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POSTBIOTIC-BASED ACTIVE FOOD PACKAGING FOR NATURAL PRESERVATION: ANTIMICROBIAL MECHANISMS, DELIVERY SYSTEMS, STABILITY AND FOOD APPLICATIONS

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Abstract:

The rising demand for healthy, clean-label, minimally processed, and eco-friendly foods has spurred research into natural preservation technologies. Recently, postbiotics have gained significant attention as stable antimicrobial agents capable of replacing live microorganisms. Diverse postbiotic compounds—including organic acids, bacteriocins, antimicrobial peptides, and enzymes derived from non-living microbial cells—can be effectively applied for food preservation.

In particular, incorporating postbiotics into active food packaging directly targets the food–package interface. Researchers have evaluated various packaging systems, such as films, coatings, bilayer structures, cellulose nanofibers, alginate coatings, and polylactic acid (PLA) films, to deliver postbiotics for preserving meat, poultry, seafood, and dairy products. However, packaging efficacy depends heavily on the specific postbiotic characteristics, carrier materials, release rates, food matrix properties, storage conditions, and compound stability.

While postbiotic-based packaging demonstrates clear potential in controlling microbial growth, enhancing quality, and extending shelf life, key challenges remain. These include standardizing production, characterizing active principles, optimizing controlled release, ensuring safety performance, and scaling laboratory prototypes to industrial levels. Further research must focus on refining postbiotic formulations, engineering advanced delivery systems, and performing comprehensive toxicological and technical evaluations at commercial scales.

Keywords: *Postbiotics, Active Food Packaging, Antimicrobial Activity, Natural Preservation, Controlled Release, Food Shelf Life.*

1. Introduction

Food spoilage and contamination by pathogenic and spoilage microorganisms constitute a serious threat to food safety and quality, as well as economic loss. Despite the extensive application of traditional preservation techniques and synthetic additives, the search for new effective antimicrobial agents for food preservation is ongoing. Active packaging is a promising area of food packaging engineering, offering additional functions such as interaction with food to extend its shelf life. The bioactive compounds inherent in antimicrobial active packaging can directly act on the surface of food and its microorganisms. Postbiotics are presented as promising antimicrobial preparations derived from food-grade microorganisms. They contain inactive microbial cells or their components, and therefore, some of the beneficial effects of postbiotics can be manifested even when a living culture is not included in the product. In addition, postbiotic products are characterized by greater stability during storage.

The antimicrobial mode of action of postbiotics is associated with the presence of organic acids, bacteriocins, antimicrobial peptides, enzymes, and other metabolites that can inhibit individual strains of bacteria or entire bacterial communities [1,2]. The ability of postbiotics to inhibit bacterial biofilms has also been confirmed. This indicates their perspective for application in active food packaging. Studies have been devoted to studying the antimicrobial activity of postbiotics and methods of their delivery to food. At the same time, data on the use of postbiotics in packaging materials are relatively few, while such studies are of great interest and importance. The goal of this article is to analyze the latest trends in the development of postbiotic active packaging materials, focusing on antimicrobial mechanisms and food applications.

2. Postbiotics: Concept and characteristics

2.1 Definition and general characteristics

Postbiotics represent a diverse group of non-viable microbial preparations and microbial-derived components with biological activity. Their composition can include microbial cell components and metabolites depending on the production process and source microorganism [1]

An important technological advantage of postbiotics is their potential stability compared with live probiotic cultures. The absence of viable cells reduces concerns related to survival during processing and storage and can facilitate their incorporation into different food and packaging systems [2,9]

2.2 Sources of postbiotics

Lactic acid bacteria (LAB), including species belonging to Lactobacillus, Lacticaseibacillus Lactiplantibacillus, Pediococcus, and Bifidobacterium, are important sources of postbiotic preparations. Cell-free supernatants obtained from LAB fermentation have received particular attention because they contain mixtures of antimicrobial metabolites.

Examples among the reviewed studies include postbiotics from Lactobacillus rhamnoes, Lacticaseibacillus paracasein, Pediococcus acidilactici, Bifidobacterium spp., Lactobacillus acidophilus, and Bifidobacterium animal [4, 5, 10, 11].

