Lactic Acid Bacteria-Derived Postbiotics: Definition, Characterization, Health Implications, and Food Applications

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Abstract

Postbiotics, which consist of inanimate microorganisms and/or their components, are gaining increasing attention in the food industry due to their stability, safety, and health benefits. Unlike probiotics, postbiotics do not require viable bacterial cells, making them easier to incorporate into food products while maintaining their functional properties. These bioactive components, including peptides, organic acids, exopolysaccharides (EPS), and bacteriocins, contribute to food preservation by inhibiting pathogenic and spoilage microorganisms, improving food safety, and extending shelf life. Beyond their role in food technology, postbiotics provide significant health benefits, particularly in gut health regulation. They support the intestinal microbiota, enhance immune function, exhibit anti-inflammatory properties, and contribute to the prevention of gastrointestinal disorders. Lactic acid bacteria (LAB) are among the most extensively studied and widely utilized microorganisms in the production of postbiotics. LAB-derived postbiotics have shown potential in modulating metabolic health, reducing the risk of obesity and diabetes, and improving overall well-being. This book highlights the applications of LAB-derived postbiotics in food systems, their mechanisms of action, and their contributions to human health.

Keywords: lactic acid bacteria, postbiotics, functional foods, health benefits

1. Introduction

While the health advantages of probiotics are widely recognized, current studies indicate that these benefits are not solely reliant on live bacteria; rather, postbiotic components, particularly those derived from fermentation processes, also provide significant biological impacts (Scott et al., 2022). Therefore, postbiotics have become an increasingly popular category among microbiota-targeted approaches, such as probiotics and prebiotics. However, there are significant uncertainties in the literature and practice regarding the definitions of these concepts and their distinctions from one another. In particular, the terms probiotic, prebiotic, postbiotic, and parabiotic often cause confusion, leading to a terminological complexity (Salminen et al.,2021). Probiotics are defined by FAO/WHO and International Scientific Association for Probiotics and Prebiotics (ISAPP) as "live microorganisms that, when administered in adequate amounts, confer a health benefit on the host" (Hill et al., 2014). Prebiotics are defined as "non-digestible food components that selectively stimulate the growth and/or activity of beneficial host microorganisms, thereby supporting the host's health" (Gibson et al., 2017). Parabiotics, on the other hand, is a term proposed to describe inactivated microorganisms that have lost viability but retain their structural integrity, emphasizing effects such as immunomodulation that do not require live cells (Taverniti & Guglielmetti, 2011).

The term postbiotic was first proposed by Tsilingiri and Rescigno in 2013, referring to "the metabolic products of probiotics" (Tsilingiri & Rescigno, 2013). However, this definition did not clearly delineate the scope and boundaries of postbiotics. A more precise definition was later established by the ISAPP in 2021, defining postbiotics as "preparations of inanimate microorganisms and/or their components that confer a health benefit on the host" (Wei et al., 2024). This definition emphasizes that postbiotics should not contain live cells, but may include inactivated cells (such as heat-killed bacterial cells) and/or components derived from them (such as organic acids, short-chain fatty acids (SCFAs), peptides, and cell wall fragments) (Bhatia et al., 2024). Nevertheless, different perspectives exist in the literature. Some researchers limit the term postbiotics strictly to metabolites and cell components (Aguilar-Toalá et al., 2018), while others include entire inactivated microbial cells within the scope of postbiotics (Taverniti & Guglielmetti, 2011; Tao et al., 2024).

Postbiotics are used to support health and well-being. *in vivo* and *in vitro* studies have demonstrated that certain postbiotics exhibit a range of biological activities, including immunomodulatory, anti-inflammatory, cell growth inhibitory, antimicrobial, and antioxidant effects (Erginkaya & Konuray-Altun, 2022) Furthermore, postbiotics prevent the development and spread of various types of pathogens in the gut. In particular, postbiotics can limit gram-negative bacteria such as *Escherichia coli*, *Salmonella* Typhimurium, *Clostridium perfringens*, *L. monocytogenes*, and vancomycin-resistant *Enterococci* (Urban et al., 2024).

Postbiotics, produced by various microorganisms, are widely utilized in commercial food products and pharmaceutical formulations due to their functional properties. Especially LAB are the most researched and used microorganisms in postbiotic production. LAB, which have a wide range of industrial applications, stand out with their various properties, particularly in fermented foods (Ağagündüz et al., 2022). The recently modified genus *Lactobacillus* is the most studied LAB and the group most used to produce postbiotics (Pimentel et al., 2023). LAB is a heterogeneous group of Gram-positive and catalase-negative bacteria that possess a strictly fermentative metabolism, with lactic acid as their primary metabolic end product. These organisms naturally inhabit humans, animals, and plants. Their long history of safe use, often classified as Generally Recognized as Safe (GRAS), combined with various interesting metabolic properties, has led to a wide range of industrial applications. The flavor, texture, and preservative qualities of many fermented foods such as cheese, yogurt, sausages, and sourdough bread are determined by the use of species belonging to the seven main genera of LAB: *Lactobacillus* (milk, meat, vegetables, cereals), *Lactococcus* (milk), *Leuconostoc* (milk, vegetables), *Pediococcus* (vegetables, meat), *Oenococcus* (wine), *Enterococcus* (milk), and *Streptococcus* (milk) (Akpoghelie et al., 2025).

LAB are classified into different genera/species based on their ability to ferment sugars, their acid production characteristics, and their growth at specific temperatures. Additionally, LAB can be classified as homofermentative or heterofermentative based on their metabolic pathways for carbohydrate fermentation (Ayivi et al., 2020).

Homofermentative LAB (*Lactococcus, Streptococcus*) predominantly convert glucose into lactic acid with a theoretical yield exceeding 90% through homolactic fermentation. Heterofermentative LAB (*Leuconostoc, Wiessella*) metabolize glucose via heterolactic fermentation, producing lactic acid alongside carbon dioxide, acetic acid, and/or ethanol (Peyer et al., 2016).

LAB are known for their ability to produce various health-promoting metabolites, including EPS, fructooligosaccharides, GABA, SCFAs, conjugated linoleic acids, bacteriocins, and selenoproteins. These metabolites have demonstrated promising health benefits, such as antioxidant properties, immune regulation, and enhancement of epithelial barrier function, making LAB the primary material for the most commonly used probiotics and postbiotics (Zhao et al., 2024). The majority of postbiotic production is accomplished through physical or enzymatic methods, encompassing processes such as cell lysis, autolysis, and the application of heat or ultrasound. In these processes, metabolites of living cells or cell structural components are released. For instance, certain lactic acid bacteria species have been observed to demonstrate immunomodulatory and antimicrobial properties even following heat inactivation (Taverniti & Guglielmetti, 2011).

Furthermore, the quality and quantity of postbiotics are directly influenced by the production environment and fermentation conditions. Factors such as carbon and nitrogen sources, pH, temperature and oxygen status have been demonstrated to alter the composition of the postbiotic components produced by altering the metabolic profiles of LABs (Żółkiewicz et al., 2020). Postbiotics offer a number of advantages compared to live probiotics. As they do not contain live microorganisms, they eliminate concerns related to viability, making their production, storage, and transportation significantly easier. Their production processes are suitable for industrial-scale manufacturing, supporting commercial scalability. Moreover, postbiotics exhibit specific mechanisms of action and, through better accessibility of Microbe-Associated Molecular Patterns (MAMP) to Pattern Recognition Receptors (PRR), they can trigger more targeted and controlled immune responses These properties allow for selective interactions that reduce the risk of unintended side effects (Pimental et al., 2023).

Unlike probiotics, postbiotics do not carry the risks of infections, production of harmful metabolites, or transfer of antibiotic resistance genes within the gut microbiota. Therefore, postbiotics are considered a safer option, particularly for immunocompromised individuals and those with compromised intestinal barrier function. Additionally, postbiotics offer extended shelf life, ease of transportation and storage, and flexibility for incorporation into various food and feed products (Zhao et al., 2024). (as shown in Fig 1). Given these advantages, postbiotics have found extensive applications in the food and medical sectors (Urban et al., 2024).

