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REVIEW ARTICLE

Bioactivities of postbiotics in food applications: a review

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ABSTRACT

Postbiotics, which consist of beneficial compounds produced by probiotic bacteria, have emerged as promising natural preservatives in food applications. This article examines the health-promoting properties of postbiotics and their role in improving food preservation and formulating nutrient-enriched foods. An organized investigation of published works was carried out through key research databases, including ScienceDirect, Scopus, PubMed, and Google Scholar, using keywords such as "Postbiotics," "Biopreservation," "Food Safety," "Functional Foods," "Antimicrobial Activity," "Anti-inflammatory," and "Bioactivities". The findings reveal that postbiotics exert antimicrobial effects through multiple mechanisms, including the production of organic acids, bacteriocins, fatty acids, antimicrobial peptides, hydrogen peroxide, and vitamins. These bioactive substances actively suppress the proliferation of harmful and spoilage-causing microbes, consequently prolonging the preservation period of food items. Furthermore, postbiotics have been integrated into functional foods to modulate the host immune response and mitigate inflammatory conditions. Emerging applications of postbiotics also include their use in active food packaging systems, biofilm eradication, and cosmetic formulations. Although research on postbiotics is advancing, further investigations are required to elucidate the mechanisms of postbiotics and optimize their applications in both clinical and non-clinical contexts. This review emphasizes the potential of postbiotics to enhance food safety, improve nutritional quality, and contribute to overall health promotion.

Keywords: Postbiotics; Antimicrobial; Food safety; Functional foods; Bioactivity

INTRODUCTION

The modern consumer is increasingly interested in natural and minimally processed foods, often associating these attributes with health and well-being. These factors significantly influence consumer acceptance of food products (1). However, food safety remains a critical global concern. The World Health Organization's 2015 data revealed approximately 600 million global cases of foodborne diseases each year, with mortality rates reaching roughly 420,000 individuals (2). Food spoilage is a natural process that renders food unfavorable or unsafe due to changes in taste, texture, odor, or appearance. While spoiled food may not always cause illness, it is typically rejected due to these undesirable alterations. Biopreservation, using helpful bacteria or their natural products to keep food fresh longer, has emerged as a promising solution to these challenges. This approach is gaining attention in the food sector as a natural alternative to synthetic preservatives, which have been linked to issues such as microbial resistance, toxicity, and health concerns (3). To qualify as a viable biopreservative agent, microbial strains or their bioactive compounds should demonstrate: (1) broad-ranging antimicrobial efficacy against both spoilage organ-

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isms and pathogens, (2) durability across diverse processing environments, and (3) minimal impact on food sensory characteristics (4).

The food industry has witnessed significant advancements in preservation technology in recent years, with particular emphasis on natural antimicrobial agents including probiotic cultures and their metabolites. These strategies are particularly relevant in developing nations, where they are viewed as innovative solutions to food preservation challenges (5). However, despite the benefits of probiotics, certain limitations have been identified. Several concerns have been identified regarding probiotic applications: (1) potential virulence determinants in certain strains, (2) variable colonization dynamics that might alter indigenous microbiota (particularly in infants), (3) metabolic alterations including biogenic amine synthesis, (4) absence of standardized therapeutic protocols, and (5) limited evidence from extensive longitudinal clinical studies. These drawbacks have led to the exploration of postbiotics, inactivated microbial biomass or their metabolites, as viable alternatives to live probiotics. Postbiotics offer specific advantages, including stability, safety, and targeted bioactivity, positioning these compounds as potentially advantageous for food preservation and health promotion (6).

The food sector has recently witnessed increasing utilization of postbiotics, driven by consumer demand for foods free from chemical preservatives (7). Postbiotics offer several advantages over traditional preservation methods, including greater stability during food processing and the ability to remain active for extended periods. In contrast, live probiotic bacteria, while beneficial, face limitations due to their sensitivity to environmental factors such as food composition, pH, and temperature, which can compromise their viability and functionality. Emerging applications of postbiotics in food systems predominantly address three critical industry needs: nutraceutical food formulation, spoilage delay technologies, and safety assurance systems (7). Their application aligns with the shift toward natural and sustainable food preservation methods. This review explores the definitions, characteristics, and recent applications of postbiotics, with a focus on their role in elevating food protection standards and addressing consumer preferences for minimally processed, health-promoting food.