3. Antimicrobial mechanisms of postbiotics

The antimicrobial activity of postbiotics is multifactorial and is associated with the combined action of several bioactive compounds present in the preparations. Depending on the source microorganism and production process, these compounds may include organic acids, bacteriocins, antimicrobial peptides, enzymes, and other microbial metabolites. Their simultaneous activity can affect microbial cells through different mechanisms, making postbiotics promising candidates for controlling pathogenic and spoilage microorganisms in food preservation.

3.1 Organic acids

Organic acids, including lactic acid, acetic acid, and other fermentation-derived acids, are important antimicrobial components of many postbiotic preparations. Their antimicrobial activity is associated with a reduction in environmental pH and disruption of microbial intracellular homeostasis. In their undissociated form, organic acids can pass through the microbial cell membrane and subsequently dissociate within the cytoplasm. This process can decrease intracellular pH, disturb metabolic processes, and increase cellular stress.The resulting disruption of cellular homeostasis can inhibit microbial growth and survival, thereby contributing to the preservation and microbiological stability of foods [2].

3.2 Bacteriocins and antimicrobial peptides

Bacteriocins are ribosomally synthesized antimicrobial peptides produced by various microorganisms, particularly lactic acid bacteria. Depending on their structure and target microorganism, bacteriocins can interact with the cell membrane, form pores, alter membrane permeability, and interfere with essential cellular functions. Bacteriocins have also been extensively investigated as natural antimicrobial agents in active food packaging. For example, [12] developed a biopolymeric active packaging system incorporating a bacteriocin, whereas [13] investigated a plantaricin BM-1-coated multilayer film for the preservation of chilled meat. These studies demonstrate the potential of bacteriocins for antimicrobial food packaging. However, because the systems used purified or specifically characterized bacteriocins, they should be considered complementary evidence from bacteriocin-based active-packaging research rather than direct evidence of the activity of complete postbiotic preparations.

3.3 Enzymes and other bioactive metabolites

In addition to organic acids and antimicrobial peptides, postbiotic preparations may contain enzymes, small peptides, exopolysaccharides, and other microbial metabolites that can contribute to their biological activity. Depending on their composition, these compounds may affect microbial growth, cellular integrity, adhesion, or other physiological processes. The presence of multiple bioactive components may result in combined or synergistic effects, potentially providing broader antimicrobial activity than that achieved by a single purified antimicrobial compound [13]. However, the specific contribution of individual components depends on the microorganism used, fermentation conditions, preparation method, and composition of the resulting postbiotic.

3.4 Antibiofilm activity

Biofilm formation is an important microbial survival strategy because microorganisms embedded within biofilms can exhibit increased tolerance to environmental stresses and antimicrobial treatments. Therefore, inhibition of biofilm formation is an important additional mechanism for controlling food-associated microorganisms. Postbiotics may interfere with different stages of biofilm development, including microbial adhesion, initial attachment, extracellular matrix formation, and biofilm maturation. Recent studies investigating gastric microbiota-derived postbiotics and *Lacticaseibacillus paracasei*-derived postbiotics have reported antimicrobial and antibiofilm activities, supporting the potential of postbiotic preparations for controlling microorganisms beyond planktonic growth [3][14].

4. Postbiotic delivery systems in active food packaging

The activity of the bio-polymer film packaging as carrier of postbiotic compounds strongly depends on technological options implemented during its elaboration. Basically, different approaches could be implemented to develop a biopolymer material with antimicrobial properties as active food packaging such as direct incorporation into the polymeric matrices [15], coating on the surface of the packing or of the product, bilayer or multilayer design [8], and use of electrospun nanofibers[14].

4.1 Direct incorporation into polymer films

One of the most straightforward approaches consists of directly incorporating the postbiotic preparation into the polymer film [15]. This should involve technological modifications that could specifically impair mechanical and optical properties of the final film besides its barrier properties and release profile.[7] reported the fabrication of postbiotic supplemented polylactic acid films for rainbow trout preservation. In this contribution, authors demonstrated the capacity of this kind of biodegradable films to incorporate postbiotic compounds from different bacterial strains.

4.2 Coating

Postbiotic preparation could be also applied as a coating directly to the surface of food packaging or the food surface itself. This approach is especially attractive when the antimicrobial activity of the compound is needed just on the surface of the packing. In this case, coatings could provide the necessary amount of an antimicrobial substance on the surface of the food contact packaging or even on the food product itself [6]. evaluated alginate coating supplemented with postbiotic compounds from bifidobacterium spp. as preservation tool for turkey meat. Similar results were reported using alginate-based coatings functionalized with Lactobacillus rhamnosus as a postbiotic substance [4].