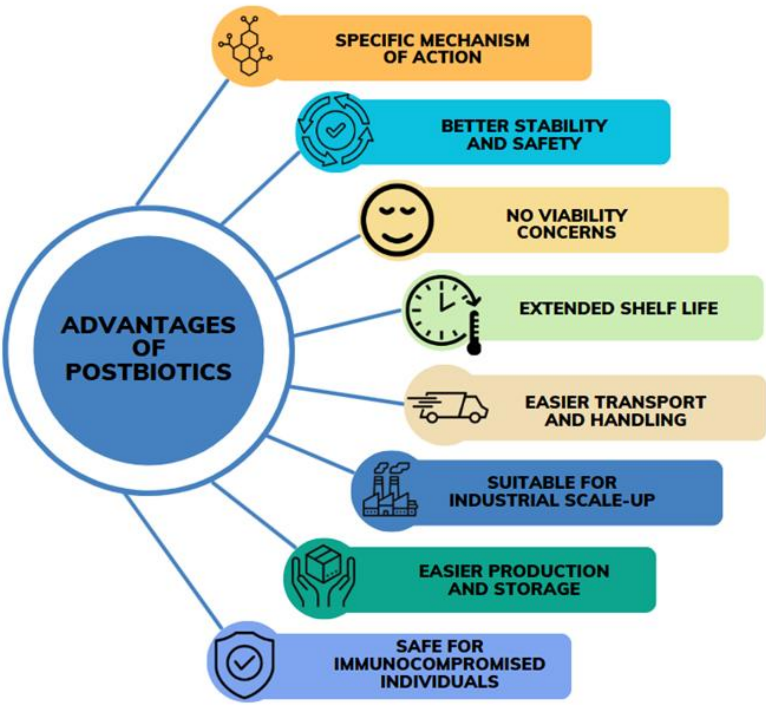

Figure 1 Schematic representation of advantages of postbiotics.

In recent years, many researchers have obtained various postbiotics from different strains of LAB and studied the health effects of the obtained postbiotics *in vivo* and *in vitro*. In addition, studies have been conducted on the food applications of the obtained postbiotics. The aim of this book is to provide a comprehensive overview of postbiotics derived from LAB, with a particular focus on their production processes, biological activities, functional mechanisms, and potential applications in food systems and health promotion.

2. Extraction and Characterization of Postbiotics by LAB

Postbiotics are typically produced by culturing LAB in a suitable culture medium, most commonly De Man, Rogosa, and Sharpe (MRS) broth, followed by an extraction process. This extraction commonly involves centrifugation at 4,000–12,000 × g for 10 min at 4°C or dialysis to separate bacterial components. When postbiotics are derived from MRS broth, the resulting bacteria-free fermentate exhibits an acidic nature and a characteristic brown to brownish-yellow coloration (Moradi et al., 2021). Postbiotics can be formulated in both liquid and dry forms, with the latter commonly produced through spray drying or lyophilization. Among these preservation techniques, lyophilization is the predominant method, although spray drying is also employed. The selection of the appropriate postbiotic application method is primarily determined by the specific characteristics and requirements of the target food matrix (Dunand et al., 2019). The overview of postbiotic production from LAB and its use in foods and health-promoting systems is presented in Fig 2.

In a study where postbiotics were produced from *Lactiplantibacillus plantarum* using three different culture media (milk, MRS, and whey), it was determined that all postbiotics exhibited antimicrobial activity. However, the postbiotic obtained from the MRS medium demonstrated greater antibacterial and antifungal properties compared to those derived from milk and whey. Furthermore, the study reported that the heating technique used for postbiotic extraction showed superior effectiveness in releasing antimicrobial metabolites when compared to centrifugation and sonication techniques (Khakpour et al., 2024). In another study, the carbon and nitrogen sources used in culture media for postbiotic production by LAB were compared; fructose and xylose enhanced the growth of certain strains, while ribose improved antimicrobial activity. Animal-derived components were successfully replaced with plant-based and microbial nitrogen sources (soy, wheat, and yeast), which effectively supported microbial growth and antibacterial activity (Garrote Achou et al., 2025).

A wide range of instrumental techniques and advanced analytical approaches have been employed for the qualitative and quantitative assessment of postbiotics (Moradi et al.,2021).

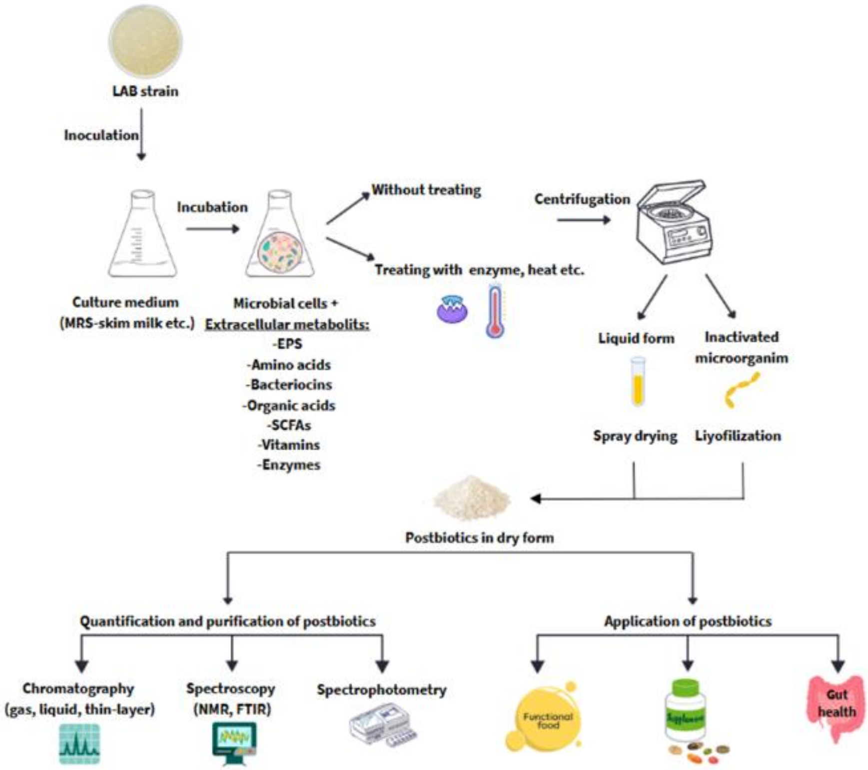

Figure 2 Overview of postbiotic production and use in foods and health promoting systems.

Due to the structural complexity of postbiotics—such as varying polymerization degrees and glycosidic bonds—their analysis often requires advanced equipment and several purification steps. Common techniques include chromatography (gas, liquid, thin-layer), spectroscopy (NMR, FTIR), and spectrophotometry. The choice of method depends on the specific analytical goal and characterization needed (Liang & Xing, 2023). Wu et al., (2024) evaluated the potential of postbiotics obtained from fermented milk using *Lacticaseibacillus paracasei* and *Lactiplantibacillus plantarum* strains. The metabolite profile was analyzed by LC-MS, with amino acids measured using the Hitachi L-8900 amino acid analyzer through ion-exchange chromatography, and fatty acids analyzed by HPLC. The fermentation process led to an increase in levels of essential amino acids such as threonine, leucine, and lysine, as well as non-essential amino acids like serine, glycine, and cysteine. Among organic acids, citric, succinic, and 2-hydroxypropanoic acid were notably enriched, while beneficial fatty acids such as DHA, EPA, oleic, linoleic, and nervonic acid were also significantly increased. In the study by Jalali et al., (2024a), postbiotics derived from *Lacticaseibacillus rhamnosus* and *Limosilactobacillus reuteri* were characterized using HPLC (for SCFA analysis), UV-VIS spectrophotometry (for DPPH, protein, and sugar measurements), and ELISA (for riboflavin detection). Identified compounds included acetic, propionic, butyric, and lactic acids, D-lactate, total phenolics, flavonoids, riboflavin, catalase, SOD, and GSH-px. The postbiotics exhibited strong antimicrobial and antioxidant activities without causing cytotoxic or hemolytic effects, indicating their potential use as natural preservatives in food safety applications.

3. Classification of Postbiotics Produced by LAB

3.1 Exopolysaccharides (EPS)

EPS are secondary metabolites synthesized during the growth and metabolic activity of LAB. These biopolymers may be loosely associated with the bacterial cell surface or secreted directly into the extracellular environment (Zhang et al., 2024a). These high-molecular-weight compounds are synthesized through the coordinated action of various proteins and specific enzymes. Their production is regulated by gene clusters involved in polysaccharide biosynthesis, including glycosyltransferase (GT) genes, polymerase genes, and genes responsible for EPS chain length determination and export (Zang et al., 2025). LAB-derived EPS (LAB-EPS) are classified into homopolysaccharides (HoPS) and heteropolysaccharides (HePS) based on their chemical composition and biosynthetic mechanisms. HoPS are composed of a single type of monosaccharide arranged in repeating subunits, such as glucose or fructose, and are further categorized into α-D-glucans, β-D-glucans, fructans, and polygalactans. HePS are composed of repeating subunits consisting of 3 to 8 different monosaccharides, typically including D-glucose, D-galactose, and L-rhamnose, along with rare monosaccharides such as fucose, arabinose, mannose, N-acetylgalactosamine, N-acetylglucosamine, and glucuronic acid (Yang et al., 2023; Wang et al., 2023). Approximately 30 species of LAB have been identified as EPS producers (Xu et al., 2019). The EPS production abilities of various LAB strains are presented in Table 1.

