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Lactic Acid Bacterial Exopolysaccharides- Its Functional Role, Therapeutic Potential, and Industrial Relevance

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Abstract

Exopolysaccharides (EPS) produced by lactic acid bacteria (LAB) are high-molecular-weight polymers composed primarily of carbohydrate units secreted into the extracellular environment. These natural biopolymers have garnered growing attention due to their multifaceted applications in food, health, and biotechnology. EPS synthesized by LAB can be structurally classified into homopolysaccharides and heteropolysaccharides, with their composition and function being strain-specific and influenced by environmental and genetic factors. In food systems, LAB-derived EPS significantly enhance texture, viscosity, water retention, and stability, contributing to improved mouthfeel and sensory properties, particularly in fermented dairy and plant-based products. Moreover, EPS act as natural, clean-label alternatives to synthetic thickeners and stabilizers.

Beyond technological benefits, LAB-EPS have demonstrated promising biofunctional properties, including prebiotic activity, antioxidant potential, immunomodulatory effects, and cholesterol-lowering capabilities. These health-promoting attributes position LAB-EPS as strong candidates for incorporation into functional foods and nutraceuticals. Advances in genetic and metabolic engineering, including CRISPR-Cas9 and systems biology approaches, have further enabled the targeted modification of LAB strains to enhance EPS yield and tailor polymer functionality.

Industrial interest in LAB-EPS extends to biomedical, cosmetic, and environmental applications—ranging from drug delivery and wound healing to biodegradable films and eco-friendly packaging. However, challenges such as scalable production, structural standardization, and regulatory clarity must be addressed to facilitate commercial adoption.

This review highlights recent progress in understanding LAB-EPS biosynthesis, structural diversity, functional properties, and emerging applications. It emphasizes the need for interdisciplinary collaboration and sustainable production strategies to unlock the full potential of LAB-derived EPS in next-generation bio-based solutions.

Keywords: Exopolysaccharides, CRISPR-Cas9, Natural Biopolymers

1. Introduction

Exopolysaccharides (EPS) are complex, high-molecular-weight polymers primarily composed of carbohydrate subunits that are secreted extracellularly by a broad spectrum of microorganisms. Among these, lactic acid bacteria (LAB) represent one of the most significant producers, particularly in the context of food fermentations. In recent years, LAB-derived EPS have emerged as compounds of great interest due to their dual role in improving food product quality and offering potential health benefits.

EPS can be structurally classified into two major categories: homopolysaccharides, which are made up of only one type of monosaccharide (e.g., glucose or fructose), and heteropolysaccharides, which contain two or more different monosaccharides. The structure and functionality of these biopolymers are not only species-specific but also influenced by genetic, environmental, and nutritional factors, making their properties highly strain-dependent.

In fermented food systems, LAB play a pivotal role not only in fermentation but also in enhancing the sensory and rheological properties of the final product through EPS production. As organisms recognized as Generally Regarded As Safe (GRAS),

LAB have a long tradition of use in the fermentation of dairy products (such as yogurt and cheese) and plant-based foods (such as pickles, sauerkraut, and sourdough bread). The EPS synthesized by these bacteria contribute to improved viscosity, creaminess, water-holding capacity, and mouthfeel—attributes highly valued in modern food formulations.

Beyond their technological advantages, LAB-derived EPS have been increasingly studied for their biofunctional properties. Several strains have been reported to produce EPS that exhibit prebiotic effects, antioxidant activity, cholesterol-lowering potential, and immunomodulatory actions. These bioactivities position LAB-EPS as promising candidates for use in functional foods, dietary supplements, and nutraceuticals aimed at promoting human health.

Driven by growing consumer demand for clean-label, naturally derived, and eco-friendly ingredients, EPS from LAB are being explored as sustainable alternatives to synthetic food additives and texturizers. Furthermore, the application potential of these polymers extends beyond the food industry. LAB-derived EPS are being investigated for their roles in biomedical applications (such as drug delivery and wound healing), cosmetics (as moisturizers and skin protectants), and biodegradable packaging (as film-forming agents and stabilizers).

This review aims to provide an in-depth exploration of exopolysaccharides produced by lactic acid bacteria. Key areas covered include their biosynthetic pathways, structural diversity, functional and health-related properties, and their multifaceted applications in both food and non-food sectors. Additionally, the review highlights recent advancements in LAB-EPS research, identifies current knowledge gaps, and discusses future challenges associated with their commercial utilization.