4.3 Bilayer films

Bilayer design is an attractive approach allowing to incorporate antimicrobial compounds into one of the layers while maintaining excellent mechanical properties provided by another polymer layer. Therefore, one layer could be designed for the encapsulation and prolonged release of antimicrobial components while another layer could protect the film and provide mechanical stability [8]. reported development of a novel active bilayer film containing postbiotics for chicken breast fillet preservation. This approach provides targeted delivery of antibacterial compounds with a decreased impact on mechanical properties of the film compared to a homogenous design.

4.4 Electrospun nanofibers

Electrospinning is an emerging technology allowing to fabricate ultrafine fibers with good surface-area-to-volume ratio allowing to increase the efficiency of bioactive substance incorporation and control over its release rate [14]. Basically, this method could be used as a tool to create fiber networks from solutions of biodegradable polymers containing postbiotic compounds.[14] investigated postbiotic supplemented cellulose acetate electrospun nanofibers as a novel concept of active packaging for fresh-chilled chicken breast meat preservation. As the promising tool for development of antimicrobial packaging, the technology needs to be investigated in more details to evaluate its technological, economic and regulatory feasibility.

4.5 Cellulose based films

Materials derived from cellulose are promising candidates for fabrication of antimicrobial barrier films due to their availability and excellent film-forming properties. Indeed, [4] evaluated antimicrobial properties of nanocellulose films supplemented with postbiotic compounds from Lactobacillus rhamnosus bacteria for minced meat preservation.

5. Stability and controlled release

5.1 Stability of postbiotic components

Although postbiotics may have greater technological stability than live probiotics, individual bioactive components can still be sensitive to temperature, pH, moisture, oxygen, and interactions with packaging polymers. Recent literature emphasizes the need to characterize the stability of postbiotic preparations throughout processing and storage [1][9] Controlled release is one of the most important considerations in active packaging. If antimicrobial compounds are released too rapidly, their protective effect may decline before the end of storage. Conversely, insufficient release may result in inadequate antimicrobial activity.

The polymer matrix, concentration of postbiotic, food composition, temperature, moisture, and packaging structure can all influence release behavior. Active packaging research generally emphasizes the need to balance antimicrobial migration with packaging performance and food safety.

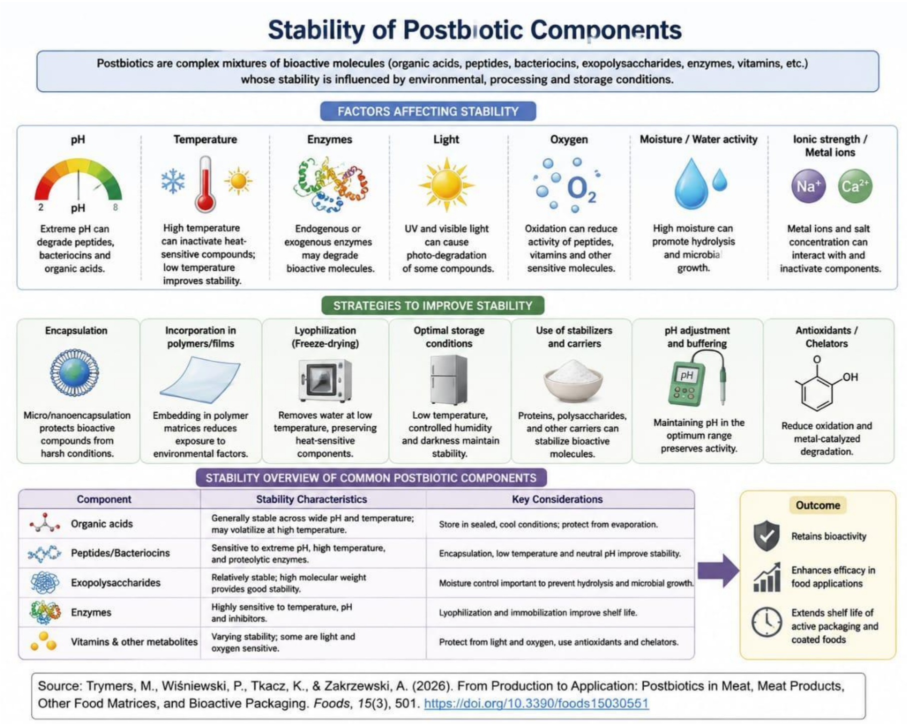


Figure 1: Stability of postbiotic components and factors influencing their bioactivity during processing and storage

5.2 Interaction with food matrix

Food composition can substantially influence antimicrobial activity. Proteins, fats, salts, moisture, pH, and microbial load may interact with active compounds and alter their availability.