Table 1 Extraction condition and yield of LAB-EPS obtained from different medium.

Lab strain	İnoculation rate	Medium	Exraction condition	Yield	References
Pediococcus pentosaceus D3	5.4%	Blueberry juice	-anhydrous ethanol 12 h at 4 ◦C. centrifugation at 4500 rpm for 15 min	2.35 g/L	(Yang et al., 2024)
Lactiplantibacillus plantarum ITD-ZC-107	10 %	Brain Heart Infusion (BHI) culture medium containing bagasse or agave leaves	-(-4 ◦C) 96 % (v/v) ethanol 24 h at 4 ◦C. centrifugation at 3000 rpm for 5 min.	Agave leaves 114.00 mg/mL Bagasse 73.50 mg/mL	(Vázquez-Vargas et al., 2024)
L. plantarum: *L. fermentum*; *L. mesenteroides*	2%	Yeast extract broth containing sugar beet molasses	-95% cold ethanol, at 4 ◦C for 12 h. 4000 r/min for 20 min,	13.96-22.26 g/L	(Ren et al., 2024)
Lactobacillus rhamnosus KF5 *Lactobacillus plantarum* C182 *Pediococcus acidilactici* CCFM18 *Leuconostoc mesenteroides* F27	Unspecified	MRS broth	-ethanol (96 mL/100 mL), kept overnight at 20 ◦C centrifuged for 30 min at 3200 rpm (4 ◦C).	2.86-9.18 g/L	(Nemati & Mozafarpour, 2024)
L. delbrueckii ssp. bulgaricus	Unspecified	MRS broth	-chilled (-20 ◦C) ethanol	1.6-2.6 $g·L^{-1}$	(Mikshina et al., 2024)

Limosilactobacillus fermentum AG8 *Lactiplantibacillus plantarum* AG9		MRS with 0.4 % flaxseed mucilage (FSM)	72 h at 4 ◦C. centrifugation 15 min at 8000 rpm,	8.1, 7.3, and 6.1 $g\cdot L^{-1}$,	
L. plantarum MY04	3%	MRS broth	-95% aqueous ethanol overnight 25 ◦C centrifugation (7104×*g* for 10 min at 25 ◦C),	1.15 g/L	(Lu et al., 2023)
L. mesenteroides Lactobacillus sp Pediococcus sp.	Unspecified	MRS broth supplemented with 5 % (wt/vol) sucrose	-chilled 96 % (vol/vol) ethanol stored overnight at 4 ◦C. centrifugation (20 min at 12,000 g)	0.5–18.0 g/L	(Garmasheva et al., 2024)
Leuconostoc citreum Leuconostoc mesenteroides Pediococcus pentosaceus Leuconostoc pseudo-mesenteroides	1%	Exopolysaccharides selection medium	-cold absolute ethanol overnight at 4 ◦C 9000 rpm for 20 min at 4 ◦C	2.9-3.85 g/L	(Abid et al., 2018)
Weissella confusa/cibaria strains	2%	MRS broth supplemented with 10% (w/v) sucrose	-75% ethanol centrifuged at 5,500 × g at 4 ◦C for 15 min	5.2-47.1 g/L	(Buksa et al., 2021)
W. cibria	~7 log CFU/g	Sourdough containing sucrose	-85% (v/v) chilled ethanol	28.06 g/kg	(Du et al., 2023)

			soaked overnight centrifuged at 6000*g* for 20 min		
L. delbrueckii strain GRIPUMSK *L. hirsilactics strain* CH4	Unspecified	MRS broth with 2% of sucrose	-Ethanol hold on to 4 ◦C centrifugation at 4 ◦C at 12 000 rpm for 30 min	690 and 620 mg/L	(Srinivash et al., 2023)
Weissella cibaria FAFU821	2 %	MRS medium with 100 g/L sucrose	-cold 95 % (v/v) ethanol overnight at 4 ◦C centrifuged at 4000 rpm for 10 min	4.88 g/L	(Zhang et al., 2023)

EPS derived from LAB exhibit diverse structural and functional properties, contributing to various health-promoting effects. These include immunomodulatory activity, intestinal barrier repair, antitumor and antimicrobial properties, cholesterol-lowering effects, as well as antiviral and antioxidant capabilities (Kavitake et al., 2023). For example, Tarannum et al. (2023) reported that the EPS produced by *Lactiplantibacillus* sp., *Lactococcus* sp., *Lacticaseibacillus* sp., and *Lactobacillus* sp. isolated from bovine milk exhibited strong antioxidant activity and demonstrated potent antimicrobial effects against both Gram-negative and Gram-positive pathogens, including *Bacillus cereus*, *Salmonella typhi*, *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*.

LAB-EPSs have been widely utilized in the food industry due to their multifunctional properties and established safety. In the dairy industry and beverage production, these EPS have been utilized as thickeners, emulsifiers, stabilizers, gelling agents, and moisturizers, contributing to the enhancement of aroma, flavor, and texture in various products. (Zang et al., 2025). Additionally, in food packaging applications, the biodegradability and safety of LAB-EPS present opportunities for the development of innovative and sustainable materials (Moradi et al., 2021).

3.2 Amino acids

Postbiotics of LAB have been demonstrated to encompass a range of amino acids that enhance their bioactive characteristics. A variety of research has been undertaken to investigate the significance of amino acids in postbiotics and their effects on food safety and health. It has been posited that amino acids present in postbiotics may confer health benefits, including enhanced gut health and the inhibition of pathogens, through the exertion of immunomodulatory and antimicrobial effects (Correia et al., 2022). A number of postbiotic studies have demonstrated that the presence of amino acids can also promote the reduction of pathogenic biofilms, which pose a significant challenge to food safety (Che et al., 2024). Postbiotics derived from LAB, specifically *Lacticaseibacillus paracasei* ABK and *Lactobacillus helveticus* H9, show increased levels of free amino acids in reconstituted skim milk, enhancing their viability as sources of important amino acids for human nutrition (Rozhkova et al., 2023). One study identified 17 components including sugars, vitamins and amino acids in the postbiotic of *Lacticaseibacillus rhamnosus* LR-32. This postbiotic showed significant effects in inhibiting *Streptococcus* mutans biofilm development and virulence-related gene expression (Santana et al., 2024).

One of the most important synthesized amino acids by LAB is γ-aminobutyric acid (GABA) (Galli et al., 2022). GABA is a non-protein amino acid synthesized through the decarboxylation of glutamate and its sodium salt, a reaction catalyzed by the enzyme glutamate decarboxylase (GAD) (Ghazanfari et al., 2024). Numerous studies have demonstrated that various LAB species, including *Lactobacillus brevis*, *L. brevis*, *Lactobacillus plantarum*, *Lactobacillus paracasei*, and *Lactococcus lactis*, possess the capability to synthesize GABA (Mohammadzadeh et al., 2025). For example, Ayağ et al. (2025) isolated LAB strains from artisanal Turkish cheeses and identified strains with the potential to produce high levels of GABA. As a result, all strains possessing GAD gene were genetically identified as *Lactiplantibacillus plantarum*. GABA is recognized as a primary inhibitory neurotransmitter in the central nervous system, exerting various beneficial effects, including vascular reinforcement, regulation of insulin secretion and cardiovascular system (Jena & Choudhury, 2024; Devi et al., 2023). Additionally, a study determined that *Leuconostoc* strains can produce the amino acids tryptophan and ornithine, which act as precursors for bioactive metabolites and participate in various metabolic processes. These amino acids contribute to the reduction of anxiety, stress levels, and fatigue, while potentially enhancing the secretion of growth hormones (Ramos et al., 2022).

