essential. Therefore, this study aims to briefly overview of the current status and future directions of postbiotics in food packaging.

Keywords: Antimicrobial packaging, Food packaging, Lactic acid bacteria, Postbiotics, Sustainability.

Introduction

The increasing demand for sustainable and natural food preservation techniques has driven innovation in food preservation, with postbiotics emerging as promising alternatives. Postbiotics are derived from probiotics and other beneficial microorganisms and consist of microbial metabolic by-products, such as organic acids, bacteriocins, and bioactive peptides, which exhibit diverse functionalities, including antimicrobial and antioxidant properties (de Toledo Guimarães et al., 2023). Their stability, ease of incorporation into packaging materials, and safety profile make them viable substitutes for synthetic preservatives for extending the shelf life of various food products (Isaac-Bamgboye et al., 2024). Recent research, including our systematic review (Sharafi et al., 2024b), has highlighted the effectiveness of postbiotics in preserving diverse food categories,

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such as dairy, meat, poultry, and seafood. Postbiotics derived from lactic acid bacteria and other microorganisms can be incorporated into packaging films and coatings using different methods such as direct integration into polymer matrices or surface coatings (Ceylan, 2024; Sharafi et al., 2024a). These active packaging systems inhibit the growth of common foodborne pathogens and spoilage organisms, thereby maintaining food quality and extending the shelf life. Several studies have demonstrated the efficacy of postbiotics in reducing microbial contamination without the need for live microorganisms, offering a more stable and risk-free alternative to probiotics. For example, the antimicrobial action of postbiotics against *Listeria monocytogenes*, *Escherichia coli and Staphylococcus aureus* has been shown to significantly reduce contamination levels in packaged various food products(Ansari et al., 2024; Hosseini et al., 2022; Marques et al., 2017). Furthermore, incorporating postbiotics in packaging film demonstrated the antioxidant activity in packaged meat (Shafipour Yordshahi et al., 2020). It should be noted that the presence of acidic compounds and the flavor reminding of culture medium can create a sensorial negative impact on food products. In addition, instability and fast release, which decreases postbiotic functionality are other disadvantages of direct usage. Hence, the application of postbiotics via the wrapping method can enhance the stability of postbiotics metabolites and improve controlled release properties (Sharafi et al., 2024b). Despite its potential, the adoption of postbiotics in commercial food packaging presents several challenges. This study provides general information on the challenge of applications of postbiotics in the food packaging system.

Postbiotics challenges

Preparation and application

The four steps of preparing postbiotics from probiotics are, in order: resuscitation of probiotic, propagation of probiotic, postbiotics harvesting and treatments (Moradi et al., 2021). However, postbiotics can be incorporated into food packaging polymers either in liquid or powder (freeze-dried) (Sharafi et al., 2024b). Loading postbiotics into food packaging material can be conducted in various ways, such as integrating postbiotics into carrier polymers directly, sandwiching film containing postbiotics between two external layers and coating the film in a postbiotics solution (Moradi et al., 2020). Generally, there have been many studies on the use of bacteria-derived postbiotics in food packaging, which have partially addressed some of the challenges. Recent research has shown significant promise for yeast-derived postbiotics for enhancing the safety and shelf life of packaged foods (Franco, 2024). However, some research gaps in the application of yeast postbiotics in food packaging should be addressed in future studies. For instance, yeast postbiotics are sensitive to processing or enzymatic degradation and have specific aroma and flavor characteristics that negatively affect the sensory properties of applied foods (Chan & Liu, 2022). Interestingly, mold metabolites with functional activities, such as antimicrobials, also belong to the postbiotic family and can be used in food packaging. Since the postbiotic from molds such as *Aspergillus oryzae* is a new research topic, there are many challenges in its production and quality control (Seidler et al., 2024). In this realm, the use of sophisticated analytical techniques such as high-performance liquid chromatography and mass spectrometry is demanded for the identification and quantification of metabolites, which is crucial for understanding the bioactive profile of fungal postbiotics. However, the fungal postbiotics components' heterogeneity and the need for specific markers for bioactivity assessment are the main obstacles in standardizing these measures (Seidler et al., 2024).

In addition, the use of genomic and metabolomic techniques to design modified probiotic strains with high postbiotic production performance will open a new research window in the regard of postbiotics. Future in-depth investigation of beneficial bacteria as postbiotic producers is another important research branch in the development of food packaging and preservation. Therefore, in future research, the focus on providing standardization methods is necessary for the optimal use of postbiotics derived from bacteria, yeast, genetically modified probiotics and molds in food packaging. Another novel finding from the broad spectrum of postbiotics in food packaging is the degradation of mycotoxins during food storage (Moradi et al., 2020). Specific enzymes found in postbiotics are mainly responsible for mycotoxin degradation (Hiththatiyage et al., 2025). Postbiotics components such as enzymes effectively This property is usually accompanied by antifungal effects against toxigenic fungi (Khani et al., 2024). Next, in the postbiotics preparation step, there is a need to focus on refining postbiotic production techniques, such as fermentation optimization, centrifugation, dialysis, column purification, and the use of advanced biotechnological tools to enhance their efficacy and spectrum of activity (Homayouni-Rad et al., 2024). Before the application of postbiotics in food packaging, thermal pretreatment is conducted to inactivate the remaining bacterial cells in the postbiotic solution, as well as its indigenous enzymes (Sharafi et al., 2024c). Therefore, to maintain the biological activity of postbiotics, non-thermal treatment such as pH adjustment along with microfiltration should be the focus of future research.