Therefore, successful activity in a laboratory film does not necessarily guarantee equivalent effectiveness in a real food system. This is an important limitation when comparing studies performed using different food matrices.

6. Food applications

6.1 Meat and poultry

Meat and poultry are among the most promising applications for postbiotic active packaging because they are highly susceptible to microbial spoilage. [4] investigated nanocellulose films containing L. rhamnosus postbiotics for minced meat. Similarly,[6] examined postbiotic-enriched alginate coatings for turkey meat, while [8] investigated a postbiotic-containing bilayer film for chicken breast fillets. [16][8] demonstrated the application of postbiotic-supplemented PLA films for rainbow trout, showing the potential of biodegradable polymer-based active packaging for seafood preservation. Collectively, these studies indicate that postbiotic packaging can be applied through different material platforms rather than being restricted to one packaging technology.

6.2 Dairy products

Dairy products represent another important application because microbial contamination can compromise quality and safety. [5] investigated a chitosan-based active packaging film prepared with the cell-free supernatant of *Lacticaseibacillus paracasei* ALAC-4 for Mongolian cheese preservation. [11] investigated cheese whey containing postbiotics from Lactobacillus acidophilus LA5 and Bifidobacterium animalis BB12 as a preserving liquid for high-moisture mozzarella. These studies demonstrate that postbiotic preservation can be implemented both through packaging films and through direct food-associated preservation systems.

6.3 Fresh produce

Active antimicrobial films may also be useful for fresh produce because microbial contamination can occur during handling, storage, and distribution. [15] developed a sustainable antimicrobial food packaging film with potential application in fresh produce packaging. Although this study is not exclusively a postbiotic-based system, it provides supporting evidence for the broader feasibility of sustainable antimicrobial packaging materials for fresh foods.

6.4 Other food applications

The broader food literature indicates that postbiotics may have applications across meat, seafood, dairy, and other food matrices. Their use may support microbial control while avoiding the incorporation of viable microorganisms into the packaging system [2][9].

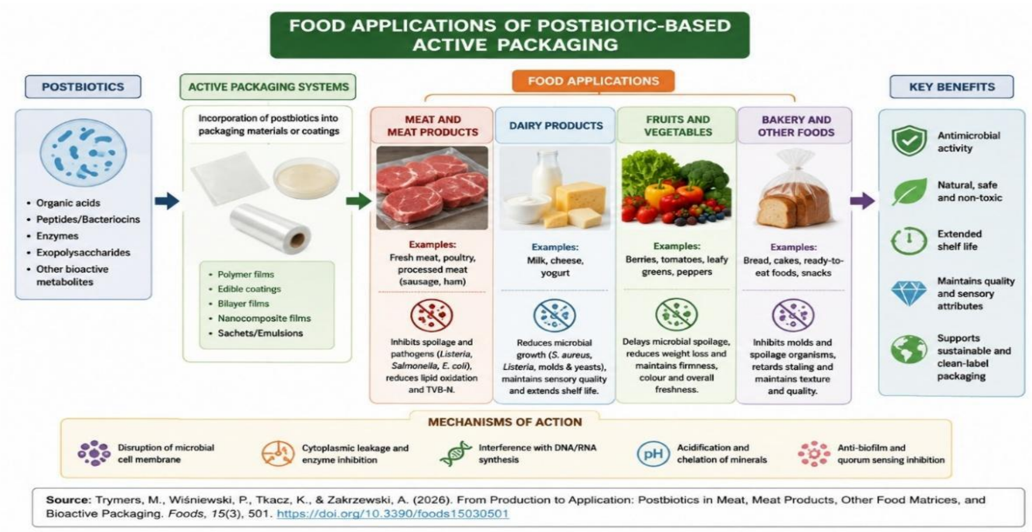


Figure 2: From Production to Application: Postbiotics in Meat, Meat Products, Other Food Matrices, and Bioactive Packaging. Foods

7. Critical discussion of recent literature

Recent literature indicates that postbiotic-based active packaging is emerging as a promising approach for improving food safety and extending shelf life. Unlike conventional antimicrobial packaging based mainly on bacteriocins or cell-free supernatants, recent studies increasingly explore postbiotics in films, coatings, bilayer systems, and nanocomposites. Postbiotics contain a complex mixture of biologically active compounds, including organic acids, bacteriocins, peptides, and antioxidant metabolites. However, comparison among studies remains difficult because researchers use different microbial strains, preparation methods, concentrations, and definitions of postbiotics.