Definition of postbiotics. Postbiotics comprise physiologically active compounds synthesized through microbial metabolic processes, including those found in the gut and those present in fermented foods. The scientific literature often employs 'postbiotic' as a collective term encompassing related concepts including biogenics, cell-free supernatants, abiotic metabolites, pseudobiotic substances, and postbiotic, though "postbiotic" is the most widely accepted and commonly used term (8).

Probiotics comprise viable microbial strains that mediate beneficial health effects through host-microbe interactions, primarily by enhancing or restoring gut microbiota. In contrast, prebiotics are non-digestible nutrients that act as substrates that preferentially stimulate the expansion and functional output of health-promoting gut microbiota. Synbiotics refer to combinations of probiotics and prebiotics, which coordinately or independently improve health. Recently, new categories such as paraprobiotics (inactive or non-viable probiotic cells) and postbiotics (bioactive metabolites derived from probiotics) have gained attention. Research has shown that even inactivated microbial biomass, whether whole cell or disrupted, can offer significant health benefits. The physiological influence of the gut microbiome is not only dependent on the viability of microorganisms but also on the bioactive compounds they produce. When administered in sufficient quantities, postbiotics can positively influence host health (9). Broadly, postbiotics can be defined as microbiota-generated substances, including metabolic byproducts and structural elements, which demonstrate clinically relevant health-promoting properties. The ISAPP consensus defines postbiotics as inactivated microbial formulations containing cellular constituents that demonstrate clinically validated host health benefits when properly administered (10).

Postbiotics represent the latest development in the ongoing exploration of gut health. When prebiotics are consumed, they are fermented by gastrointestinal bacteria, resulting in the production of bioactive postbiotics. These metabolic by-products, also known as paraprobiotics, offer many of the benefits associated with probiotic products. However, the relationship between postbiotic production and their subsequent health effects remains an active area of research. Examples of postbiotics include essential nutrients such as vitamin B12, vitamin K, folate, and various amino acids, as well as other bioactive compounds like lipopolysaccharides, enzymes, short-chain fatty acids (SCFAs), bacterial lysates, and cell-free supernatants (10). In vitro studies have demonstrated that postbiotics possess antibacterial, anti-inflammatory, immunomodulatory, anti-proliferative, and antioxidant properties, highlighting their potential to enhance human health (10).

In addition to their health benefits, postbiotics offer significant advantages as functional ingredients in food production and commercialization. Unlike probiotics, postbiotics do not require viability to exert their effects, making them suitable for addition to foods that might otherwise compromise the survival of live bacteria. This stability expands the range of functional foods that can be developed and marketed. Postbiotics are also more stable and secure to handle during large-scale production and storage compared to live bacteria, enhancing their practicality for industrial applications. Furthermore, their non-viable nature makes them safer for use in both food and pharmaceutical products, reducing risks associated with live microbial cultures (11). These attributes position postbiotics as a promising and versatile tool for improving gut health and advancing the functional food industry.

Classification of postbiotics. Postbiotics comprise a diverse group of metabolites produced by the microbiota, which can be categorized according to their structural organization, elemental makeup, and modes of action. Structurally, postbiotics include compounds such as short-chain fatty acids (SCFAs), exopolysaccharides, cell wall fragments, enzymes, proteins, peptides, teichoic acids, and plasmalogens. From an elemental perspective, postbiotics can be categorized into carbohydrates (e.g., teichoic acids and galactose-rich polysaccharides), proteins (e.g., p40, p75 molecule, lactocepin), lipids (e.g., butyrate, acetate, propionate, lactate, dimethyl acetylderived plasmalogen), vitamins (e.g., B-group vitamins), organic acids (e.g., 3-phenyllactic acid and propionic acid), and complex molecules (e.g., lipoteichoic acids and peptidoglycan-derived muropeptides) (12).