3.3 Bacteriocins

Bacteriocins are antimicrobial peptides effective against a wide range of spoilage microorganisms and foodborne pathogens (Chen et al., 2020). The genus *Lactobacillus* is the most bacteriocin-producing genus within the LAB family, representing 30.95% of all bacteriocinogenic LAB genera, followed by the genus *Enterococcus*, which accounts for 24.18% of the total (Kassaa et al., 2019). Bacteriocins produced by LAB (bLAB), which have well-known biochemical and biosynthetic properties and are potentially applicable, include nisin, pediocin, lactocin, plantaricin, curvacin, sakacin, and enterocin. Among these bacteriocins, nisin, pediocin, and lactocin have been approved for use in food products (Kaya & Simsek, 2019). bLAB are typically characterized by their tolerance to high thermal stress, activity over a broad pH range, lack of color, odor, and taste, and susceptibility to degradation by proteolytic enzymes (Daba & Elkhateeb, 2020). bLAB are usually classified into distinct categories, including Class I (heat-stable peptides with post-translational modifications (PTMs), <5 kDa), Class II (heat-stable peptides without modifications, <10 kDa), Class III (large, heat-sensitive proteins, >10 kDa), Class IV (complex proteins with lipid or carbohydrate) and Class V (Cyclic peptides, 5.5-7.5 kDa) (Niamah et al., 2024; Choi et al., 2023).

Bacteriocins are a valuable asset in ensuring the safety and quality of food products due to their antimicrobial properties. With growing consumer demand for minimally processed foods devoid of synthetic preservatives, bacteriocins present a promising naturally derived alternative for extending shelf life and preserving food quality (Liang et al., 2025). The antibacterial mechanism of bacteriocins occurs by interacting with the cell surface, increasing its permeability, and preventing the formation of proteins, nucleic acids, and cell walls (Akpoghelie et al., 2025). Many previous studies have determined that bacteriocins from LAB isolated from various fermented foods have an inhibitory effect on foodborne pathogens (Yi et al., 2020). Garcia et al. (2022), demonstrated that nisin and pediocin, produced by *Lactococcus lactis* subsp. *lactis* ATCC 11454 and *Pediococcus acidilactici* RS2, respectively, could reduce the counts of *Listeria monocytogenes*, aerobic bacteria, yeasts, and molds on the surface of melons. *Latilactobacillus sakei* 205, isolated from traditional dry-cured fermented sausages, has been reported to exhibit a broad bacteriocin activity spectrum and inhibit the growth of major foodborne pathogens such as *Listeria monocytogenes* and *Salmonella* (Martín et al., 2023).

In addition to their antimicrobial activities, certain bacteriocins possess clinical applications, functioning as adjuncts or alternatives to antibiotics, while others exhibit medicinal properties, including anticancer, antiviral, and antiprotozoal (antileishmanial) activities (Daba & Elkhateeb, 2024). Nisin has been utilized as a therapeutic agent for bovine mastitis caused by complex bacterial infections, including *Enterococcus* spp., *Staphylococcus* spp., and *Streptococcus* spp. (Hernández-González et al., 2021).

3.4 Organic acids

During fermentation, LAB produce organic acids that enhance the flavor of food and prevent spoilage. The organic acids produced by LAB include lactic acid, acetic acid, citric acid, propionic acid, formic acid, and succinic acid (Punia Bangar et al., 2022). Lactic acid is the end product of carbohydrate fermentation and is the major acid produced by LAB (T, 2018). However, it can be commercially produced through both chemical synthesis and fermentation. Chemical synthesis generates a mixture of two isomers, whereas fermentation results in a purely optical form of lactic acid. Approximately 90% of the total lactic acid worldwide is produced through bacterial fermentation (Desniar et al., 2020).

The production levels and types of organic acids during fermentation are influenced by the microbial species, culture composition, and growth conditions (Özcelik et al., 2016). Salomskiene et al. (2019), stated that the tested LAB strains exhibited strain-specific abilities in organic acid production, with *Streptococcus thermophilus* 43 producing citric acid, *Lactococcus lactis* 140/2 producing sorbic acid, and *Lactobacillus helveticus* R producing lactic acid. Organic acids reduce the pH, creating an inhospitable environment for the proliferation of potentially pathogenic microorganisms and fungi in food products (Ozogul et al., 2021). In both pure cultures and mixed microbial fermentations, it has been demonstrated that organic acid blends dramatically lower populations of foodborne pathogens such as *Salmonella* and *E. coli* (Grilli et al., 2015). Lactic acid, phenyllactic acid (PLA), hydroxyphenyllactic acid (OH-PLA), and indole lactic acid (ILA) produced by *L. plantarum* UM55 CFS were individually tested against *Aspergillus flavus*, and all compounds exhibited inhibitory effects on fungal growth and aflatoxin production (Guimarães et al., 2018).

Pediococcus has been reported to accelerate the food waste composting process by producing lactic acid, which inhibits acetic acid formation, thereby activating local composting microorganisms (Tran et al., 2019). The organic acids produced by *Lactiplantibacillus plantarum* BIOTECH 1074 have been reported to exhibit anti-vibrio properties and be effective in preventing vibriosis, which poses a significant threat to aquaculture (Dumandan et al., 2024).

Additionally, organic acids produced by LAB contribute to the desired flavor and aromas of food. The addition of *Lactobacillus plantarum* and *Streptococcus thermophilus* strains to grape juice has significantly improved the contents of tartaric acid, malic acid, and citric acid (Chen et al., 2024a). Strains of *Lactobacillus casei*, *Lactobacillus delbrueckii* subsp. *bulgaricus*, and *Streptococcus thermophilus*, along with *Limosilactobacillus fermentum* and *Enterococcus* spp., contribute to the desired aroma, flavor, and safety of dairy products (especially cheese) through the production of acetic, formic, pyruvic, and lactic acids (L. F. Silva et al., 2023).

3.5 Short chain fatty acids (SCFAs)

Lactobacillus species ferment carbohydrate-derived compounds, such as pyruvate, through the glycolytic and phosphoketolase pathways under heterofermentative conditions, resulting in the production of SCFAs. The primary SCFAs generated include formic acid, acetic acid, propionic acid, butyric acid, and valeric acid, which serve as important metabolic byproducts of this process (Hadinia et al., 2022). SCFAs are also produced by the gut microbiota (GM) during the fermentation of indigestible polysaccharides (Yi et al., 2025). Strains of the *Lactobacillus* genus considerably affect the composition of the GM, promoting a shift toward a more favorable profile (Azad et al., 2018). Balmori et al., (2024) stated that pomelo juice fermented with *Lacticaseibacillus paracasei* contained a significantly higher amount of SCFAs compared to the non-fermented juice and that the fermented juice beneficially influenced GM in an *in vitro* colonic model.

SCFAs have many health benefits. The most studied health benefits are anti-inflammatory properties, gut barrier integrity and metabolic regulation (Yilmaz, 2024). SCFAs can strengthen the immune system, reduce inflammation, and support the intestinal barrier, all of which play an important role in cancer prevention and management (Mobasherpour et al., 2024). With these protective effects, they may serve as a complementary approach to cancer treatment alongside chemotherapy and immunotherapy (Balendra et al., 2024). Previous studies have demonstrated that SCFAs are postbiotics that help reduce fat accumulation in the liver (Lu et al., 2025), cholesterol assimilation (Qayyum et al., 2023) and neuroprotective (Saadh et al., 2025). SCFAs, such as acetate and propionate, have been shown to traverse the blood-brain barrier and exert a demonstrable influence on cerebral function. This correlation between gastrointestinal health and cognitive function constitutes a component of the concept known as the gut-brain axis. One study examined the potential of *Lactiplantibacillus plantarum* postbiotics to regulate the gut-brain axis through the production of SCFAs. The research revealed that this mechanism may improve neurological functions during Salmonella infection (Wu et al., 2022). Similarly, Jiang et al., (2025) investigated the ability of three *Lactiplantibacillus plantarum* strains, isolated from yak yogurt, to mitigate benzo(a)pyrene (BaP)-induced neurotoxicity and associated gut-brain axis damage. The results demonstrated that the strains effectively alleviated BaP-induced neurobehavioral damage and significantly enriched SCFA-producing bacteria in the GM.

3.6 Vitamins

Certain strains of LAB possess the capability to biosynthesize water-soluble vitamins, including those belonging to the B-complex group (Carrizo et al., 2016). B vitamins are organic compounds that play a crucial biological role in directly or indirectly regulating body homeostasis. However, since they cannot be synthesized endogenously, their external intake is essential to sustainably meet physiological requirements (Zhu et al., 2020a). Strains with high vitamin biosynthesis capabilities have significant potential for enhancing fermented products with naturally occurring vitamins (Hugenschmidt et al., 2010). Various studies have confirmed that LAB strains isolated from different fermented foods can synthesize vitamins B1 (thiamine), B2 (riboflavin), B3 (Niacin), B5 (Nicotinamide), B6 (pyridoxine), B9 (folate), and B12 (cobalamin) (Table 2). The main characteristics of LAB that make them perfect candidates for in situ vitamin generation in food are their metabolic versatility, biosynthetic aptitude, and responsiveness to fermentation processes (Arena et al., 2014). Producing fermented foods with high B-vitamin content boosts their nutritional and commercial value and removes the need for fortification (Burgess et al., 2009).