2. Biosynthesis of Exopolysaccharides in Lactic Acid Bacteria

The biosynthesis of exopolysaccharides (EPS) by lactic acid bacteria (LAB) is a genetically regulated and environmentally sensitive process involving several well-coordinated steps. The capability to produce EPS varies significantly among LAB species and strains, reflecting the complex interplay of genetic makeup and external factors such as nutrient availability and environmental stress.

2.1 Genetic Architecture Underpinning EPS Production

The production of EPS in LAB is orchestrated by a specific set of genes typically organized in what is known as the eps gene cluster. This cluster comprises genes responsible for multiple stages of EPS assembly, including sugar nucleotide synthesis, initiation, elongation, chain length determination, and polymer export. Key functional components of this cluster include:

- Glycosyltransferases: Enzymes that sequentially add sugar residues to form oligosaccharide chains.
- Priming glycosyltransferase (EpsE): Catalyzes the initiation step of polymer formation.
- EpsC and EpsD: Play essential roles in regulating polymer chain length and assembly.
- Membrane transport proteins (e.g., Wzx and Wzy): Facilitate the translocation of repeating units across the cytoplasmic membrane and their subsequent polymerization.

The composition and arrangement of genes within the eps cluster can vary not only across LAB species but also among strains of the same species, contributing to significant heterogeneity in the structure and function of the resulting EPS [3, 4].

2.2 Biosynthetic Mechanisms

LAB employ two major biosynthetic strategies for EPS formation, depending on the type of polysaccharide being synthesized:

- Wzx/Wzy-dependent pathway (primarily for heteropolysaccharides):
  This pathway involves the stepwise synthesis of oligosaccharide repeating units on a lipid carrier molecule, undecaprenyl phosphate, which are then flipped across the membrane and polymerized into longer chains.
- Glycosyltransferase-driven polymerization (mainly for homopolysaccharides):
  This simpler pathway does not require a lipid carrier; instead, sugar monomers are directly polymerized into long-chain polysaccharides by specific glycosyltransferases.

Activated nucleotide sugars such as UDP-glucose, GDP-mannose, and dTDP-rhamnose serve as the primary donors in these processes. The intracellular availability of these precursors critically influences the quantity and composition of EPS produced.

2.3 Influence of Environmental and Nutritional Factors

EPS biosynthesis is highly responsive to environmental cues and nutritional inputs. Factors that significantly impact production include:

- Carbon source: Sugars such as glucose and sucrose are preferred, with sucrose being especially effective in promoting homopolysaccharide synthesis.
- pH and temperature: LAB typically produce optimal EPS yields at pH 5.5–6.5 and temperatures between 30–37°C.
- Stress conditions: Exposure to oxidative, osmotic, or acidic stress can enhance EPS production, likely as a microbial defense mechanism.
- Medium composition: The carbon-to-nitrogen (C/N) ratio, presence of trace minerals, and availability of growth factors can influence both the quantity and structural complexity of the EPS [5].

2.4 Advances in Genetic and Metabolic Engineering

Recent developments in synthetic biology have opened new avenues for optimizing EPS production in LAB:

- Metabolic engineering: Altering central metabolic pathways to redirect flux toward EPS precursor biosynthesis.
- Genome editing tools (e.g., CRISPR-Cas9): Precise modification of eps gene clusters to design LAB strains that produce tailored EPS with specific structural or functional traits.
- Systems biology approaches: Integration of genomic, transcriptomic, proteomic, and metabolomic data provides a holistic understanding of the regulatory networks controlling EPS biosynthesis [6].

Such tools enable the rational design of LAB strains for enhanced EPS yield and functionality, with potential

applications in food texture optimization, prebiotic development, and biomedical innovation.

3. Functional and Rheological Properties of Exopolysaccharides from Lactic Acid Bacteria

Exopolysaccharides (EPS) synthesized by lactic acid bacteria (LAB) play a pivotal role in modulating the sensory and physical characteristics of fermented foods. These naturally secreted polymers exhibit distinctive water-binding, viscoelastic, and emulsifying properties, making them highly desirable as functional additives—particularly in clean-label and fat-reduced food formulations.

3.1 Improvement of Texture and Mouthfeel

One of the primary functional advantages of LAB-derived EPS is their ability to enhance the texture and sensory appeal of fermented products. By increasing viscosity and contributing to a creamier consistency, EPS significantly improve mouthfeel. For example, EPS-producing strains such as *Lactobacillus delbrueckii* subsp. *bulgaricus* and *Streptococcus thermophilus* have been shown to improve gel firmness and reduce syneresis in yogurt. This eliminates the need for synthetic stabilizers and results in a smoother, more desirable product texture [7].