Functionally, postbiotics exhibit multi-system biological activities, including anti-obesogenic, antioxidant, anti-inflammatory, hypocholesterolemic, anti-hypertensive, and anti-proliferative properties. Many of these compounds also demonstrate immunomodulatory capabilities, making them valuable for promoting health and preventing disease (12). This multifaceted classification highlights the complexity and versatility of postbiotics, underscoring their potential as bioactive agents in both clinical and non-clinical applications.

Postbiotics isolation and purification. The recovery and refinement of paraprobiotics and postbiotics from various probiotic species involve a range of methodologies tailored to the specific characteristics of the target metabolites. Postbiotics can be extracted from probiotic bacteria using cell disruption techniques, including thermal treatment (13), enzymatic hydrolysis (14), solvent extraction (15), radiation (ionizing and UV rays) (16), high-pressure processing (17), and sonication (18). Emerging methods such as ohmic heating, supercritical CO2 extraction, drying, pulsed electric field (PEF) treatment, and pH modulation also show promise for postbiotic production. A critical consideration during postbiotic production is the application of inactivation factors (19) that maintain the structural integrity of the cells while ensuring the release of bioactive metabolites. For intracellular postbiotics, disruption of the bacterial membrane is necessary, often requiring combined treatments to effectively extract intracellular metabolites. Subsequent recovery and refinement steps, such as centrifugation, dialysis, lyophilization, and column chromatography, are employed to isolate and refine the postbiotic compounds (20). Postbiotics can be isolated from cell-free supernatants. The removal of viable cells is typically achieved through centrifugation and/or filtration. While postbiotics can often be isolated using these methods, certain cases may require additional steps, such as microfiltration, to separate the postbiotic fraction effectively. The optimization of extraction methodologies is fundamentally governed by the inherent chemical characteristics of the desired compounds (21). The physiological efficacy of postbiotics is directly determined by their extraction protocols, necessitating precise optimization of probiotic inactivation parameters to preserve bioactive constituents. This ensures the production of high-quality postbiotics with preserved functional properties (11).

Postbiotics bioactivity mechanism. Postbiotics exhibit significant bioactivity, particularly in inhibiting pathogenic bacteria and preventing food spoilage. Their antimicrobial efficacy depends on several factors, including the specific probiotic strain from which they are derived, the type of target bacterium (with Gram-positive bacteria generally being more resistant than Gram-negative bacteria), and the concentration of postbiotics applied (22). Postbiotics demonstrate targeted antimicrobial activity through fortification of gut epithelial tight junctions, and molecular mimicry that blocks pathogenic adhesion sites, modulating host gene expression, and altering the local microenvironment to inhibit pathogen growth. For example, an in vitro study revealed that postbiotics obtained from *L. plantarum* significantly reduced the adhesion and invasive capacity of *L. monocytogenes*, highlighting their potential as inhibitory agents. In animal studies, the administration of postbiotics from probiotic bacteria such as *L. casei*, *L. acidophilus*, and *L. delbrueckii* increased gut IgA levels of the intestines, reducing the intensity of infections caused by *E. coli* and *S. enteritidis* (23). Similarly, culture supernatants from *Bifidobacterium* and *Lactobacillus* strains have demonstrated antibacterial activity by preventing the invasion of EIEC into enterocytes. The cell-free fractions also modulated the expression of protective genes, strengthened the intestinal barrier, and improved the gut environment, likely due to the competitive inhibition of pathogenic bacterial adhesion to receptor sites (24). In the subsequent sections, we characterize the bacterial and host interaction mechanisms for each postbiotic category.

