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LACTIC ACID BACTERIA AS A SOURCE OF EXOPOLYSACCHARIDES WITH IMPORTANT INDUSTRIAL APPLICATIONS

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ABSTRACT

Exopolysaccharides (EPS) are high-molecular-weight extracellular metabolites secreted by various bacteria, including lactic acid bacteria (LAB), which participate in the cellular energy metabolism and support their adaptation to stress conditions. LAB produces a wide variety of EPS, which are primarily classified according to their location in the cell and sugar composition. The main EPS bioproducers are representatives of the genera Lactobacillus, Lactococcus, Leuconostoc, Weissella and Streptococcus. The number of EPS produced varies among different bacterial species, as cultivation conditions and the composition of the medium are crucial for their yield. In addition to improving the rheological and organoleptic properties of foods, LAB EPS also exhibit several health-promoting activities, such as prebiotic, antioxidant, antimicrobial and immunomodulatory effects. Owing to their structural diversity and functionality, LAB EPS are widely used in the food, biotechnology and medical industries, with considerable potential for expanding their applications. This review aims to summarize the current research state on EPS produced by LAB, focusing on their structure, classification, biosynthetic pathways, safety profile as well as their potential applications in practice.

Keywords: exopolysaccharides, lactic acid bacteria, biosynthetic pathways, prebiotic.

INTRODUCTION

In recent years, microorganisms and their metabolites have attracted increasing attention due to their broad potential for application in a wide range of industries, including the food, pharmaceutical, chemical, and cosmetic industries, as well as agriculture and biofuel production [1]. Among beneficial microorganisms, LAB are distinguished by their generally recognised as safe (GRAS) status and proven bioactive properties.

LAB represent a heterogeneous group of microorganisms characterized by their ability to produce lactic acid as the main product of fermentation. The major LAB genera include *Lactobacillus* (reclassified into 25 genera in 2020), *Lactococcus, Leuconostoc, Pediococcus*, *Streptococcus*, *Carnobacterium, Enterococcus, Oenococcus,* and *Weissella* [2, 3]. They are Gram-positive, predominantly non-motile, non-spore-forming, cocci or rod-shaped bacteria with low G+C content in DNA. These bacteria generally lack the enzymes catalase, nitrate reductase and cytochrome oxidase, do not liquefy gelatin and do not produce indole and hydrogen sulfide [4, 5]. LAB have been used in food production since ancient times due to their ability to improve the organoleptic properties, nutritional value and safety of food products. Some of them can also be used as probiotics due to their health effects, including maintaining the gut microbiota balance, supporting digestion and immune function, enhancing the intestinal barrier integrity, and contributing to the prevention or alleviation of some gastrointestinal disorders, mild cognitive impairments and allergic conditions [6]. Furthermore, some LAB are also exploited as microbial producers of functional ingredients, such as enzymes,

vitamins, low-calorie sweeteners, hydrogen peroxide, bacteriocins and EPS [7].

EPS are secondary metabolites synthesized intracellularly or extracellularly and can be attached to the cell surface or secreted into the extracellular environment [8]. Their main physiological function is to provide biological protection against various environmental stresses [9]. They are mainly composed of glucose, galactose, or rhamnose residues linked by glycosidic bonds, forming linear or branched polymers with a molecular mass of 10^4 - 10^6 Da. LAB EPS are mainly classified according to their location, sugar composition, structure, and monomer type. They are neutral or slightly acidic in nature, which contributes to their potential as prebiotics for modulating the intestinal microbiota and as functional ingredients in foods [10]. In addition, they exhibit immunostimulatory, anticancer, antioxidant, anti-inflammatory, and antimicrobial activities, including antiadhesive and antibiofilm effects [10, 11]. These functional and biological properties highlight the potential of LAB-derived EPS for use as stabilizers, thickeners, and emulsifiers in foods, carriers for drug and genetic material delivery in the pharmaceutical industry, biostimulants and feed additives in agriculture, humectants in cosmetics, etc. [10].

The aim of this review is to present the current scientific advances in the field of EPS produced by LAB, with a focus on their structure and classification, main biosynthetic pathways, practical applications, and safety profile. In addition, the prospects for their future applications, as well as the existing limitations and challenges hindering their wider implementation, are outlined.

Structure, classification and biosynthesis of LAB EPS

EPS are high-molecular-weight polymers synthesized intracellularly or extracellularly and can be attached to the cell surface or secreted into the extracellular matrix [8]. Microbial EPS are mainly produced by bacteria, yeasts and filamentous fungi, but this review focuses on EPS produced by LAB. These polymers are mainly composed of carbohydrate moieties, including glucose, fructose, galactose, rhamnose residues linked by glycosidic bonds. In some cases, non-carbohydrate substituents such as acetate, pyruvate, succinate and phosphate are also attached [8, 10].

Depending on their location, EPS are divided into free (slime) EPS, which are weakly associated with the cell surface or completely secreted into the extracellular environment, and capsular EPS. Capsular EPS protect cells from phage or protozoan attack, phagocytosis, osmotic stress, exposure to antibiotics and heavy metals, and desiccation. They also participate in adhesion, aggregation, and colonization processes, as well as facilitating the exchange of genes and metabolites [8, 9].

Depending on their sugar composition, EPS are divided into homopolysaccharides (HoPS) and heteropolysaccharides (HePS) (Fig. 1). HoPS consist of repeating units of the same type of monosaccharide (glucose, fructose or galactose), forming linear or branched chains with a molecular mass of 10^5 - 10^6 Da and yields of up to more than 10 g L^{-1}. Based on the structure and monomer type, HoPS are subdivided into four groups: α-glucans, β-glucans, β-fructans and polygalactans.

• α-Glucans are composed of glucose residues linked by α-(1→2), α-(1→3), α-(1→4) or α-(1→6) glycosidic bonds [8]. They can be linear or branched, most often at position 3 and less often at positions 2 or 4 [12]. Their synthesis is catalyzed by glucansucrases, which have been identified in representatives of the genera *Leuconostoc*, *Streptococcus*, *Lactobacillus* and *Weissella*. α-Glucans are divided into four subclasses depending on the predominant glycosidic bonds:

- Dextrans (Fig. 2A) – water-soluble glucans whose main chain is composed of α-(1→6) bonds, with individual branches formed by α-(1→2), α-(1→3) or α-(1→4) bonds [8]. Due to its high viscosity, dextran is considered as one of the most effective plasma substitutes used in the treatment of shock and blood loss [13]. It is synthesized by *Leuconostoc mesenteroides*, *Leuconostoc dextranicum*, *Weisella cibaria* and *Lactobacillus* sp. [12].

- Reuterans (Fig. 2C) - branched, water-soluble glucans consisting mainly of α-(1→4), with individual α-(1→6) bonds in their structure. They are characterized by moderate viscosity due to their branching pattern [8]. The molecular mass of reuteran is usually 2.8×10^7 Da [15]. Strains producing the enzyme reuteransucrase, which is involved in reuteran synthesis, include *Limosilactobacillus reuteri* 121 and ATCC 55730 [12].