Innovations in food packaging technologies, including nanotechnology and smart packaging, can further enhance the stability and functionality of postbiotics. For instance, embedding postbiotics into nanocomposites can improve their controlled release and interaction with food surfaces, leading to prolonged antimicrobial activity (Sharafi et al., 2024b). In addition, an industrially viable approach for preparing films and coatings containing postbiotics should be developed. For example, extrusion is an inappropriate technique for preparing nanocellulose-based films because nanocellulose disperses in water, which leads to a reduced extrusion process performance (Li et al., 2022). Other technologies, such as ultrasound, can enhance the performance of postbiotics in active packaging systems (Rasouli et al., 2021). Additional information on the release and migration of postbiotics from carrier polymers should be provided in the future. In addition, an obligatory investigation of the interaction between postbiotics and film or coating components should be performed to ensure that no toxic substances are created. On the other hand, there are some limitations from the sensory aspects of postbiotics in food packaging that should be addressed. Since postbiotics are usually produced in de Mann, Rogosa and Sharpe (MRS) media, their brown color harms the color properties of white-colored foods (Jo et al., 2023). Therefore, culture media with a pale yellow or white appearance, such as cheese whey, could be a great substitute for commercial brown-colored culture media (Sharafi et al., 2022). Another obstacle in the use of postbiotics in food is their sourness properties (Zhong et al., 2024), which provides a more future research field in joint use with aromatic compounds such as essential oils (Sharafi et al., 2024c). Furthermore, the application of postbiotics individually in packaging may have insufficient activity in food packaging, so hurdle technology that combines the postbiotics with other preservation techniques is a new insight to improve the safety of food products.

Safety

From a safety perspective, postbiotics can overcome several problems associated with probiotics. Postbiotics, don't have any live microorganisms, therefore, unable to cause diseases associated with probiotic administration, such as bacteremia (Salminen et al., 2021). However, some of the postbiotics components cannot be considered safe based individually on the microbial precursor. For example, lipopolysaccharides derived from gram-negative bacteria can cause toxic shock and sepsis when released from dead bacteria (Salminen et al., 2021). On the other hand, some postbiotics inhibit harmful bacteria, whereas others can promote their growth and, by creating an imbalance in the microbiome, can lead to metabolic problems and secondary infections (Bourebaba et al., 2022). However, the effects of postbiotics on the microbiome are determined by various factors, such as genetics, diet, different human lifestyles, and the host environment (Isaac-Bamgboye et al., 2024). The application of high concentrations of postbiotics as functional agents in food packaging may cause side effects such as gastrointestinal complications, allergies, or intolerance. For instance, the overdose consumption of *Lactobacillus acidophilus* postbiotics resulted in significant side effects such as dehydration, abdominal distension, and varying degrees of vomiting (Malagón-Rojas et al., 2020). Furthermore, in sensitive consumers, postbiotics can act as allergens and may not be safe for people with allergies to cow milk or eggs (Martín-Muñoz et al., 2012). However, further studies are needed to investigate the toxic effects of consuming food packaged with polymers containing postbiotics, especially edible packaging. To address this issue, omics methods such as post-biomics can be used (Szydłowska & Sionek, 2022). Research on the safety and potential risks of postbiotics remains limited, and more studies are needed to better understand their effects and safety.

Commercial perspective

Due to great antimicrobial and antioxidant capacities, postbiotics can be used commercially in food packaging systems (Sharafi et al., 2024b). However, there are some limitations in this area that need to be addressed. Collaboration between industry and academia is crucial for advancing the commercial application of postbiotics in active packaging systems (Gervasoni et al. 2023). As consumer demand for clean-label products continues to grow, the development of regulations and clear guidelines for the use of postbiotics in food packaging is essential to facilitate market penetration (Sharafi et al., 2024b). Already, postbiotic components such as nisin in food markets, including the food and beverage, bakery, and dairy sectors, are accepted by consumers. However, postbiotics and its components have various limitations in industrial and research applications (Yeşilyurt et al., 2021). In commercial postbiotic production, the label of kosher or halal in different target markets should be clarified. It should be noted that religious beliefs and life philosophies directly restrict the food consumption of their followers (Karahalil, 2020). Therefore, market leaders must raise consumer awareness regarding the use of biotic products (Ayyash et al., 2021). Although challenges remain, ongoing research and technological advancements are likely to overcome these barriers, paving the way for postbiotics to play a pivotal role in food safety and shelf-life extension. With a focus on innovation and regulatory support, postbiotics could soon become the cornerstone of sustainable food packaging.

Conclusion

Due to great functional performance such as antimicrobial and antioxidant activities, postbiotics can applied in food packaging systems. These functional agents have properties that make them stronger and safer than synthetic preservatives. However, postbiotics have many limitations, such as preparation, application, safety, and challenges in large-scale production. Therefore, future research should be conducted to gain a deeper understanding of the potential of postbiotics and their limitations as preservative agents for food packaging. Generally, postbiotics with a wide spectrum of functional activities improve the quality and shelf life of food products.

Conflicts of interest

The authors declare no conflicts of interest.

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