Organic acids. Organic acids are renowned for their antimicrobial properties. Lactic acid, a by-product of bacterial fermentation, is particularly effective in inhibiting pathogenicity (25). Similarly, citric acid and acetic acid create an acidic environment that suppresses the growth of pathogens. Among organic acids, lactic acid (pKa = 3.86) and acetic acid (pKa = 4.76) are especially effective in inhibiting pathogen growth by reducing pH levels under both in vitro and in vivo conditions. Their antimicrobial activity is primarily attributed to their impact on bacterial cell membranes, which involves lowering intracellular pH and disrupting membrane integrity (26).

A study by Chang-Hui Hu et al. (2019) revealed the antimicrobial effects of organic acids produced by three strains of *L. plantarum* against *E. coli* and *Salmonella*. The results demonstrated that the organic acids effectively inhibited the growth of pathogenic bacteria, with lactic acid and acetic acid showing particularly strong antibacterial activity. These findings suggest that combining different organic acids could serve as a promising strategy for developing novel antimicrobial agents for biopreservation in the food industry (27). This approach highlights the potential of postbiotics, particularly organic acids, as natural and effective tools.

Bacteriocins. Bacteriocins, proteinaceous antimicrobials, are produced by a wide range of bacteria, including Archaebacteria and Eubacteria. For thousands of years, humans have harnessed the potent antimicrobial properties of bacteriocins in fermented foods. These molecules are categorized based on their size, mechanism of action, and inhibitory spectrum. Bacteriocins offer numerous benefits, such as inhibiting the growth of gastrointestinal pathogens and demonstrating remarkable stability under varying heat and pH conditions. Their primary mode of action involves targeting the bacterial membrane, disrupting the bacterial peptides, and inhibiting the formation of spores (28).

In a study by Yao Wang (2019), bacteriocins produced by *L. plantarum* LPL-1, isolated from fish, were tested against *L. monocytogenes*. The results showed that these bacteriocins effectively inhibited the growth of *L. monocytogenes* by cytoplasmic acidification and membrane nanopore formation (29). Similarly, Sam Woong Kim et al. (2020) investigated the effects of bacteriocins produced by *L. taiwanensis* on *S. gallinarum* and *E. coli*. The study revealed that the bacteriocins from *L. taiwanensis* inhibited bacterial growth by lysing the membrane of pathogenic bacteria and damaging their protein structure (30). These peptide antimicrobials represent promising candidates as powerful tools for inhibiting food spoilage and pathogenic bacteria.

Fatty acids. Fatty acids and their derivatives have been acknowledged as effective alternatives to antibiotics for over a century, with their antimicrobial properties being well-documented. They are considered potential postbiotics due to their significant antimicrobial activity. For example, long-chain fatty acids such as eicosapentaenoic acid (EPA) are effective against Gram-positive bacteria, while medium-chain fatty acids like lauric acid and myristic acid exhibit strong activity against microbial growth. Their antimicrobial mechanisms include increasing membrane permeability, causing cell lysis, disrupting the ETC, enzyme denaturation, and disrupting the bacterial peptides and proteins (31). These actions make fatty acids potent agents against a wide range of pathogens. In a study by Bruna Higashi et al. (2020), fatty acids derived from *L. acidophilus, L. fermentum, L. paracasei*, and *L. brevis* were tested against *K. oxytoca*. The results demonstrated that these fatty acids effectively inhibited the growth of *K. oxytoca* by lysing its cell wall (32). This highlights the potential of fatty acids as natural antimicrobial agents, particularly in applications such as food preservation and biopreservation, where they can serve as safe and sustainable alternatives to synthetic preservatives.