- Alternans (Fig. 2D) - water-soluble glucans characterized by alternating α-(1→3) and α-(1→6) bonds and low viscosity [8]. They are produced by the

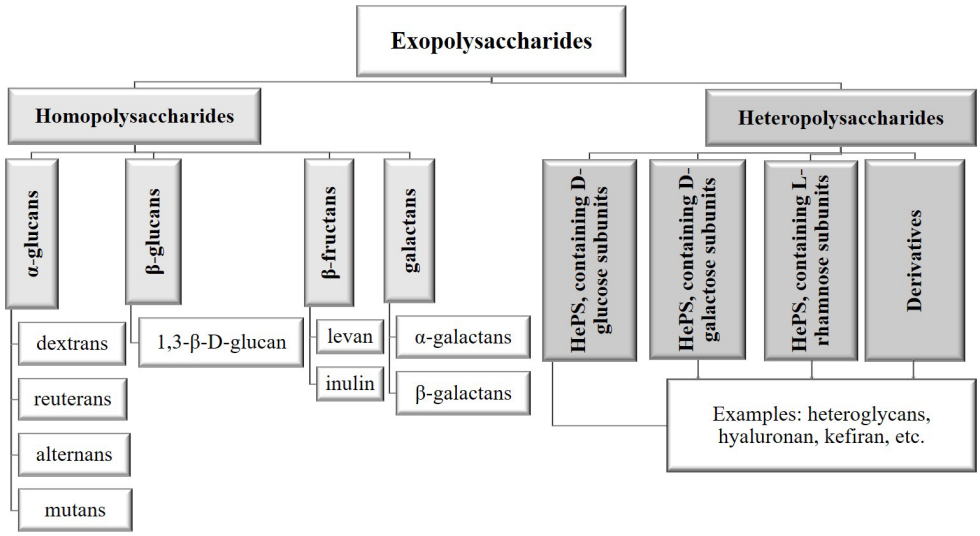


Fig. 1. Classification of LAB EPS based on their constituent monomers. Adapted from Bajpai et al. [14].

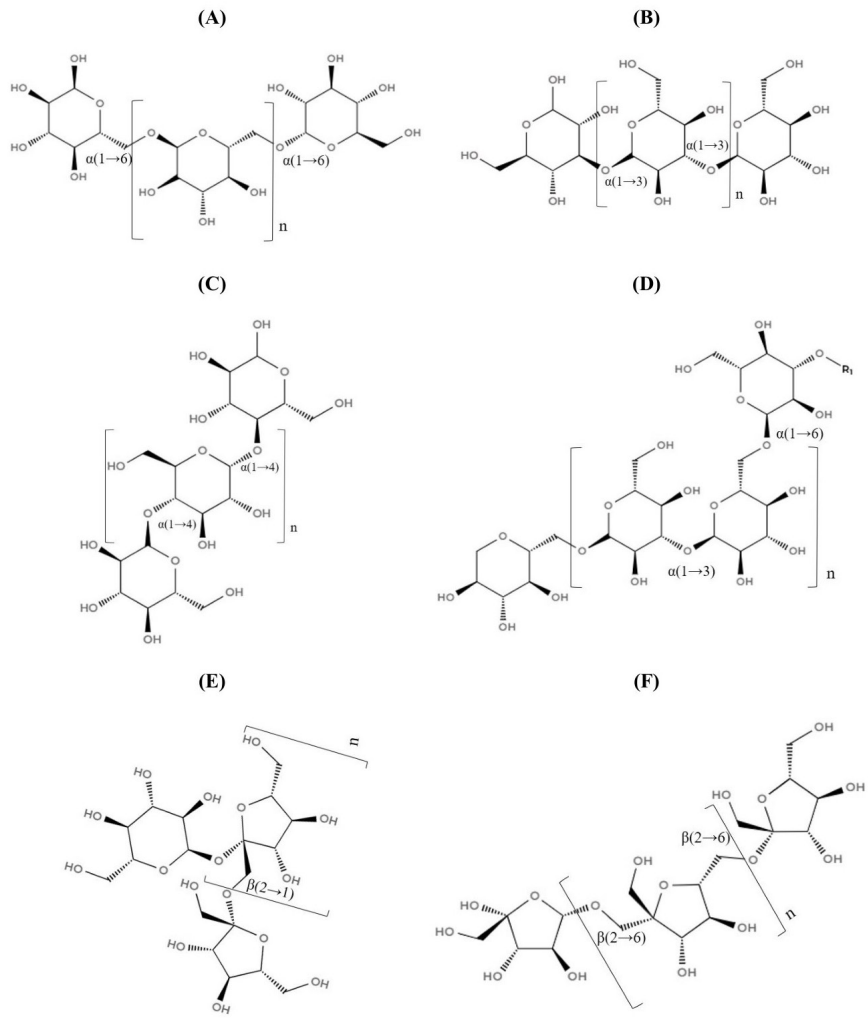


Fig. 2. Chemical structures of dextran (A), mutan (B), reuteran (C), alternan (D), inulin (E) and levan (F). Adapted from Sorensen et al. [16].

species *Leuconostoc citreum* and *L. mesenteroides* [12].

- Mutans (Fig. 2B) - water-insoluble glucans consisting mainly of α-(1→3) bonds and α-(1→6)-linked branches. They form hard and highly insoluble matrices [8]. Mutan-producing LAB include some strains of *L. mesenteroides, L. reuteri, Streptococcus salivarius, Streptococcus sobrinus* and *Streptococcus mutans* [12].

• β-Glucans are branched glucans whose main chain is composed of β-(1→3) and β-(1→4) bonds, while the side chains contain β-(1→2) bonds [8, 11]. Their biosynthesis is catalyzed by the enzyme 1,3-β-glucan synthase, produced by representatives of the genera *Pediococcus* (*P. claussenii, P. parvulus*), *Lactobacillus* (*L. brevis*), *Oenococcus* (*O. oeni*) and *Streptococcus* sp. [12]. The good water-holding capacity and high viscosity of β-glucans contribute to improving the technological and functional properties of food products.

• β-Fructans are water-soluble polymers composed of D-fructose residues linked by β-(2→6) or β-(2→1) bonds. Their synthesis occurs through the enzymatic polymerization of fructose by fructotransferase enzymes produced by representatives of the genera *Leuconostoc, Weissella, Streptococcus* and *Lactobacillus*. Depending on the type of bond in the main chain, β-fructans are divided into two groups:

- Levan (Fig. 2F) - a fructan composed of β-(2→6) glycosidic bonds, with side chains connected by β-(2→1) bonds [8]. It is a highly water-soluble polymer with a molecular mass of 2×10^6 Da [12, 15]. Levan is produced by *S. salivarius* SS2, *L. mesenteroides, Lactobacillus johnsonii* NCC533, *L. reuteri* and *S. mutans* [12].

- Inulin (Fig. 2E) - a polysaccharide composed of D-fructose residues linked by β-(2→1) bonds, with a molecular mass of 10^7 Da [8, 15]. Unlike levan, it is poorly soluble in water. Inulin-synthesizing LAB include *L. citreum, L. johnsonii, L. gasseri, W. confusa, W. cibaria, S. mutans* and *L. reuteri* [12].

• Galactans (polygalactans) are rare water-soluble polymers composed of five repeating units of galactose. They are synthesized by various representatives of the genera *Streptococcus, Leuconostoc*, *Lactobacillus* (*L. bulgaricus*) and *Weisella* (*W. confusa*) [8, 11, 12]. Depending on the type of bond, galactans are divided into two groups:

- α-Galactans - polymers in which the galactose residues in main chain are linked by α-(1→6) and α-(1→3) bonds.