Biodegradable polymers such as chitosan, alginate, bacterial cellulose, and nanocellulose have attracted considerable attention as carriers for postbiotic compounds. Chitosan is particularly useful because it has inherent antimicrobial activity, good film-forming ability, and biodegradability.[8] reported that chitosan–alginate films containing Lactiplantibacillus plantarum A10 postbiotics showed enhanced antimicrobial activity, including inhibition zones of up to 25 mm against Escherichia coli and Listeria monocytogenes. The films also extended the storage life of chicken fillets by approximately five days. These findings demonstrate the practical potential of postbiotic films, although optimization is required because increasing postbiotic concentration can alter tensile strength, solubility, moisture content, and water vapour permeability.

An important strength of recent research is the increasing use of real food systems rather than only laboratory cultures. Studies involving meat, poultry, fish, and dairy products provide more realistic evidence of postbiotic effectiveness. For example, postbiotic preparations from Lactiplantibacillus same I have shown potential for controlling L. monocytogenes in beef. Nevertheless, antimicrobial effectiveness may differ substantially in real foods because pH, salt, water activity, proteins, and lipids can influence antimicrobial compounds.

Another important development is multifunctional packaging. Recent studies suggest that postbiotic-containing films may provide both antimicrobial and antioxidant effects. Gham, for example, demonstrated that chitosan films containing postbiotics could reduce microbial growth and oxidative deterioration in salmon. Advanced technologies such as electrospinning and nanocomposite formation may further improve the stability, loading capacity, and controlled release of postbiotic compounds.

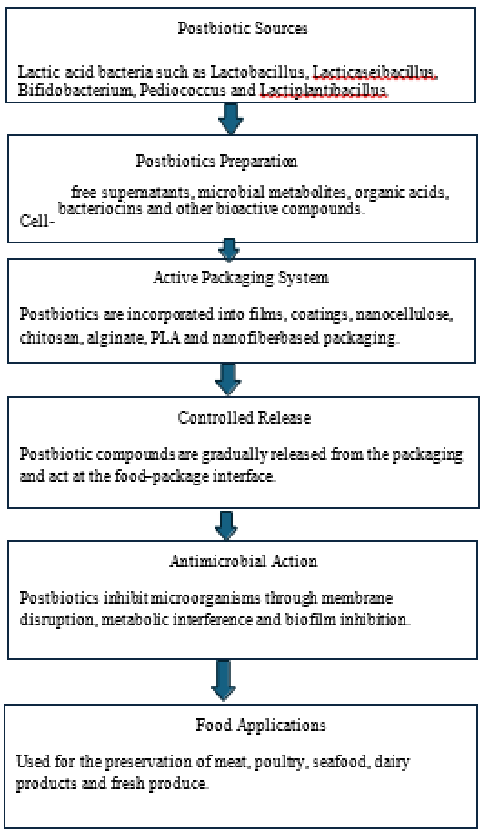
Despite these advances, standardisation remains the major limitation. Differences in strain selection, culture conditions, preparation, inactivation, concentration, and characterization make it difficult to compare results between studies. Future research should therefore establish standardized methods for postbiotic production and characterization. In addition, researchers should evaluate sensory quality, physicochemical properties, food safety, shelf life, and consumer acceptance. Overall, postbiotic-based active packaging has strong potential as a sustainable food-preservation technology, but greater standardisation and validation under real food conditions are necessary before widespread industrial application.

8. Comparative table and figure of postbiotic-based active packaging studies

The literature demonstrates a progression from conventional bacteriocin-containing films toward more diverse postbiotic delivery systems, including coatings, biodegradable films, bilayers, nanocellulose structures, and electrospun nanofibers.