Antimicrobial peptides. Antimicrobial peptides (AMPs) are bioactive molecules produced by microorganisms that exhibit potent antimicrobial activity through various mechanisms. These peptides are broadly classified into two types: ribosomal peptides, which are synthesized by bacteria, and non-ribosomal peptides. Ribosomal peptides, in particular, demonstrate strong antimicrobial activity in vitro by disrupting microbial membranes. AMPs are ubiquitous in bacteria and target different cellular components depending on their structure and mode of action. For some peptides, the primary target is the bacterial cell membrane, while others act on the cytoplasm and other intracellular structures. Their mechanisms include creating an acidic environment within the bacterial cell membrane, forming physical pores that lead to cellular content leakage, activating lethal processes, and damaging critical intracellular components (33). In a study by Forkus et al. (2017), antimicrobial peptides derived from *E. coli* Nissle 1917 were shown to inhibit the growth of *S. enterica* by damaging its cell wall (34). Similarly, Nithya (2012) demonstrated that antibacterial peptides produced by *B. subtilis* effectively inhibited the growth of *L. monocytogenes* and *E. coli* by targeting and damaging sensitive bacterial structures (35).

Hydrogen peroxide. Hydrogen peroxide, a metabolite produced by lactic acid bacteria, is a well-known antimicrobial compound generated by various bacteria. Its inhibitory and antibacterial effects depend on factors such as hydrogen peroxide concentration, the specific bacterial strains involved, and environmental conditions. The oxidative biocidal property of H_2O_2 is primarily attributed to its strong oxidizing activity, which damages cytoplasmic proteins and other critical cellular structures in bacterial cells (36). In a study by Abbasi et al. (2020), the production of hydrogen peroxide by *L. acidophilus, L. rhamnosus, Bifidobacterium longum*, and *B. infantis* was shown to inhibit the growth of methicillin-resistant *Staphylococcus aureus* (MRSA) (37). This highlights the potential of hydrogen peroxide as a natural antimicrobial agent, particularly in combating antibiotic-resistant pathogens.

Vitamins. Probiotic bacteria are known to produce significant amounts of vitamins, with their production being particularly enhanced in dairy products. These micronutrients suppress microbial proliferation. Vitamins can be obtained by lysing probiotic bacteria such as *L. plantarum*. Among these vitamins, vitamin C stands out for its strong antimicrobial properties. It reduces the pH of microbial membrane, ultimately causing structural disintegration of both the lipid bilayer and the peptidoglycan matrix (38).

Postbiotics effects on physical and mental health. Postbiotics have emerged as promising agents for addressing a wide range of physical and mental health challenges, including pathogenic infections, carcinogenesis, oxidative stress, and sleep-related disorders. These bioactive metabolites, derived from probiotic microorganisms, exhibit antimicrobial, anticancer, antioxidant, and immunomodulatory properties, making them valuable tools for improving public health.

Emerging viral infections are a major global concern, and postbiotics have shown potential in exerting antiviral effects, particularly against enveloped viruses. Postbiotics demonstrate antiviral activity by blocking viral attachment, preventing host cell entry and inhibiting reverse transcriptase function. Their efficacy exhibits significant variability, with strain-dependent activity and virus-specific efficacy. For instance, cell-free metabolites of *L. rhamnosus* have been shown to prevent enterovirus and coxsackievirus attachment to HeLa, Vero, and Hep-2 cell lines (39).

Postbiotics demonstrate significant antioxidant capacity, which can damage nucleic acids, proteins, lipids, and carbohydrates. They achieve this through the activity of antioxidant enzymes, which neutralize reactive oxygen species (ROS). Accumulating researches have demonstrated the antioxidant potency of postbiotics, with *L. fermentum* strains exhibiting high glutathione peroxidase (GPx) activity and *L. plantarum*-derived postbiotics increasing serum glutathione peroxidase levels. Genetically modified *Lactobacillus* strains producing catalase or superoxide dismutase (SOD) have demonstrated superior efficacy in alleviating symptoms of chronic inflammatory intestinal disorders, including CD and IBD in murine models. Additionally, in vivo studies revealed that catalase-positive *Lactococcus lactis* has been shown to decrease tumor multiplicity in mice (40).