- β-Galactans - polymers in which the galactose residues are linked by β-(1→3) or β-(1→6) glycosidic bonds [8].

HePS are much more complex polymers, with a backbone containing 3 to 8 different monosaccharide residues, their derivatives or substituted forms in variable ratios, linked by β-(1→3) or β-(1→4) and α-(1→2) or α-(1→6) bonds [8, 13]. D-glucose, D-galactose and L-rhamnose residues are predominant, while monosaccharides such as ribose, mannose, fucose, fructose, N-acetylglucosamine and N-acetylgalactosamine, as well as some inorganic substituents such as glucuronic acid, phosphate and glycerol, are less common [8, 11].

HePS can have a linear or branched structure, with a molecular mass in the range of 10^4 - 10^6 Da. In contrast to HoPS, the yield of HePS is significantly lower (25 - 600 mg L^{-1}), which is due to their complex biosynthetic pathways and the higher metabolic costs associated with the incorporation of different sugar residues [8]. They are produced by *Streptococcus, Lactococcus* and *Leuconostoc* spp., as well as representatives of the lactobacilli group [8, 17].

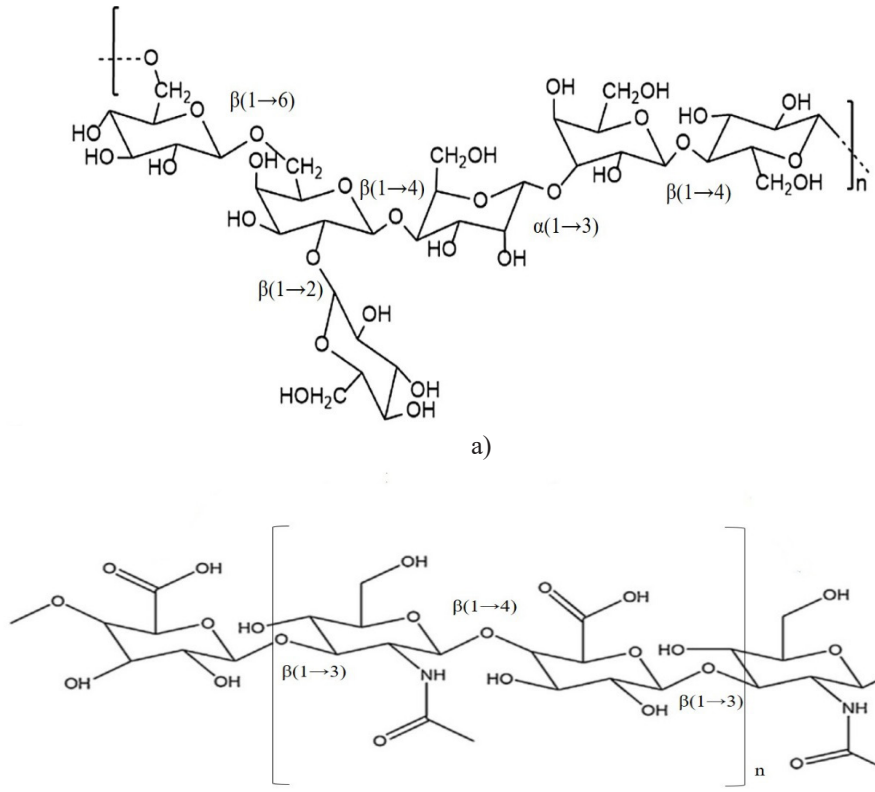
Well-known examples of HePS produced by LAB are kefiran and hyaluronan. Kefiran (Fig. 3A) is a water-soluble, branched glucogalactan, the main chain of which consists of glucose and galactose residues linked by β-(1→4) and α-(1→3) bonds, while its side chains are formed by β-(1→2) and β-(1→6) bonds [18]. It is synthesized by the species *Lactobacillus kefiranofaciens, Lactobacillus kefirgranum, Lactobacillus parakefir*, *Lactobacillus kefir* and *Lactobacillus bulgaricus* [8].

Pathways and factors influencing LAB EPS biosynthesis

EPS biosynthesis occurs either intracellularly or extracellularly, with maximum production observed during the late logarithmic phase. Approximately thirty LAB species belonging to the genera *Lactobacillus*, *Lactococcus*, *Leuconostoc*, *Weissella*, and *Streptococcus* are known to produce EPS. They primarily utilize two pathways for EPS biosynthesis: extracellular synthesis and Wzx/Wzy-dependent pathway, with the latter being considered the predominant route [8].

Extracellular synthesis pathway

The extracellular synthesis pathway is characteristic



a)

b)

Fig. 3. Chemical structures of kefiran (A) and hyaluronan (B). Adapted from Moradi et al. [22] and Zhu et al. [23].

of several HoPS-producing strains belonging to the genera *Lactobacillus*, *Weissella*, *Leuconostoc*, and *Pediococcus*. HoPS biosynthesis proceeds in two main stages: enzymatic hydrolysis of a donor substrate followed by polymerization, during which the released monosaccharide residues are transferred to the non-reducing end of the growing polysaccharide chain. The resulting polymer is released into the extracellular environment. Sugars such as sucrose, maltose, and maltotriose serve as donor substrates. The polymerization of HoPS is carried out by enzymes belonging to the glycosyl hydrolase family, with fructansucrases catalysing the synthesis of β-fructans and glucansucrases catalyzing the formation of α-glucans [8]. The genes encoding these enzymes are located on the chromosome (in thermophilic LAB) or on plasmids (in mesophilic LAB), contributing to strain variability and adaptation to diverse ecological niches [8, 24].

Unlike the other HoPS, β-glucans are synthesized via a synthase-dependent pathway. In this process, β-glycosyltransferases utilize nucleotide sugars as substrates to assemble repeating structural units within the cytoplasm, after which the resulting polymer is transported to the extracellular environment [8].

Wzx/Wzy-dependent pathway

HePS synthesis in LAB proceeds primarily via the Wzx/Wzy-dependent pathway. Compared with the extracellular pathway, this pathway is more complex, involving a variety of enzymes, carriers, and transport proteins encoded by genes located on the chromosome or on plasmids. It is widespread among lactobacilli and representatives of the genera *Lactococcus*, *Leuconostoc*, and *Streptococcus*. The main stages include the transport and/or phosphorylation of sugars, the formation of activated sugar nucleotides, the assembly, translocation, and polymerization of repeating sugar units, and the subsequent export of the newly formed polysaccharide [8].