The inclusion of an additional benefit, such as vitamin-producing capability, can mitigate vitamin deficiency both through the consumption of fermented foods, where enrichment occurs naturally in situ, and during colonization by these intestinal strains, facilitating *in vivo* synthesis (Khromova et al., 2022). A new soy milk beverage containing the B12-producing strain *Lactobacillus reuteri* CRL 1098 was evaluated using pregnant mice. The findings demonstrated that giving female mice and their young fermented soy milk stopped the onset of every symptom linked to a nutritional B12 deficit (Molina et al., 2012). The dairy sector frequently uses LAB, and it is practical and profitable to add the riboflavin-producing strain to fermented foods like cheeses, yoghurt, and fermented milks in order to raise riboflavin concentrations (Thakur et al., 2016). Levit et al., (2019) evaluated the administration of a vitamin-producing and immunomodulatory LAB mixture (*L. plantarum* CRL 2130, a riboflavin-overproducing strain; *S. thermophilus* CRL 808, a folate-producing strain; and *S. thermophilus* CRL 807, a strain with immunomodulatory properties) in combination with an anti-inflammatory drug during the remission phase of a recurrent colitis mouse model. The combination of the drug and the LAB mixture was reported to be the most effective in reducing intestinal damage at both macroscopic and histological levels, as well as in lowering proinflammatory cytokines (IL-6 and TNF-α) in intestinal fluids.

Table 2 Applications of LAB producing B-group vitamins in foods

Vitamin	Producing bacterium/strain	Product/Subject	Result/Effect	References
Vitamin B1 (Thiamine)	*Lactiplantibacillus plantarum* ATCC 14917	Rice yogurt	-High B1 content (77.49 mg/100g)	(Fawzi et al., 2022)
Vitamin B2 (Riboflavin)	*Limosilactobacillus reuteri* AMBV339	Coconut beverage and Butter milk	-High B2 content -A 100 mL glass of coconut beverage or buttermilk meets the daily riboflavin requirements for children, adolescents, and adults at 0.5, 1.4, and 1.3 mg/day, respectively.	(Spacova et al., 2022)
	Lactococcus cremoris ESI 277 pNZ:TuB.rib *Lactococcus lactis* INIA 12 pNZ:TuR.rib	Soy beverage	-285 ‰ increase compared to the control sample	(Langa et al., 2024)
	Lactobacillus plantarum CRL 725	Soymilk	-A 126% increase compared to the initial concentration	(Juarez del Valle et al., 2014)

	Lactobacillus plantarum M5MA1-B2	Kefir-like cereal-based beverages	-High B2 content	(Yépez et al., 2019)
	L. plantarum strain Lp900	Cauliflower-white bean mixture	-113% increase relative to the control sample	(Thompson et al., 2020)
Vitamin B3 (Niacin)	*Lb. Casei*	Cashew apple juice	-At the end of 48 hours of fermentation, a 157% increase compared to the control sample	(Kaprasob et al., 2018)
Vitamin B6 (Pyridoxine)	*Lactiplantibacillus plantarum* ATCC 14917	Rice yoghurt	-High B6 content (615.04 mg/100g)	(Fawzi et al., 2022)
	Lb. casei	Cashew apple juice	-At the end of 48 hours of fermentation, a 190% increase compared to the control sample	(Kaprasob et al., 2018)
	L. plantarum (LP-56)	Chickpea milk	-High B6 content compared to the control sample	(P. Zhang et al., 2022)
Vitamin B9 (Folate)	*Lactiplantibacillus plantarum* P2R3FA	*injera*, a traditional cereal-based fermented Ethiopian food,	-Increased vitamin content can meet up to 29% of the recommended folate 24ntak efor children and women of reproductive age	(Ashagrie et al., 2025)

	Streptococcus thermophilus k47 *Lactobacillus delbrueckii* subsp. *bulgaricus* 25 *Lactobacillus delbrueckii* subsp. *lactis* 75	Yogurt	-A 593% increase compared to commercial yogurt	(Hosseini et al., 2024)
	Lactococcus lactis subsp. lactis FP368 *Streptococcus thermophilus* FP268	Goat milk	-A four to six-fold increase in the original folate content of milk over 24 hours -A daily intake of one cup (237 mL) would supply 19% of the RDA	(Pacheco Da Silva et al., 2016)
	L. plantarum strain 299v	Cauliflower-white bean mixture	-60% increase relative to the control sample	(Thompson et al., 2020)
	Lactobacillus salvarius, *Lactococcus lactis*	White cheese	-67% increase relative to the control sample	(Arasteh et al., 2023)
	L. plantrum GSLP-7 V	Yogurt	-Normalization of serum folate and homocysteine levels after 10 days in folate-deficient rats	(J. Zhang et al., 2020)
Vitamin B12 (Cobalamin)	*Lactobacillus salvarius*, *Lactococcus lactis*	White cheese	-177% increase relative to the control sample	(Arasteh et al., 2023)
	Lactobacillus reuteri	Furu (fermented tofu)	-34% increase relative to the	(Bao et al., 2019)

		control sample	
L. plantarum *L. sanfranciscensis*	Probiotic-chocolates with 45% cocoa	-On average, a 957% increase in in vitro colonic fermentation compared to the control sample	(Hossain et al., 2022)
Lb. casei	Cashew apple juice	-At the end of 48 hours of fermentation, a 31% increase compared to the control sample	(Kaprasob et al., 2018)
L. reuteri F2	Soymilk	In a cobalamin-free medium, exhibiting the highest ratio ever recorded (132.2 ± 1.9 μg/L)	(Kumari et al., 2021)
L. plantarum 299	Cauliflower-white bean mixture	-A significant increase of 66% compared to the control sample	(Thompson et al., 2020)

3.7 Enzymes

Probiotic LAB play a crucial role in immune regulation and health benefits by producing postbiotic enzymes (Rao et al., 2024). Postbiotic enzymes have powerful antibacterial, anti-inflammatory, and immune-supporting effects, which can be especially helpful for managing conditions like irritable bowel syndrome and inflammatory bowel disease (Harris, 2024). Enzymes such as proteases, lipases and carbohydrases produced by probiotic bacteria support the digestion and absorption of macronutrients by catalyzing pivotal metabolic events in the gut.

Moreover, these enzymes have been reported to have therapeutic effects in the treatment of various disorders, including lactose intolerance, gluten sensitivity and inflammatory bowel diseases (Ganesh et al.,2025).

Microbial lipases represent a crucial class of biotechnologically significant enzymes, primarily due to their diverse functional properties. These enzymes are extensively utilized in various food processing applications, particularly in the production of dairy and meat products. Their role involves the selective hydrolysis of triglycerides in fats, leading to the release of free fatty acids, which contribute directly to flavor development or serve as precursors for flavor compounds (Esteban-Torres et al., 2015). A study determined that the co-culture of *L. brevis* and *L. plantarum* produces lipase with high activity (Ramyasree & Dutta, 2013). The majority of minerals in grains are present in the form of phytate, which is strongly associated with phytic acid. This interaction significantly reduces the bioavailability of these minerals (Nuobariene et al., 2015). LAB phytases, owing to their significant health benefits and low risks, can be employed to enhance metal ion solubilization by hydrolyzing phytic acid in phytate-rich foods. (Sharma et al., 2020). Furthermore, LAB can enhance the bioavailability and bioactivity of polyphenols through the catalytic action of phenolic acid decarboxylase. Conversely, during LAB fermentation, phenolic compounds are released as a result of the conversion of conjugated phenolic compounds into their free forms. (Adebo & Gabriela Medina-Meza, 2020). Usal et al. (2024) reported that *Lactiplantibacillus plantarum*, *Weissella confusa*, *Lactococcus lactis* subsp. *hordniae*, and *Pediococcus acidilactici* strains exhibit high extracellular phytase activity and phenolic acid decarboxylase enzyme activity. Nitrite, when excessively consumed, can lead to the production of N-nitrosamines, which are potential carcinogens associated with the development of various cancers. It has been determined that various *Lactobacillus* species reduce the amount of nitrite in nitrite-containing fermented products through the enzyme nitrite reductase. (Yuan et al., 2024). For example, Zhu et al. (2020b) demonstrated that the *L. plantarum* strain possesses nitrate and nitrite reductase activities and that these activities can reduce nitrate and nitrite in fermented sausages. In addition, the LAB-derived alkaline phosphatase enzyme has been shown to be effective in the biodegradation of chlorpyrifos, a common organophosphorus pesticide (Kavitha et al., 2024).