The anticancer properties of postbiotics are another area of interest, with their efficacy depending on the probiotic strain, the type of postbiotic, and the target organ (21). For example, postbiotics from *L. paracasei* have been shown to inhibit human colorectal carcinoma cell growth through cell wall proteins (41). Similarly, bacteriocins produced by *Enterococcus* and *L. plantarum* exhibit cytostatic and apoptotic effects against cancer cells, highlighting their potential as anticancer agents (42).

Beyond physical health, postbiotics influence mental health and sleep quality through the microbiome-gut-brain axis. Dysbiosis, an altered gut microbial ecosystem, exhibiting both decreased species richness and a disrupted equilibrium between symbiotic and harmful bacteria, has been linked to poor sleep quality, stress, anxiety, and depression. The gut microbiome produces a range of neuroactive and immunomodulatory metabolites, including short-chain fatty acids (SCFAs), secondary bile acids, and neurotransmitters, which influence brain function and behavior. Certain strains of *Bifidobacterium*, *Lactobacillus*, and related genera (*Lacticaseibacillus, Limosilactobacillus, Lactiplantibacillus,* and *Levilactobacillus*) have been shown to reduce stress and anxiety, potentially through neural, endocrine, and immune mechanisms, as well as modulation of clock gene expression (43). These results validate the therapeutic promise of microbial-derived bioactive compounds in improving both physical and mental health.

Bioactivities of postbiotics in food application. The concept of "postbiotics" has emerged from numerous studies indicating that the viability of probiotics is not a prerequisite for conferring health benefits (21, 44).

Compared to viable probiotic strains, postbiotic formulations demonstrate superior processing stability, maintaining 90-95% bioactivity after high-temperature pasteurization and extended shelf storage. Additionally, postbiotics are better absorbed through metabolic processes and exhibit high signaling capacity, enabling them to demonstrate multi-organ bioavailability and eliciting targeted physiological responses (44).

When formulating foods with postbiotics, several factors must be considered, including the specific probiotic strain used, the growth medium, growth conditions, inactivation techniques (conventional methods like pasteurization or sterilization, or emerging technologies such as ultrasound, UV, high pressure, or irradiation), separation processes (centrifugation and filtration), concentration methods (spray drying or freeze drying), and the incorporation of postbiotics into the food matrix (45).

Advances in food biotechnology enable the development of next-generation nutraceuticals featuring with high bioactive potential by incorporating postbiotics into product formulations. Although research in this area is still limited, some examples include yogurt and whey-based sports drinks containing inactivated lactic acid bacteria (LAB) such as *L. bulgaricus, S. thermophilus, L. acidophilus, L. gasseri* CP2305, and *L. casei* 01 (11).

Beyond their health benefits, postbiotics also contribute to food safety. Potential applications include the biopreservation of diverse food products, the secretion of compounds that exhibit potent microbial inhibitory effects, advanced packaging systems incorporating functional biomaterials, and proactive biofilm management in food processing systems (46). However, critical knowledge gaps remain in integrating postbiotics into the food industry.

Biopreservation. Biopreservation employs selected microbial strains and their bioactive derivatives, postbiotics, to inhibit food spoilage organisms, thereby enhancing product stability (47). For non-vegetarian foods, postbiotics can be applied directly as coatings (e.g., on fish fillets) or through spraying (e.g., on meat). The application method depends on the type of postbiotic and the specific meat product, ensuring the preservation of nutritional and organoleptic qualities. For instance, postbiotics from *P. acidilactici, L. sakei,* and *S. xylosus* have been shown to reduce *S. typhimurium* contamination (48). Similarly, incorporating *S. cerevisiae* fermentation products into poultry diets has demonstrated potential in controlling *S. enterica*. Studies have also found that postbiotic-based preservatives are as effective as commercial preservatives in enhancing the product stability of vacuum-packaged cooked sausages, offering a natural alternative for food preservation (49). Beyond their antibacterial properties, postbiotics are being explored for their antiviral potential. Strains such as *L. amylovorus*, *L. plantarum*, and *E. hirae* have shown promising antiviral activity against enterovirus isolates, likely due to mechanisms like hydrogen peroxide production, organic acid secretion, and competitive exclusion (50).