EPS synthesis begins with the uptake of exogenous sugars, such as glucose, galactose, and lactose, into LAB cells via the phosphoenolpyruvate-dependent

phosphotransferase system (PTS) or specific permeases. The PTS facilitates the simultaneous transport and phosphorylation of sugars, whereas in the permease-mediated mechanism, phosphorylation is carried out by intracellular kinases specific to the respective sugar [8, 10]. For instance, glucose is phosphorylated to glucose-6-phosphate by the enzyme glucokinase [10]. Lactose or its phosphorylated form is hydrolysed by the enzyme β-galactosidase into glucose and galactose or their corresponding phosphorylated derivatives. The resulting phosphorylated sugars (glucose-6-phosphate, galactose-1-phosphate) are subsequently converted to glucose-1-phosphate by phosphoglucomutase or galactose-1-phosphate uridylyltransferase, respectively [8]. The latter is activated by UTP-glucose-1-phosphate uridylyltransferase to yield UDP-glucose. This can be epimerized to UDP-galactose by the action of UDP-glucose 4-epimerase. In parallel, dTDP-rhamnose is formed through specific enzymatic reactions involving dTDP-glucose pyrophosphorylase, dTDP-glucose 4,6-dehydratase, and dTDP-4-dehydrorhamnose 3,5-epimerase [10]. The resulting activated sugar nucleotides are sequentially incorporated into oligosaccharide repeating units by specific glycosyltransferases. These enzymes transfer monosaccharide residues onto the lipid carrier undecaprenyl phosphate, located on the inner side of the cytoplasmic membrane. Following assembly, the repeating units are translocated to the outer side of the membrane by the flippase (Wzx). There, the protein Wzy catalyses their polymerization through a series of enzymatic modifications [8]. This results in the formation of high-molecular-weight HePS, which is subsequently exported or anchored to the cell surface via PCP-ABC systems or LCP-mediated attachment to the cell wall. The molecular mass of the HePS is determined by Wzz (polysaccharide co-polymerase), which is involved in regulating polysaccharide chain length [10].

The number of EPS produced by LAB is determined by the composition of the culture medium (sources of carbon, nitrogen, minerals, and vitamins) and the cultivation conditions (temperature, pH, incubation time, agitation, and oxygen availability).

Application of LAB EPS

Food industry

In the food industry (Fig. 4), LAB EPS can be produced *in situ* during fermentation or added *ex situ* in purified form. *In situ* EPS production enhances the texture, stability, and functional properties of food, whereas the *ex situ* addition allows the targeted use of EPS as emulsifiers, stabilizers, thickeners, gelling and moisture-retaining agents. Purified LAB EPS, in particular, are gaining importance as "clean-label" alternatives to commercial hydrocolloids. This highlights the versatility of LAB-derived EPS as functional ingredients in various dairy and bakery products, and beverages [25].

For instance, adding EPS produced by specific LAB strains to dairy products such as yoghurt, cream cheese, and milk-based beverages improves creaminess and prevents syneresis, resulting in a more desirable texture and an extended shelf life [25, 26]. In certain yoghurts, LAB EPS have also been found to exhibit prebiotic

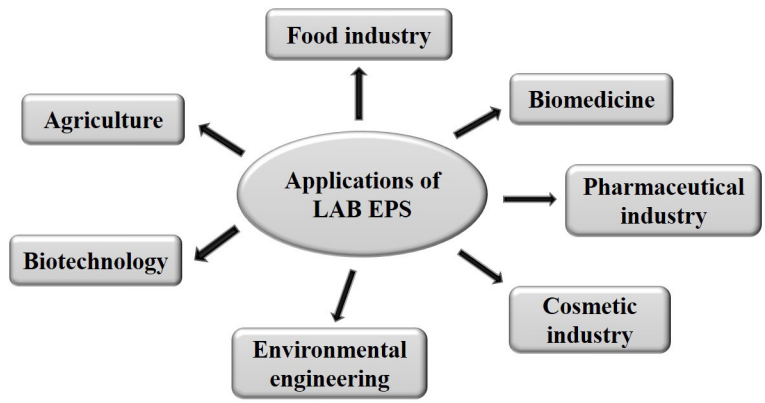


Fig. 4. Application of LAB EPS.

potential, supporting the growth of probiotics and thereby modulating the gut microbiota [10]. In frozen dairy desserts, LAB EPS inhibit ice recrystallization and improve melt resistance, thereby helping to preserve sensory properties and extend shelf life [25].

During sourdough fermentation, LAB EPS can improve dough rheological properties, subsequently enhancing the volume and softness of the final baked products [26].

Beyond their roles as structure-forming and stabilizing agents, EPS can also be used as emulsifiers. Zammouri et al. reported that dextran-rich fractions from *W. cibaria* and *L. lactis*, characterized by anionic polymer chains with low-to-moderate zeta potential, reduce interfacial tension by approximately 40 % and stabilize oil-in-water emulsions for more than 30 days [27].

Furthermore, LAB EPS can function as food preservatives by inhibiting the growth of spoilage and pathogenic microorganisms. They form a protective layer around food particles or within the food matrix, thereby contributing to the preservation of food quality and safety [26].

A summary of the food applications for EPS derived from LAB in various food products is presented in Table 1.

Biomedicine

LAB EPS are considered promising biopolymer

Table 1. Food applications of EPS from different LAB strains. Adapted from Hussein et al. [28].

Type of EPS	LAB source	Food application	Ref.
Homopolysaccharides			
Dextran	*Leuconostoc dextranicum* *Lacticaseibacillus casei* *Latilactobacillus sakei* *Limosilactobacillus fermentum* *Streptococcus* spp.	Prebiotic, cryoprotectant in ice cream, improves freshness, softness and mouthfeel of crumbs, loaf volume, improves viscosity and moisture retention in confectionaries	[29]
Reuteran	*Limosilactobacillus reuteri*	Used in bakery	[30]
Alternan	*Leuconostoc mesenteroides*	Prebiotics, sweetener in confectionaries, thickener, emulsifier, stabilizer, thickener, fat or calorie reducer, bulking agent and extender in foods	[28, 31]
α-Glucan	*Weissella cibaria* MG1 *Limosilactobacillus reuteri* ff2hh	Adjunct culture in Cheddar cheese	[32]
β-Glucan	*Levilactobacillus brevis* G-77	Starter culture	[14]
Inulin	*Lactobacillus johnsonii* NCC 533 *Limosilactobacillus reuteri* 121	Prebiotics, substitute of fat in food products	[33]
Levan	*Streptococcus salivarius* *Limosilactobacillus reuteri* *Lactobacillus sanfranciscensis* *Leuconostoc mesenteroides*	Prebiotic, thickener, stabilizer, emulsifier and flavor enhancer in food industry, water solubility and adjunct culture in cheese	[28, 34]
Galactan	*Weissella confusa* KR780676	Emulsifier in food industry	[35]
Heteropolysaccharides			
Kefiran	*Lentilactobacillus kefiranofaciens*	Improve viscoelastic properties of acid milk gels, improve rheological properties in wheat doughs, stabilizer in ice cream	[18]
Hyaluronan	*Streptococcus* spp. *Enterococcus faecalis* *Lactococcus lactis*	Improve viscoelastic, water-binding and gelling properties of ice cream, yoghurt and milk beverages	[36]

materials for applications in clinical and biomedical practice, particularly in the development of prebiotics, wound dressings, hydrogels and cryogels, and 3D matrices [10, 26].

They can serve as prebiotics by selectively promoting the growth and activity of beneficial gut microbiota. The intake of LAB EPS may contribute to increasing the number of viable bifidobacteria and lactobacilli in the colon, which is associated with maintaining the integrity and functionality of the intestinal barrier and potentially reducing the risk of gastrointestinal disorders. Furthermore, EPS possess immunomodulatory properties and may influence both innate and adaptive immunity, potentially contributing to host defence against infections [26].