3.8 Inanimate microorganism

Inanimate microorganisms, a core component of postbiotics, are defined as nonviable probiotic microorganisms that have been rendered inactive through targeted inactivation techniques, while preserving their structural integrity and functional properties (Tao et al., 2024). Inanimate microorganisms can be generated through various inactivation methods, including acid exposure, heat treatment, ultrasonic disruption, freezing treatment, and ultraviolet irradiation. Among these, heat treatment is the most widely employed approach (Wei et al., 2024). Heat inactivation of strains involves exposing them to a specific temperature that effectively eliminates microbial activity while preserving beneficial metabolites and microbial components released after cell lysis. In a study, *Lactobacillus plantarum* strains inactivated using heat treatment were reported to restore intestinal barrier integrity, enhance bile acid metabolism, and reduce inflammation in the liver (Peng et al., 2024). In another study, heat-inactivated *Pediococcus acidilactici* CECT 9879 strains were found to modulate gut microbiota composition in mice, leading to reductions in fasting blood glucose levels and insulin resistance (Yavorov-Dayliev et al., 2025). Additionally, it has been reported that inactivated LAB inhibit oral pathogens and modulate the dental plaque microbiota (Li et al., 2024). The use of inactivated microorganisms offers several advantages over their viable counterparts. These include the elimination of cold chain requirements, simplified storage and transportation—facilitating broader application, particularly in resource-limited settings—along with enhanced safety due to the absence of infection risk in immunocompromised individuals. Moreover, the inactivation process can prevent the transfer of virulence factors or antibiotic resistance genes, provided that the microbial genetic material is effectively degraded. Inactivated microorganisms also retain their functional properties when administered alongside antibiotics or antifungal agents, avoiding potential antagonistic interactions (Warda et al., 2019).

4. Use of LAB postbiotics in foods

The mounting research endeavours in the domain of functional foods are precipitating the emergence of a novel generation of products, encompassing probiotic foods (Imperial & Ibana, 2016). Nevertheless, a salient issue pertains to the utilisation of probiotics, as certain probiotic strains have been observed to express antibiotic-resistant genes. These resistant traits have the capacity to be transmitted to pathogenic bacteria. For various reasons such as these, the use of postbiotics in food products instead of probiotics has come to the fore (Sabahi et al., 2023). Although the use of probiotics in food products has been practiced for many years, the presence and application of postbiotics in foods is a relatively new topic (Balthazar et al., 2022). Postbiotics are gaining more and more attention in the food industry due to their functional properties and easier handling compared to live probiotic cells. LAB represent one of the most essential microbial groups utilized in the food industry and are the predominant microorganisms used as probiotics (Ferreira & Mendes-Faia, 2020). The postbiotics of these bacteria are also used in the food industry.

In the context of food and pharmaceutical applications, the utilisation of freeze-dried (lyophilization) and spray-dried postbiotic extracts is recommended, a method that facilitates ease of handling and storage (Thorakkattu et al., 2022). Studies on postbiotics and food products have generally focused on infant formulas, beverages and cereal-based products, but there are still few studies on food product applications (Silva et al., 2020) LAB postbiotics can improve gut health and offer health advantages comparable to live probiotics when included into food products. Food producers consider them advantageous due to their safety, extended shelf life, ease of shipping, and reduced refrigeration requirements (Sarkar, 2024). New technologies may enable the preservation of bioactive components of postbiotic products, enhancing their health effects (Balthazar et al., 2022).

4.1 Antimicrobial activity

LAB produces various antimicrobial compounds, including organic acids, hydrogen peroxide, diacetyl, bacteriocins, and dipeptides, which contribute to pathogen suppression (Yi et al., 2020). These components exhibit significant antibacterial activity against a variety of pathogens, such as *S. aureus*, *E. coli*, and *Candida albicans.* A study indicates that postbiotics exhibiting antimicrobial properties derived from *L. acidophilus* and *L. helveticus* may be utilized in the formulation of functional dairy products and could aid in the prevention of infectious disorders by suppressing pathogenic bacteria and fungi (Mabrouk et al., 2024). Postbiotic derivatives of *Lactobacillus* have been demonstrated to inhibit biofilms of several organisms, including pathogens such as *C. albicans, S. aureus,* and *Porphyromonas gingivalis*. It was hypothesized that this effect was related to the components of the postbiotic (Santana et al., 2024). A study was conducted in which postbiotics obtained from *Lactobacillus acidophilus* were shown to have a concentration-dependent antimicrobial effect against *S. aureus*, with a Minimum Inhibitory Concentration (MIC) of 100 mg/ml (Khani et al., 2025).

Many studies have reported that postbiotics of LAB exhibit antimicrobial effects in foods (Table 3). Postbiotics including *Pediococcus acidilactici* and *Latilactobacillus sakei* were administered to chicken drumsticks using the cut-up method, resulting in a substantial decrease in *Salmonella* Typhimurium levels (İncili, 2022). Similarly, the levels of *E. coli* and *S. aureus* were reduced by 5.54 log and 6.9 log, respectively, when Lactobacillus rhamnosus and *Limosilactobacillus reuteri* postbiotics were sprayed on the surface of red meat (Jalali et al., 2024b). Nanopaper coatings based on *Lactobacillus plantarum* increased food safety by lowering the total mesophilic-psychrophilic bacterial load and *Listeria monocytogenes* by about 5 log (Shafipour Yordshahi et al., 2020). In conclusion, these effects, which vary depending on the application method and food matrix, indicate that postbiotics can be considered as an alternative biopreservation strategy in food safety

Table 3 Applications of postbiotics produced by LAB as antimicrobial in food products/ systems.

Origin of Postbiotic	Applied food products/food systems	Application method of postbiotics	Method Method for determining antimicrobial activity	Results/Effect	Reference
Lentilactobacillus kefiri LK1 *Enterococcus faecium* EFM2	Bovine mastitis pathogens	-	*in vitro*, spectrophometric	- Antimicrobial and antibiofilm activity against *S. aureus, E. faecalis, P. aeruginosa*, and *E. coli* strains at an optimum concentration of 25%	(Kim et al., 2024a)
Pediococcus acidilactici (PA), *Latilactobacillus sakei/Staphylococcus xylosus* (LS)	Chicken drumsticks	Dipping	Agar-plating method	-Effectively reduced *S.* Typhimurium count	(İncili et al., 2022)
Lactobacillus rhamnosus and *Limosilactobacillus reuteri*	Red meat	Spraying	Agar-plating method	-Reduction of 5.54 log CFU/g and 6.9 log CFU/g against *E. coli* and *S. aureus*, respectively	(Jalali et al., 2024)
Lactobacillus brevis TD4	Fresh beef	Edible coating	Agar-plating method	-Effectively inhibited the growth of microbial agents, including total viable count, psychrotrop	(Abbasi et al., 2024)

				hic bacteria, *Staphylococcus aureus*, *Escherichia coli*, total coliform bacteria, and fungi	
Lactobacillus curvatus B.67 and *Lactobacillus plantarum* M.2	Food contact surfaces	-	*in vitro*	-Inhibition of *L. monocytogenes* and its biofilm	(Hossain et al., 2021)
Lactobacillus acidophilus LA5 and *L. casei* 431 and *L. salivarius*	Ground meat and whole milk.	Homogeneous mixing	Agar-plating method	-Antimicrobial activity exceeding 50% against *L. monocytogenes* and biofilm removal activity	(Moradi et al., 2019)
Lactobacillus curvatus B67	Processed meat sausage	Inoculation	Agar-plating method	-Strong antimicrobial activity against *Listeria monocytogenes* and *Salmonella enterica* ser. Typhimurium, and effective reduction of pathogenic biofilm cells	(Toushik et al., 2023)
Lactobacillus acidophilus LA-5	Strawberry	Dipping method	Agar-plating method	-Reducing fungal count by 2.85 log10 CFU/g Significant delays in weight loss,	(Sharafi et al., 2024a)

				pH, and total soluble solids changes compared to uncoated fruits with edible coatings	
Lactobacillus plantarum	Meat wrapping nanopaper	Impregnated by ex-situ	Agar-plating method	-A significant reduction of approximately 5 log in *L. monocytogenes,* total mesophilic and psychrophiles count	(Shafipour Yordshahi et al., 2020)
Lactobacillus acidophilus Lactiplantibacillus plantarum	Yogurt	Incorporating	Agar-plating method	-Approximately 4 Log10 reduction in *Listeria monocytogenes* count -A substantial decline in the viability of *Salmonella Typhimurium*, *Staphylococcus aureus*, and *Escherichia coli*	(Davarzani et al., 2024)