Postbiotics serve as a biocontrol alternative to systematically reduce hazards in dairy products, fruits, and vegetables. For example, postbiotics have been used to control cheese blowing defects and as sanitizers in food processing environments (46).

Functional food preparation. The primary mechanism for stimulating the host immune system involves the use of functional foods fortified with postbiotics. In vitro studies on exopolysaccharides from *L. plantarum* suggest their potential use in nutraceutical formulations and activating tumor suppressors (51).

Postbiotic metabolites, mediate gut immune responses. Clinical trials have demonstrated that postbiotics from *B. longum* effectively activates the immune regulation (52). The efficacy of postbiotic metabolites in managing inflammatory conditions depends on several factors, particularly the type of postbiotic strain used. Lin et al. (53) investigated the relationship between metabolite activity and strain selection, finding that multi-strain postbiotics exhibit superior anti-inflammatory responses. This highlights the importance of careful selection and combining strains to maximize the health benefits of the postbiotics.

Food packaging. Active food packaging systems utilize engineered materials to preserve product quality. This postbiotic-based active packaging system aims to preserve food quality and prevent microbial spoilage during storage and transportation to consumers. Postbiotics can be incorporated into these systems in different ways, like thin coatings, covalent immobilization, integration into the packaging matrix, or lamination onto polymers (54). These methods often utilize organic acids, peptides, and bacteriocins, with organic acids like lactic acid, citric acid, and acetic acid being particularly effective due to their ability to disrupt pathogen growth by lowering cytoplasmic pH and impairing membrane function. Peptides and bacteriocins, on the other hand, act through pleiotropic mechanisms, including degrading cell membranes, inhibiting macromolecule synthesis, and blocking microbial growth (54).

Removal of biofilms. Biofilms, which are structured communities of microorganisms encased in a polysaccharide or protein substances, pose a significant challenge in the food sector. Pathogens such as *L. monocytogenes*, *Y. enterocolitica*, *C. jejuni*, *S. aureus*, and *B. cereus* are known to form resilient biofilms that resist traditional sanitation protocols. Postbiotics offer a promising solution for dismantling these biofilms. Research has confirmed that microbial metabolites obtained from *L. acidophilus* LA5, *L. casei* 431, and *L. salivarius* effectively inhibit biofilm formation by *L. monocytogenes* on polystyrene surfaces. These postbiotics, containing bacteriocins and organic acids, have been shown to significantly reduce biofilm formation by pathogens, making them valuable tools for biofilm control in the food industry (47).

Conclusion and future trends. In summary, postbiotics represent a significant and innovative addition to the "-biotics" family, offering a wide range of health and functional benefits. While their precise definition and mechanisms of action are still being refined, postbiotics derived primarily from probiotic species such as *Lactobacillus* have demonstrated significant potential in both clinical and non-clinical applications. Compared to probiotics, postbiotics offer distinct advantages, including easier preparation, extended shelf life without the need for cold chain storage, and more targeted bioactivity. However, their utilization remains in the early stages of exploration. Postbiotics provide numerous clinically-relevant efficacy in disease management, enhancement of overall well-being, and applications in food preservation through active packaging systems. They also hold promise in cosmetic applications, such as reducing inflammation and acne. While animal models and in vitro studies have shown positive biological responses to postbiotics, additional controlled trials in human subjects are essential to evaluate their safety, efficacy, and optimal dosage. Additionally, a rapidly evolving field is the use of postbiotics in biological doping.

In conclusion, postbiotics have the potential to significantly improve host health and well-being, although their exact mechanisms of action require further investigation. Advanced research utilizing -omics approaches (e.g., genomics, metabolomics, and proteomics) to study host-postbiotic interactions and the biological responses of metabolites could reveal new applications for postbiotics in both clinical and non-clinical fields. As the field evolves, postbiotics are poised to play a transformative role in food science, medicine and beyond, offering sustainable and effective solutions for health and industry.

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