EPS produced by LAB are also attracting increasing interest due to their potential applications in wound care. Their high water-absorption capacity, biocompatibility, and relatively low cost make them promising materials for the development of wound dressings and scaffolds for tissue engineering. Compared to synthetic polymers, LAB EPS can more closely mimic the structure and functional features of the extracellular matrix while providing a suitable environment for cell proliferation, migration, and differentiation during wound healing [37]. In addition, LAB EPS exhibit immunomodulatory properties that can reduce local inflammation, as well as antimicrobial properties against various pathogens [10], such as *S. aureus*, *E. coli* [38], *P. aeruginosa* [39], etc. For instance, Abdel-Monem et al. developed an ointment based on EPS from *E. faecium* MSD8. When applied to wounds in male albino rats, the ointment resulted in 94.93 % wound healing by day 7 and complete healing by day 12, while also shortening the healing time compared with the control group [37].

LAB EPS can also be used as components in hydrogels and cryogels. They can facilitate gel formation and improve their thermoreversibility, mechanical flexibility, and overall performance [10]. Unlike hydrogels, cryogels feature a macroporous structure, making them suitable for specific biomedical applications. For instance, Bulut et al. demonstrated that hydrogels and cryogels based on alternan from *L. reuteri* E81, cross-linked with epichlorohydrin, present a promising platform for the development of antibacterial wound dressings [40].

LAB EPS also have potential applications in 3D bioprinting, where they can serve both as printing materials and as components that provide mechanical stability to the resulting structures. Furthermore, owing to their mechanical and antimicrobial properties, they show potential for the development of scaffolds for tissue engineering and the creation of a favorable cellular microenvironment [10].

Pharmaceutical Industry

Drug carriers

EPS, produced by LAB, can serve as bioactive molecules, promising carriers or components of drug delivery systems due to their specific properties, bioactive functions and transport capabilities [28, 41]. Their biocompatibility, biodegradability and ability to form films, nano- or microparticles and nanofibers are of particular importance, as they provide flexibility for various clinical applications [10, 26]. The production of LAB EPS is easier than preparing biological scaffolds loaded with viable cells. In addition, EPS can be chemically or biologically modified in order to target drug delivery to specific cells or tissues, regulate their release, prolong retention in the body and increase therapeutic efficacy [26, 28]. In addition, LAB EPS can contribute to the reduction of drug toxicity [10]. Examples of applications of LAB EPS are kefiran-alginate microspheres with encapsulated ciprofloxacin, developed for oral delivery and controlled release in the GIT [42], EPS isolated from *L. gasseri*, used for the conjugation of cisplatin in cancer treatment [43], as well as EPS from *L. plantarum*, used for the synthesis of gold nanoparticles with antibacterial activity [44].

Nonviral gene carriers

LAB-derived EPS also have promising potential for application in the field of gene delivery. This potential stems from their ability to protect nucleic acids from the degrading action of lysosomal enzymes, as well as their transport properties [45]. Raemdonck et al. showed that cationic dextran-based nanocarriers, combined with photosensitizers, facilitate the transport of siRNA to the cytosol and enable transfection in Huh-7 hepatoma cells [46]. siRNA can also be delivered using PEG-modified dextran to Huh-7 and A431 human epithelial carcinoma cells [47]. These studies support the possibility of using EPS as nonviral carriers of genetic material for gene therapy of oncological diseases. However, further studies

with LAB EPS are needed to confirm their suitability for this application [48].

Diagnostics

EPS-based nanoparticles, including systems containing quantum dots and magnetic materials, show potential for use in medical imaging, diagnostics, and therapy. Multifunctional imaging agents based on EPS have also been developed and can be used in diagnostic magnetic resonance, magnetic resonance imaging, positron emission tomography and fluorescence molecular tomography [45]. As an example, superparamagnetic iron oxide nanoparticles cross-linked with a dextran coating can be cited. Their combination with photosensitizers enables the creation of theranostic agents for photodynamic therapy and for the destruction of atheromatous cells by irradiation [46]. However, at present, there are no specific examples in the literature of the application of LAB EPS for such purposes.

Environmental biotechnology

LAB EPS are also used in environmental purification and remediation [10]. Their adsorption properties are associated with functional groups such as -OH, -C=O, -COOH, -NH_2, which participate in the binding of various pollutants. For example, Li et al. reported a heteropolysaccharide (EPS R040), produced by *L. plantarum*, which exhibits high adsorption capacity for the removal of methylene blue from aqueous solutions [50]. LAB EPS can also be used to adsorb heavy metals. For example, EPS produced by *L. plantarum, L. reuteri*, and *Lactiplantibacillus* sp. ANPSCRLB, facilitated the removal of 85.3 - 96.3 % of Pb (II) [51]. Similar results have been reported by other authors who demonstrated the involvement of LAB EPS in the adsorption of metals such as Cd (II) [52, 53] and Al (III) from aqueous solutions [50]. In addition, LAB EPS can contribute to the immobilization of pollutants in soil while improving its structure and microbial composition [10].

Biotechnology

Due to their sustainability and environmentally friendly nature, LAB EPS have significant potential for industrial applications (Fig. 4). They can be used as a biodegradable alternative to synthetic plastics, due to their film-forming ability. LAB EPS can improve the water resistance and extensibility of products, their stability at high temperatures, as well as their ability to maintain their functional properties under extreme conditions [10]. They are commonly used in the food industry to produce food packaging, emulsions and encapsulated products, where EPS (dextran, levan, kefiran and hyaluronan) are combined with plasticizers such as glycerol, sorbitol, polyols, etc. [12].

LAB EPS can also be used in oil extraction processes. Their emulsifying properties can serve to reduce interfacial tension, thereby facilitating enhanced oil recovery [10]. Such properties have been reported for dextrans synthesized by species such as *L. mesenteroides* [54].

Agriculture

LAB EPS have great potential to support agricultural development as a green alternative to synthetic water-retention agents, fertilizers and pesticides. Their application to the soil has been found to promote the formation of stable aggregates and optimize pore size, thereby improving its water-holding capacity. These changes increase water-use efficiency and reduce water consumption for crop cultivation [10].

Furthermore, the formation of a matrix around plant roots improves contact with the soil environment. It facilitates the absorption of water and nutrients, which in turn favors plant growth and increases yields [26].

LAB EPS can also support the biological defense of plants against phytopathogens by activating their natural defense mechanisms. They can stimulate the synthesis of pathogenesis-related proteins and phytoalexins, which leads to a reduction in the incidence and severity of plant diseases [26]. Furthermore, under adverse conditions, such as water-deficient conditions, LAB EPS have been shown to help maintain the microbial community, increasing the abundance of beneficial microorganisms while reducing populations of harmful microorganisms [10].

LAB EPS also show significant potential for the development of animal husbandry. When administered in purified form or through EPS-producing strains to animal feed, they can improve the survival and colonization of LAB in the gastrointestinal tract, while protecting animals from pathogenic infections by stimulating their immune response [17]. For example, EPS-synthesizing LAB have been shown to exhibit antagonistic activity against pathogens such as *Campylobacter jejuni* [55], enterotoxigenic *Escherichia coli* [56], as well as antiviral

activity against rotaviruses [57], porcine epidemic diarrhea viruses [58], etc. This may contribute to increased feed utilization efficiency in food-producing animals by reducing the cost of animal treatment. These properties of LAB EPS provide promising opportunities for minimizing the use of antibiotics in animal husbandry, which in turn may help to limit the rise in antimicrobial resistance [17].