4.2 Food packaging

Edible films and coatings have gained widespread acceptance as an alternative to plastic materials in food packaging (Smaoui et al., 2022). An alternative approach to enhancing food safety involves the use of LAB strains and/or their metabolic products as biopreservatives, as they effectively inhibit the growth of pathogenic bacteria (S. P. M. Silva et al., 2023). Direct application of postbiotics in food models has been proven to show antimicrobial properties not only against foodborne pathogens but also against spoilage bacteria. However, since direct applications in food formulations can sometimes lead to undesirable outcomes, the use of the positive effects of postbiotics in food packaging has come to the forefront (Hosseini et al., 2021). Postbiotics in dry and liquid form can be easily incorporated into packaging due to their antimicrobial and antioxidant compounds. These postbiotics help extend the shelf life of food products by prevent the development of pathogens and spoilage microorganisms. They also offer a safer and sustainable alternative to synthetic preservatives, providing a more environmentally friendly option (Sharafi et al., 2024b). López-Pérez et al. (2025) evaluated the antifungal effects of edible films made with 1.5% (w/v) chitosan and supplemented with the cell-free supernatants of *Lactiplantibacillus plantarum* TEP15, *Lacticaseibacillus paracasei* TEP8, and *Lactiplantibacillus pentosus* TEJ4 against phytopathogenic fungi *Colletotrichum gloeosporioides*, *Fusarium* sp., and *Penicillium* sp. AT21H10. The films inhibited both spore germination and mycelial growth of the three phytopathogenic fungi. The study reported that the produced films could be directly applied to fruits and vegetables either pre- or post-harvest as a treatment to control diseases caused by phytopathogenic fungi. Similarly, Ceylan, (2024) produced bio-based edible films using pea protein isolate/psyllium mucilage by incorporating *Lactobacillus gasseri* postbiotics at 10% and 20% (v/v) concentrations. The obtained films exhibited antioxidant and antibacterial activities. Consequently, it was reported that pea protein/psyllium mucilage-based films containing *L. gasseri* postbiotics could be a novel alternative for environmentally sustainable bio-based films.

4.3 Food additive

Food additives are frequently used to improve the sensory qualities, nutritional value, and shelf life of foods. Because of their antibacterial and functional qualities, postbiotics made by LAB are also considered as possible food additives in this context. In China and Japan, GABA with generally recognized as safe (GRAS) status has been approved for use as a functional food additive. Consequently, the development of GABA-enriched food products has been facilitated through the utilization of GABA-producing microorganisms (Wu & Shah, 2015). Furthermore, nisin, produced by certain strains of *Lactococcus lactis* subsp. *lactis*, is a bacteriocin that is approved for use as a food preservative. Nisin is commonly found in various food products, including canned soups, ice used for preserving fresh fish, baby foods, baked goods, mayonnaise, and dairy products, particularly cheeses (Aguilar-Toalá et al., 2018).

EPS produced by LAB are high-molecular-weight polymers that exhibit physicochemical properties comparable to commercial hydrocolloids or gums, including their capacity to form networks and retain water (Lynch et al., 2018). In a study, a dextran-structured EPS complex synthesized by *Weissella confusa* JCM 1093 strains and whey protein isolate (WPI) were added to reduced-fat mayonnaise at concentrations of 2% and 5%, respectively. It was determined that the rheological properties and emulsion stability of the low-fat samples were similar to those of traditional mayonnaise and that oxidative stability was improved. The study highlighted that the EPS-WPI complex could be used as a fat replacer (Yalmanci et al., 2023). Another study has demonstrated that EPS with specific structural characteristics derived from *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *bulgaricus* can be used in combination with starch to modify the rheological and physical properties of yogurt, particularly in mixed-type formulations (Gentès et al., 2016).

Additionally, some LAB postbiotics have been patented as feed additives due to their antibacterial properties (Liang & Xing, 2023). In a study, the effects of different postbiotics on growth performance, gut health, immune status and growth-related gene expression in broilers under heat stress were investigated. In the study where postbiotics of different strains of *L. plantarum* were administered, the postbiotics generally improved gut morphology, beneficial microbiota population and immune response. Birds fed postbiotic showed higher body weight, daily weight gain and feed conversion ratio (Humam et al., 2019). LAB postbiotics are also widely used in aquaculture. While the use of postbiotics in animal feed has been investigated and shown potential in promoting growth, immunity, gut health, and resistance to diseases, further research is needed to elucidate their mechanisms of action and determine optimal dosages (Tao et al., 2024).

5. Health benefits of LAB postbiotics

Postbiotics are known for their antioxidant, immunomodulatory, and intestinal barrier-protective properties. Clinical studies have indicated that certain postbiotics, including heat-inactivated probiotics (e.g., *Lactobacillus* species), SCFAs, and bile acids (such as conjugated bile acids and ursodeoxycholic acid), can effectively mitigate metabolic disorders, including diabetes and obesity (Chen et al., 2024b). Lactic acid, acetic acid, and bacteriocins produced by various *Lactobacillus plantarum* strains collectively contribute to the generation of multiple postbiotic metabolites, which exert selective cytotoxic effects and induce apoptosis. These effects are influenced by strain-specific and cancer cell type-specific activities, while normal cells remain unaffected (Heniedy et al., 2024). Studies have shown that including LAB postbiotics into food products can offer health benefits including enhanced lipid metabolism, improved hydration and skin health, immune system regulation, reduction of chronic disease symptoms and better gut health and constipation management (Pimentel et al., 2023). Table 4 presents the health benefits of postbiotics produced by various LAB strains

Table 4 Health benefits of postbiotics produced by LAB.

Origin of Postbiotic	Study	Health Benefits	References
Limosilactobacillus fermentum CECT5716	*in vitro*	-Immunomodulatory effect, strong anti-inflammatory properties	(Amar et al., 2024)
Lentilactobacillus kefiri DH5	*in vivo*	-Anti-sarcopenic effect	(Han et al., 2023)
L. casei Zhang *L. plantarum* P-8	*in vivo*	-Restoring oral microecological balance for dental caries	(Liu et al., 2023)
Leuconostoc mesenteroides DH 1606 *Leuconostoc mesenteroides* DH 1608	*in vivo*	-Decrease in insulin resistance and serum triglyceride levels	(Seo et al., 2022)
Lactiplantibacillus plantarum LRCC5282	*in vivo*	-Obesity improvement by modulation of the gut microbiome	(Lim et al., 2024)
Lactobacillus helveticus KLDS 1.8701	*in vivo*	Immunomodulatory effect	(Xin et al., 2024)
Limosilactobacillus reuteri	*in vivo*	-Anti-colitis benefits	(Zhou et al., 2024)
Lacticaseibacillus paracasei SD1 *and Lacticaseibacillus rhamnosus* SD11	*in vivo*	-İmproving conditions for colorectal cancer	(Wanitsuwan et al., 2024)
Lactobacillus strains	*in vivo*	-Anti-colitis benefits, antioxidant activity	(Rezaie et al., 2025)
Lactobacillus parabuchneri MF2103	*in vitro*	-Regulation of gut microbiota	(Fang et al., 2023)
L. plantarum *L. rhamnosus*	*in vitro*	-Anticancer activity	(Wasiak et al., 2024)
Lactobacillus plantarum JM015	*in vivo*	-Improvement of Salmonella-induced intestinal inflammation	(Pang et al., 2025)
Lacticaseibacillus paracasei DCF0429	*in vitro*	-Antioxidant acitivity in human epidermal tissue	(Lee et al., 2024)
Lentilactobacillus kefiri DH5	*in vivo*	-Antiobesity activity	(Youn et al., 2022)

Lactobacillus acidophilus BLAC 258 *Lactiplantibacillus plantarum* BLP 272	*in vivo*	-Cholesterol-lowering effect	(Davarzani et al., 2024)
Inactivated LAB powder	*in vivo*	-Restoring intestinal barrier integrity, enhancing bile acid metabolism, lowering inflammation in the liver	(Peng et al., 2024)
Inactivated *Lacticaseibacillus rhamnosus* GG	*in vivo*	- Reduction of weight gain, visceral fat accumulation, and the visceral hypertriglyceridemic phenotype.	(Caroline de Oliveira Melo et al., 2023)
Inactivated *Lactobacillus reuteri*	*in vivo*	- Restoration of the physiological functions of the intestinal epithelium	(Palócz et al., 2023)
Inactivated *Lactobacillus casei* GKC1, *Lactobacillus rhamnosus* GKLC1, and *Lactobacillus johnsonii* GKJ2, GKC1	*in vivo*	- Significant improvement in bone mineral density and femoral microstructural parameters, enhancement of bone microstructural integrity	(Yang et al., 2025)