Postbiotic/Active Component	Packaging System	Food Application	Main Purpose
L. rhamnosus postbiotics	Nanocellulose film	Minced meat	Antimicrobial preservation
L. paracasei cellfree supernatant	Chitosan film	Mongolian cheese	Shelf-life preservation
Bifidobacterium postbiotics	Alginate coating	Turkey meat	Quality and safety preservation
LAB-derived postbiotics	PLA film	Rainbow trout	Shelf-life extension
Postbiotics	Bilayer film	Chicken breast	Shelf-life extension
Postbiotics	Cellulose acetate electrospun nanofibers	Chicken breast	Active preservation
P. acidilactici cellfree supernatant	Packaging material	Food packaging application	Preservation potential
L. acidophilus + *B. animalis* postbiotics	Preserving liquid	Mozzarella	Microbial/quality preservation
Bacteriocin	Biopolymeric film	Food packaging	Antimicrobial packaging
Plantaricin BM-1	Multilayer plastic film	Chilled meat	Microbial preservation

Flowchart 1: Conceptual framework for postbiotic-based active food packaging



This framework is consistent with recent literature describing postbiotic bioactivities, active packaging approaches, and emerging delivery systems.

9. Challenges and future perspectives

9.1 Standardization of postbiotic preparations

One of the main challenges in the use of postbiotics is the lack of standardization in their composition. Postbiotic preparations obtained from different microbial strains or produced under different conditions may vary considerably in their antimicrobial activity. Therefore, future studies should provide detailed information about the microbial strain, fermentation conditions, inactivation process, active compounds, concentration, and antimicrobial potency. Such standardized reporting would make it easier to compare results between studies and improve the reliability of postbiotic-based food packaging research.

9.2 controlled release

Maintaining the antimicrobial activity of postbiotics throughout the complete storage period is another important challenge. If the active compounds are released too quickly, their protective effect may decrease before the end of storage. On the other hand, slow or insufficient release may not provide adequate antimicrobial protection. Therefore, advanced approaches such as multilayer films, nanofibers, microencapsulation, and modified polymer systems could help control the release of postbiotic compounds and maintain their activity for a longer period

9.3 packaging performance

Adding postbiotics to a polymer may change tensile strength, flexibility, transparency, water-vapor permeability, and oxygen-barrier properties. Therefore, antimicrobial activity should not be evaluated independently from packaging functionality.

9.4 stability during storage

The stability of postbiotic components under different temperatures, humidity levels, pH conditions, and food environments requires further investigation. Long-term storage studies are necessary before commercial implementation.

9.5 regulatory considerations

Regulatory frameworks for postbiotics remain an evolving area. The terminology and regulatory classification of postbiotic preparations can differ depending on their composition and intended application. Recent literature identifies regulatory harmonization and standardized characterization as important barriers to commercialization (1).

9.6 industrial scale-up

Many current studies are conducted at laboratory or pilot scale. Industrial implementation will require economical production, reproducible postbiotic composition, scalable film manufacturing, compatibility with existing packaging equipment, and appropriate food-contact safety assessment.

9.7 Consumer acceptance and sustainability

Postbiotic-based packaging fits the growing interest in natural and clean-label preservation. However, consumer acceptance will depend on clear communication regarding the origin, safety, functionality, and environmental advantages of these materials.

Future research should also evaluate the complete environmental life cycle of postbiotic packaging rather than assuming that a bio-based material is automatically environmentally superior.

10. Conclusion

Postbiotic-based active food packaging represents a promising emerging strategy for natural food preservation. Postbiotics provide several potential advantages over live probiotic systems, including improved technological stability, absence of viable microbial cells, and the possibility of incorporating antimicrobial microbial metabolites into different packaging platforms. The 20 studies reviewed demonstrate considerable diversity in delivery systems, including nanocellulose films, chitosan films, alginate coatings, PLA films, bilayer films, cellulose acetate nanofibers, and other active packaging materials. Applications in meat, poultry, seafood, dairy products, and fresh produce indicate considerable potential for extending shelf life and maintaining food quality.

Nevertheless, the field remains in a developmental stage. Differences in postbiotic definitions, composition, preparation methods, antimicrobial potency, packaging matrices, and experimental conditions limit direct comparison between studies. Controlled release, stability, packaging performance, regulatory requirements, scalability, and long-term safety also require further investigation. Future research should therefore move toward standardized postbiotic characterization, mechanism-based formulation, advanced controlled-release systems, real-food and industrial scale validation, and harmonized regulatory frameworks. With these developments, postbiotics based active packaging could become an important natural preservation technology that combines food safety, shelf-life extension, and sustainable packaging objectives.

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