Cosmetic industry

In recent years, there has been a significant increase in the number of cosmetic products containing bacterial EPS, among which HA is particularly prominent [59]. It is used as a humectant due to its high water retention capacity, as a skin-conditioning agent and as a viscosity enhancer [60]. HA is also often used as an anti-aging or anti-wrinkle agent, as it can promote skin hydration and elasticity. In addition, it is widely used as a dermal filler and serves as an alternative to collagen-based fillers [59]. Several bacteria can produce hyaluronan, including some members of the genus *Streptococcus* sp. However, the risk of contamination with pathogenic factors necessitates the search for safer methods for its production, such as the use of genetically modified bacteria, such as *Lactococcus lactis* [61], *Lactobacillus acidophilus* [62], as well as genetically unmodified bacteria, such as *Enterococcus durans, Lactiplantibacillus plantarum* [19], *Streptococcus thermophilus* [63], etc.

Other, although less commonly used in cosmetics, EPS are dextran and levan. Dextran is used as a binding and structuring agent, contributing to improving the stability, volume and consistency of the products, while also having good water retention capacity. Its microbial producers are LAB belonging to the genera *Lactobacillus, Leuconostoc, Pediococcus, Streptococcus* and *Weissella*. Levan, in turn, possesses rheological and film-forming properties. It is synthesized by several bacteria, including *Streptococcus* sp. [59, 64].

In conclusion, LAB EPS possess several functional and biological properties that enable their application in a wide variety of fields – from the food and cosmetic industries to biomedicine, biotechnology, environmental engineering and agriculture. These properties make them promising biopolymers for the development of innovative and sustainable solutions across diverse industrial applications.

Safety assessment of LAB EPS

The administration of viable LAB cultures at certain concentrations is generally characterized by a good safety profile [10]. This is supported by the fact that to date, 43 LAB species are included in the list of microorganisms with a qualified presumption of safety (QPS), issued by the European Food Safety Authority (EFSA) [65]. Despite the established safety status of many LAB, some adverse reactions may be observed in the elderly and immunocompromised individuals [10]. This necessitates evaluating the safety of newly discovered EPS-producing LAB strains in a manner similar to the approach used in the evaluation of probiotic strains. This assessment may include conducting assays to determine antibiotic resistance and potential for horizontal gene transfer, adverse metabolic activities/immune responses, as well as acute, reproductive, and chronic toxicity tests [10, 66]. When using purified EPS as independent ingredients, it is necessary to evaluate their safety separately from that of the LAB strain that produces them. When intended for use in food, purified EPS fall within the scope of novel food ingredient EFSA regulations, which require establishing their safety for human consumption [16].

CONCLUSIONS

- LAB EPS are structurally diverse high-molecular-weight polymers whose properties depend on their monosaccharide composition, type of glycosidic bonds, degree of branching, molecular weight, and structural organization.
- LAB EPS are primarily classified by sugar composition into HoPS and HePS, but they can also be classified by their location, as well as the structure and type of their constituent monomers.
- The biosynthesis of LAB EPS involves complex and strain-specific metabolic pathways, with extracellular synthesis being characteristic mainly of HoPS-producing LAB, whereas the Wzx/Wzy-dependent pathway predominates in HePS synthesis.
- LAB EPS have broad food applications due to their potential as stabilizers, thickeners, emulsifiers, gelling and water-retaining agents, contributing to improved rheological, textural, sensory, and storage properties of food.
- Their biocompatibility, biodegradability, water-

binding capacity, and film-forming ability support their potential use in biomedical and pharmaceutical applications, including prebiotics, wound dressings, hydrogels and cryogels, tissue-engineering matrices, and drug-delivery systems.

- The application of LAB EPS extends to environmental biotechnology, agriculture, cosmetics, and other industrial processes, particularly as biodegradable and sustainable alternatives to conventional materials.
- LAB EPS-based systems have demonstrated promising potential for the delivery of drugs and genetic materials. However, direct evidence for their use as gene-delivery vectors remains limited.
- Despite the wide application potential of LAB EPS**,** further research is needed to improve their production and purification methods, clarify structure–activity relationships, strengthen safety assessment, and provide more direct experimental evidence for their efficacy under relevant physiological and industrial conditions.

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Authors' contributions

V.N.: Data collection and original draft preparation, writing - review, editing and supervision.

REFERENCES

1. M. Arshad, I. Arshad, H. Aslam, D. Sukmawati, A.H. Anvar, H.A. Shakir, M. Khan, M. Franco, M. Irfan, Microbial bioproducts: current advances, industrial applications, and future perspectives, J. Umm Al-Qura Univ. Appl. Sci., 11, 2025, 545-560.
2. K. Khalid, An overview of lactic acid bacteria, Int. J. Biosci., 1, 3, 2011, 1-13.
3. J. Zheng, S. Wittouck, E. Salvetti, C.M.A.P. Franz, H.M.B. Harris, P. Mattarelli, P.W. O'Toole, B. Pot, P. Vandamme, J. Walter, et a. A taxonomic note on the genus *Lactobacillus*: description of 23 novel genera, emended description of the genus *Lactobacillus* Baijerinck 1901, and union of *Lactobacillaceae* and *Leuconostocaceae*, Int. J. Syst. Evol. Microbiol., 70, 4, 2020, 2782-2858.
4. L. Settanni, G. Moschetti, Non-starter lactic acid bacteria used to improve cheese quality and provide health benefits, Food Microbiol., 27,6, 2010, 691-697.
5. Y. Chbab, S. El Ghaza, B. Ouakhzan, B. Zaadoud, E. Aouane, Isolation and characterization of probiotics (*Lactococcus* and *Enterococcus*) from processed straw, Int. J. Chem. Biochem. Sci., 24, 5, 2023, 644-650.
6. L. Ayed, S. M`hir, D. Nuzzolese, R. Di Cagno, P. Filannino, Harnessing the health and techno-functional potential of lactic acid bacteria: a comprehensive review, Foods, 13, 10, 2024, 1538.
7. P. Florou-Paneri, Panagiota, E. Christaki, E. Bonos, in: M. Kongo (Eds.), *Lactic Acid Bacteria - R & D for Food, Health and Livestock Purposes*, InTech, Rijeka, 2013, p. 589-614.
8. L. Ouarabi, L. Ouarabi, S. Hamma-Faradji, M.L. Mohedano, P. Lopez, D. Drider, Exopolysaccharides from lactic acid bacteria: Structure, biosynthesis and health benefits, Microbes Infect., 27, 2025, 105581.
9. E.M. Paulo, M.P. Vasconcelos, I.S. Oliveira, H.M. de J. Affe, R. Nascimento, I.S. de Melo, M.R. de A. Roque, S.A. de Assis, An alternative method for screening lactic acid bacteria for the production of exopolysaccharides with rapid confirmation, Cienc. Tecnol. Aliment., 32, 4, 2012, 710-714.
10. Y. Li, W. Zhang, X. Pan, Y. Xiao, L. Liu, F. Ding, G. Li, L. Zhao, Recent advances in exopolysaccharides from lactic acid bacteria: Acquisition, characterization, bioactivities, and applications, Food Biosci., 79, 2026, 108830.
11. A. Ponzio, A. Rebecchi, R. Zivoli, L. Morelli, Reuterin, phenyllactic acid, and Exopolysaccharides as main antifungal molecules produced by lactic acid bacteria: a scoping review, Foods, 13, 2024, 752.
12. C.M. Nicolescu, M. Bumbac, C.L. Buruleanu, E.C. Popescu, S.G. Stanescu, A.A. Georgescu, S.M. Toma, Biopolymers produced by lactic acid bacteria: characterization and food application, Polymers, 15, 2023, 1539.
13. U.U. Nwodo, E. Green, A.I. Okoh, Bacterial exopolysaccharides: functionality and prospects, Int. J. Mol. Sci., 13, 11, 2012, 14002-14015.