5.1 Antioxidant activity

Antioxidants found in natural foods have an important role in preventing many human diseases. Nevertheless, the employment of synthetic antioxidants has given rise to concerns regarding their potential associations with liver disease and cancer. Postbiotics have been found to have the potential to be a viable alternative to chemical antioxidants in the food and pharmaceutical sectors (Hosseinzadeh et al., 2024). The antioxidant properties of postbiotics from LAB originate from the antioxidant enzymes (superoxide dismutase, catalase) they contain, as well as from EPS (Gao et al., 2025). Studies have shown that LAB fermentation can enhance the antioxidant capacity of foods. A study determined that the antioxidant capacity of mango juice increased after fermentation with *Lactobacillus plantarum* NCU116, *Lactobacillus acidophilus* NCU402, and *Lactobacillus casei* NCU215 strains (Liu et al., 2025). Similarly, Fei et al., (2025) reported that the total phenolic content of a raspberry beverage fermented with *Lactobacillus plantarum*, *Lactobacillus pentosus*, and *Enterococcus faecalis* strains improved by at least 36.40%.

Additionally, the production of cheddar cheese using EPS-producing *Lactiplantibacillus plantarum* has been shown to significantly increase antioxidant activity (Wang et al., 2019). EPSs derived from LAB regulate key enzymes, proteins, and cytokines, thereby enhancing antioxidant activity and mitigating diseases associated with oxidative stress (Sharma et al., 2024). Sirin & Aslim, (2021) demonstrated that EPS derived from *Lactobacillus delbrueckii* ssp. *bulgaricus* B3 and *Lactobacillus plantarum* GD2 exhibit potent antioxidant properties and reduce oxidative stress-induced neurotoxicity, which is a major contributing factor to neurodegenerative diseases.

5.2 Enhancement of epithelial barrier function

The GM and its metabolites are integral in sustaining intestinal homeostasis, metabolic processes, and immune balance through complex interactions with the intestinal barrier (Chen et al., 2024b). Recent years have seen an increase in the number of studies conducted on the stabilization of the human GM. Consequently, the development of traditional probiotics and the synthesis of postbiotics derived from them has become a significant area of research (Rozhkova et al., 2023). Postbiotics offer a reliable alternative to mitigate the risks associated with live probiotic bacteria, providing a range of functional benefits for the management of both intestinal and extra-intestinal disorders (Sabahi et al., 2023). Postbiotics promote the growth of beneficial microorganisms by inhibiting pathogens through antimicrobial compounds such as bacteriocins and organic acids. Additionally, they contain structural components like fimbriae and lectins, which enhance adhesion to specific sites and support the establishment of beneficial microbial populations. Through these mechanisms, postbiotics exert positive effects on the GM (Zhao et al., 2024).

In a study, the effects of *Lactobacillus plantarum* RG14 postbiotic on gastrointestinal histology, hematology, mucosal IgA concentration, microbial population and mRNA expression related to intestinal mucosal immunity and barrier function were examined. In the study in lambs, the height and width of rumen papillae were increased in those given postbiotics, but no difference was observed in the height of duodenal, jejunum and ileal villi. Improvement in intestinal barrier integrity was observed, and overall, *L. plantarum* RG14 postbiotic supplementation was reported to support rumen development, immune status, and gastrointestinal health in weaned lambs (Izuddin et al., 2019). Zhang et al. (2024b) determined that the colonic intestinal barrier was repaired in mice that received intragastric administration of 200 mg/kg/day of EPS derived from *Lactobacillus salivarius* for seven days.

5.3 Anti-diabetic activity

Diabetes mellitus is a chronic disease influenced by factors such as genetic predisposition, poor diet and sedentary lifestyle. It is characterised by persistent hyperglycemia resulting from defects in insulin secretion and function, which in turn lead to alterations in carbohydrate, fat and protein metabolism (Choudhury & Devi Rajeswari, 2021). Alterations in the composition of the GM have been posited as a potential contributing factor to the development of diabetes, through the mechanisms of increased intestinal permeability and subsequent immune response. Fermented foods are rich in LAB and postbiotics, including bioactive metabolites, EPS, and peptides, which possess the capacity to modulate various metabolic functions and influence gene expression associated with glucose and insulin metabolism (Castro & Luchese, 2022). The non-viable by-products of probiotics, known as postbiotics, have shown promise as treatment agents for diabetes, especially type 2 diabetes (T2D). Their anti-diabetic properties are attributed to a variety of pathways, which makes them a useful substitute for live probiotics, particularly for those with impaired immune systems (Gurunathan et al., 2023).

Numerous studies have shown that postbiotics have anti-diabetic effects. They have the potential to have therapeutic advantages for the management of diabetes since they can affect glucose metabolism, enhance insulin sensitivity, and modify GM, all of which improve glycemic control and overall metabolic health (Du et al., 2024). Postbiotics can improve metabolic health by raising anti-inflammatory cytokines and decreasing pro-inflammatory cytokines. They encourage the synthesis of SCFA, which is associated with decreased inflammation and enhanced insulin sensitivity (Kim et al., 2024b). A study conducted on a mouse model supplemented with GABA-rich yogurt (2 mg/mL) showed enhanced insulin sensitivity, regulation of serum lipid levels, pancreatic tissue regeneration, and improved glucose tolerance (Li et al., 2020).

5.4 Anti-obesity activity

Overweight and obesity are prevalent global health problems, and the potential benefits of postbiotics against this condition are attracting increasing attention. Postbiotics have been shown to exert anti-obesity effects through a variety of mechanisms, including increasing energy expenditure, inhibiting adipose tissue formation, suppressing food intake, and regulating lipid metabolism (Park et al., 2023). While preliminary clinical research indicates that postbiotic treatment causes considerable weight reduction and changes in metabolic indicators in overweight patients, animal studies indicate that postbiotics may prevent obesity by altering the GM and metabolic pathways (Arellano-García et al., 2024). In human clinical trials, the administration of the postbiotic, inactivated *Lactobacillus amylovorus* (CP1563), was undertaken orally, with improvements in body composition and anthropometric indices being reported. In the context of animal studies, a wide range of postbiotics were examined, and the anti-obesity efficacy of these substances was substantiated (Eslami et al., 2024). Sato et al. (2021) reported that a dietary intake of 50 g GABA per kg of diet over a six-week period significantly reduced food consumption, body weight gain, and fat accumulation while inducing ketogenesis, suggesting potential anti-obesity effects in lean mice. Postbiotics derived from *Lactobacillus paracasei, Lactobacillus rhamnosus* GG and *Lactobacillus casei* DG have been reported to have the following effects: suppression of obesity in rats, prevention of alcoholic liver disease in mice and reduction of intestinal inflammation, respectively (Davarzani et al., 2024).

6. Conclusion and future remarks

The book has been undertaken to comprehensively address current scientific studies on LAB-derived postbiotics and to detail the potential benefits and applications of these compounds. Postbiotics, which are biological components generated from LAB, are gaining popularity due to their positive health effects and use in food systems. In addition to the benefits provided by probiotics, postbiotics have been shown to exhibit various biological functions, including immune system regulation, antioxidant, antibacterial, anti-obesity, and anti-diabetic effects. The functional properties of postbiotics are contingent on the specific LAB strains and fermentation conditions employed during their production.The advantages of postbiotics in food and health, including their durability, long shelf life and evaluation as safe biological components, are widely recognised in the functional food and pharmaceutical sectors. The mechanisms of action, the particular health consequences, and the stability of postbiotics in food formulations still need to be clarified by more study. The evolution of individualised methods to promote gastrointestinal health depends on a thorough knowledge of the dynamic interplay between probiotic bacteria, their metabolites and the host. With the integration of artificial intelligence and the development of personalized nutrition approaches, postbiotics are expected to take center stage in next-generation functional and sustainable nutrition strategies in the coming period, thanks to their stable structures and predictable biological effects. In this context, there is a necessity for increased clinical trials and technological optimisation studies to be conducted to understand the long-term effects of postbiotics derived from different LAB species on human health and to enable their more effective use in food systems.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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