14. V.K. Bajpai, I.A. Rather, R. Majumder, S. Shukla, A. Aeron, K. Kim, S.-C. Kang, R.C. Dubey, D.K. Maheshwari, J. Lim, Y.-H. Park, Exopolysaccharide and lactic acid bacteria: Perception, functionality and prospects, Bangladesh J. Pharmacol., 11, 2016, 1-23.
15. N. Kaur, P. Dey, Bacterial exopolysaccharides as emerging bioactive macromolecules: from fundamentals to applications, Res. Microbiol., 174, 4, 2023, 104024.
16. H.M. Sorensen, K.D. Rochfort, S. Maye, G. MacLeod, D. Brabazon, C. Loscher, B. Freeland, Exopolysaccharides of lactic acid bacteria: production, purification and health benefits towards functional food, Nutrients, 14, 14, 2022, 2938.
17. M.L. Werning, A.M. Hernandez-Alcantara, M.J. Ruiz, L.P. Soto, M.T. Duenas, P. Lopez, L.S. Frizzo, Biological functions of exopolysaccharides from lactic acid bacteria and their potential benefits for humans and farmed animals, Foods, 11, 2022, 1284.
18. B. Gentry, P. Cazon, K. O`Brien, A comprehensive review of the production, beneficial properties, and applications of kefiran, the kefir grain exopolysaccharide, Int. Dairy J., 144, 2023, 105691.
19. A.E. Shaheen, H.M. Gebreel, L.A. Moussa, A.E. Zakaria, W.A. Nemr, Protoprotection against UV-induced skin damage using hyaluronic acid produced by *Lactiplantibacillus plantarum* and *Enterococcus durans*, Curr. Microbiol., 80, 2023, 262.
20. K.C. Hor, L. Lew, S.B. Choi, M. Liong, Effects of ultrasonication on the production of hyaluronic acid by lactobacilli, Acta Aliment., 43, 2014, 324-332.
21. S.B. Choi, L.C. Lew, K.C. Hor, M.T. Liong, Fe^{2+} and Cu^{2+} increase the production of hyaluronic acid by Lactobacilli via affecting different stages of the pentose phosphate pathway, Appl. Biochem. Biotechnol., 173, 1, 2014, 129-142.
22. Z. Moradi, N. Kalanpour, Kefiran, a branched polysaccharide: preparation, properties and applications: a review, Carbohydr. Polym., 223, 2019, 115100.
23. Z. Zhu, Y-M. Wang, J. Yang, X-S. Luo, Hyaluronic acid: a versatile biomaterial in tissue engineering, Plast. Aesthet. Res., 4, 2017, 219-227.
24. E. Korez, L. Varga, Exopolysaccharides from lactic acid bacteria: Techno-functional application in the food industry, Trends Food Sci. Technol., 110, 2021, 375-384.
25. R.H. Hernandez-Figueroa, A. Lopez-Malo, E. Mani-Lopez, Lactic acid bacteria-derived exopolysaccharides: dual roles as functional ingredients and fermentation agents in food applications, Fermantation, 11, 2025, 538.
26. W. Liu, Y. Wei, R. Xiang, B. Dong, X. Yang, Lactic acid bacteria exopolysaccharides unveiling multifaceted insights from structure to application in foods and health promotion, Foods, 14, 2025, 823.
27. A. Zammouri, M. Ziadi, A. Gharsallaoui, I. Fguiri, I. Sbissi, M. Hammadi, T. Khorchani, Characterization of novel exopolysaccharides from *Weissella cibaria* and *Lactococcus lactis* strains and their potential application as bio-hydrocolloid agents in emulsion stability, Fermentation, 10, 2024, 532.
28. K.A. Hussein, A.K. Niamah, K.R Majeed, Strategies and trends for application exopolysaccharides of lactic acid bacteria in the food and biomedical, IOP Conference Series: Earth and Environmental Science 1371, 2024, 062017.
29. N. Suryawanshi, S. Naik, J.S. Eswari, Exopolysaccharides and their applications in food processing industries, Food Sci. Appl. Biotechnol., 5, 2022, 1, 22-44.
30. M. Tieking, M.G. Ganzle, Exopolysaccharides from cereal associated lactobacilli, Trends Food Sci. Technol., 80, 2005, 1679-84.
31. A.V. Prajapati, S. Selvaraj, A microbial exopolysaccharide alternan with emerging roles in food systems and outlook for industrial advancements, Appl. Food Res., 6, 2026, 101801.
32. K.M. Lynch, P.L.H. McSweeney, E.K. Arendt, T. Uniacke-Lowe, S. Galle, A. Coffey, Isolation and characterisation of exopolysaccharide-producing *Weissella* and *Lactobacillus* and their application as adjunct cultures in Cheddar cheese. Int. Dairy J., 34, 2014, 125-134.
33. K. Buchholz, J. Seibel, Industrial carbohydrate biotransformations, Carbohydr. Res., 343, 2008, 1966-1979.
34. G. Mummaleti, C. Sarma, S. Yarrakula, R. Urla, H. Gazula, Production, properties and applications of levan polysaccharide, Food Humanity, 3, 2024, 100369.
35. D. Kavitake, S. Balyan, P.B. Devi, P.H. Shetty, Evaluation of oil-in-water (O/W) emulsifying

properties of galactan exopolysaccharide from *Weissella confusa* KR780676, J. Food Sci. Technol., 57, 2020, 1579-1585.
36. S.G. Sutariya, R. Joshi, P. Salunke, Emerging applications of hyaluronic acid in dairy and foods, Discover Food, 6, 2026, 84.
37. D.A. Abdel-Monem, S.A. Sabry, H.A. Ghozlan, E.H. Zaghloul, Preparation of novel marine *Enterococcus faecium* MSD8 exopolysaccharide ointment and in vivo evaluation of its impact on cutaneous wound healing in male albino rats, Probiotics Antimicrob. Proteins, 17, 2025, 963-975.
38. M. Ayyash, B. Abu-Jdayil, P. Itsaranuwat, E. Galiwango, C. Tamiello-Rosa, H. Abdullah et al., Characterization, bioactivities, and rheological properties of exopolysaccharide produced by novel probiotic *Lactobacillus plantarum* C70 isolated from camel milk. Int. J. Biol. Macromol., 144, 2020, 938-946.
39. A. Abdalla, M.M. Ayyash, A.N. Olaimat, T.M. Osaili, A.A. Al-Nabulsi, N.P. Shah, R. Holley, Exopolysaccharides as antimicrobial agents: mechanism and spectrum of activity, Front Microbiol., 19, 12, 2021, 664395.
40. S. Bulut, S. Tasdurmazli, E. Bedir, T. Ozbek, E. Su, K.K. Edis, E. Dertli, M.M. Ozmen, Alternan exopolysaccharide as a novel precursor for hydrogel and cryogel wound dressings, Polym. Bull., 83, 2026, 500.
41. D. Juraskova, S.C. Ribeiro, C.G. Silva, Exopolysaccharides produced by lactic acid bacteria: from biosynthesis to health-promoting properties, Foods, 11, 2022, 156.
42. L.M. Blandon, G.A. Islan, G.R. Castro, M.D. Noseda, V. Thomaz-Soccol, C.R. Soccol, Kefiran-alginate gel microspheres for oral delivery of ciprofloxacin, Colloids Surf. B. Biointerfaces, 145, 2016, 706-715.
43. N. Sharma, S.W. Kabeer, I.P. Singh, K. Tikko, Cisplatin conjugation with an exopolysaccharide extracted from *Lactobacillus gasseri* potentiates its efficacy and attenuates its toxicity, Int. J. Biol. Macromol., 225, 2023, 227-240.
44. Pradeepa, S.M. Vidya, S. Mutalik, K.U. Bhat, P. Huilgol, K. Avadhani, Preparation of gold nanoparticles by novel bacterial exopolysaccharide for antibiotic delivery, Life sciences, 153, 2016, 171-179.
45. G.M. Daba, M.O. Elnahas, W.A. Elkhateeb, Contributions of exopolysaccharides from lactic acid bacteria as biotechnological tools in food, pharmaceutical, and medical applications, Int. J. Biol. Macromol., 173, 2021, 79-89.
46. K. Raemdonck, B. Naeye, A. Hogset, J. Demeester, S.C. De Smedt, Prolonged gene silencing by combining siRNA nanogels and photochemical internalization, J. Control. Release, 145, 2010, 281-288.
47. B. Naeye, K. Raemdonck, K. Remaut, B. Sproat, J. Demeester, S. De Smedt, PEGylation of biodegradable dextran nanogels for siRNA delivery, Eur. J. Pharm. Sci., 40, 4, 2010, 342-351.
48. S. Liang, X. Wang, C. Li, L. Liu, Biological activity of lactic acid bacteria exopolysaccharides and their applications in the food and pharmaceutical industries, Foods, 13, 2024, 1621.
49. C. Tassa, S.Y. Shaw, R. Weissleder, Dextran-coated iron oxide nanoparticles: a versatile platform for targeted molecular imaging, molecular diagnostics, and therapy, Acc. Chem. Res., 44, 10, 2011, 842-852.
50. C. Li, D. Cheng, J. Ding, Z. Shi, A novel hetero-exopolysaccharide for the adsorption of methylene blue from aqueous solutions: isotherm, kinetic, and mechanism studies, J. Cleaner Prod., 265, 2020, 121800.
51. A. Singh, S. Roy, P. Saini, Exploring lead biosorption via *Lactobacillus*-based -exopolysaccharides and biofilms: a structural and functional study, Next sustain., 7, 2026, 100226.
52. M. Polak-Berecka, D. Szwajgier, A. Wasko, Biosorption of Al (+3) and Cd (+2) by an exopolysaccharide from *Lactobacillus rhamnosus*, J. Food Sci., 79, 11, 2014, T2404-8.
53. R.K. Kermanshahi, G.J. Khaniki, L. Goudarzi, Biosorption of Cd^{2+} and Pb^{2+} by exopolysaccharide extracted from *Lactobacillus fermentum* 6b; adsorption isotherm and kinetic studies, Iran J. Public Health, 52, 3, 2023, 622-632.
54. S. Patel, A. Majumder, A. Goyal, Potentials of exopolysaccharides from lactic acid bacteria, Indian J. Microbiol., 52, 1, 2011, 3-12.
55. R. Mañes-Lázaro, P.M. Van Diemen, C. Pin, M.J. Mayer, M. Stevens, A. Narbad, Administration of *Lactobacillus johnsonii* FI9785 to chickens affects

colonization by *Campylobacter jejuni* and the intestinal microbiota, Br. Poult. Sci., 58, 2017.
56. Y. Yang, S. Galle, M.H.A. Le, R.T. Zijlstra, M.G. Gänzle, Feed fermentation with reuteran- and levan-producing *Lactobacillus reuteri* reduces colonization of weanling pigs by enterotoxigenic *Escherichia coli,* Appl. Environ. Microbiol., 81, 2015, 5743-5752.
57. P. Kanmani, L. Albarracin, H. Kobayashi, E.M. Hebert, L. Saavedra, R. Komatsu, B. Gatica, A. Miyazaki, W. Ikeda-Ohtsubo, Y. Suda, et al. Genomic characterization of *Lactobacillus delbrueckii* TUA4408L and evaluation of the antiviral activities of its extracellular polysaccharides in porcine intestinal epithelial cells, Front. Immunol., 9, 2018, 2178.
58. S. Huang, Q. Yu, L. Xie, L. Ran, K. Wang, Y. Yang, L. Gan, Z. Song, Inhibitory effects of *Lactobacillus plantarum* metabolites on porcine epidemic diarrhea virus replication, Res. Vet. Sci., 139, 2021, 32-42.
59. F. Benhadda, A. Zykwinska, S. Colliec-Jouault, C. Sinquin, B. Thollas, A. Courtois, N. Fuzzati, A. Toribio, C. Delbarre-Ladrat, Marine versus non-marine bacterial exopolysaccharides and their skincare applications, Mar. Drugs, 21, 2023, 11, 582.
60. L.C. Becker, W.F. Bergfeld, D.V. Belsito, C.D. Klaassen, J.G.J. Marks, R.C. Shank, T.J. Slaga, P.W. Snyder, F.A. Andersen, Final Report of the Safety Assessment of Hyaluronic Acid, Potassium Hyaluronate, and Sodium Hyaluronate, Int. J. Toxicol., 28, 2009, 5-67.
61. L.-J. Chien, C.-K. Lee, Hyaluronic acid production by recombinant *Lactococcus lactis,* Appl. Microbiol. Biotechnol., 77, 2, 2007, 339-346.
62. F.F. Chahuki, S. Aminzadeh, V. Jafarian, F. Tabandeh, M. Khodabandeh, Hyaluronic acid production enhancement via genetically modification and culture medium optimization in *Lactobacillus acidophilus*, Int. J. Biol. Macromol*.,* 121, 2019, 870-881.
63. A.A. Mohammed, A.K. Niamah, Identification and antioxidant activity of hyaluronic acid extracted from local isolates of *Streptococcus thermophilus*, Mater. Today: Proc., 60, 2022, 1523-1529.
64. M.M. Fiume, B. Heldreth, W.F. Bergfeld, D.V. Belsito, R.A. Hill, C.D. Klaassen, D.C. Liebler, J.G. Marks, R.C. Shank, T.J. Slaga, et al., Safety Assessment of Microbial Polysaccharide Gums as Used in Cosmetics, Int. J. Toxicol., 35, 2016, 5S-49S.
65. EFSA BIOHAZ Panel (EFSA Panel on Biological Hazards), A. Allende, A. Alvarez-Ordóñez, V. Bortolaia, S. Bover-Cid, A. De Cesare, W. Dohmen, L. Guillier, L. Jacxsens, M. Nauta, et al., Update of the list of qualified presumption of safety (QPS) recommended microbiological agents intentionally added to food or feed as notified to EFSA 24: Suitability of taxonomic units notified to EFSA until March 2026, EFSA Journal, 24, 7, 2026, e10155.
66. J. Lu, Y. Mao, T. Ma, X. Liu, X. Cheng, Y. Bai, S. Li, Screening and genome analysis of lactic acid bacteria with high exopolysaccharide production and good probiotic properties, Food Biosci., 56, 2023, 103211.