3.2 Water Retention and Gel Stability

The exopolysaccharides possess hydrophilic structure, LAB-EPS exhibit a strong capacity to retain water, thereby stabilizing emulsions and preventing phase separation. This property is particularly beneficial in fermented dairy and plant-based systems, where uniform consistency and minimal whey separation are critical for consumer acceptance. Some EPS also possess weak gelling properties, which further contribute to the firmness and cohesiveness of products like set yogurts and soft cheeses.

3.3 Rheological Behaviour: Viscosity and Shear Response

Many LAB-derived EPS display pseudoplastic or shear-thinning behavior—meaning their viscosity decreases under mechanical stress such as mixing or pouring, but increases when the product is at rest. This rheological characteristic facilitates both processing and consumer handling, while maintaining a rich, thick texture. The degree of viscosity imparted by EPS is influenced by factors such as concentration, molecular weight, degree of polymerization, and branching patterns of the polymer chains [8].

3.4 Emulsification and Cryoprotection

EPS can stabilize emulsions by forming a hydrophilic barrier around dispersed lipid droplets, reducing their tendency to coalesce. This function is particularly valuable in fermented dairy emulsions and beverages. Additionally, LAB-EPS exhibit cryoprotective properties by preserving cell viability and product integrity during freezing or refrigerated storage. This makes them useful not only in food preservation but also in probiotic delivery systems [9].

3.5 Role in Low-Fat and Plant-Based Food Systems

With the rise of consumer demand for plant-based and reduced-fat alternatives, LAB-derived EPS offer a natural means of enhancing product quality without synthetic additives. In non-dairy yogurts and vegan cheese analogs, EPS compensate for the absence of dairy fats and proteins by contributing to structure, creaminess, and stability. This aligns with industry trends toward clean-label, allergen-free, and animal-free formulations.

4. Health-Promoting Effects of Exopolysaccharides from Lactic Acid Bacteria

Beyond their technological functions in food systems, exopolysaccharides (EPS) synthesized by lactic acid bacteria (LAB) possess a wide array of bioactivities that contribute positively to human health. These effects are closely linked to the polymers' intricate structural features, including monosaccharide composition, molecular weight, and branching. As a result, LAB-derived EPS are being actively explored for incorporation into functional foods and nutraceuticals aimed at health promotion and disease prevention.

4.1 Prebiotic Potential and Gut Microbiota Modulation

LAB-EPS are increasingly recognized for their prebiotic properties, wherein they selectively stimulate the growth and metabolic activity of beneficial gut microbes such as *Bifidobacterium* and *Lactobacillus* spp. These EPS are resistant to enzymatic digestion in the upper gastrointestinal tract, allowing them to reach the colon intact, where they are fermented by resident microbiota. This fermentation results in the production of short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate. SCFAs lower intestinal pH, enhance barrier integrity, suppress pathogenic microorganisms, and contribute to local and systemic immune regulation [10].

4.2 Immunomodulatory Capabilities

Numerous studies have demonstrated the ability of LAB-derived EPS to modulate immune responses. These polymers can enhance the activity of macrophages and natural killer (NK) cells, influence cytokine secretion profiles—such as promoting anti-inflammatory cytokines like interleukin-10 (IL-10) and reducing pro-inflammatory mediators like tumor necrosis factor-alpha (TNF-α)—and stimulate the gut-associated lymphoid tissue (GALT). The extent and nature of these effects vary with EPS structure, including molecular size and degree of branching, and are often strain-dependent [11].

4.3 Antioxidant Activities

EPS from LAB have shown significant antioxidant potential, demonstrated through mechanisms such as free radical scavenging, metal ion chelation, and inhibition of lipid peroxidation. These antioxidative properties are generally attributed to the presence of hydroxyl-rich sugar residues like galactose and rhamnose within the EPS matrix. By neutralizing reactive oxygen species (ROS), these EPS may offer protection against oxidative stress-related conditions including chronic inflammation, cardiovascular diseases, neurodegenerative disorders, and carcinogenesis [12].

4.4 Hypocholesterolemic Effects

Certain LAB-derived EPS contribute to cholesterol reduction through multiple mechanisms:

- Binding to bile acids in the intestine, facilitating their elimination and prompting hepatic conversion of cholesterol into new bile acids.

- Modifying cholesterol biosynthesis and uptake at the hepatic level.
- Enhancing the colonization and functionality of probiotic strains in the gut, which indirectly supports lipid homeostasis [13].

Such multifunctional effects highlight the potential of LAB-EPS in managing hyperlipidemia and related metabolic disorders.

4.5 Antitumor and Antiproliferative Activities

Preclinical investigations have revealed that some EPS produced by LAB possess anticancer properties, particularly against cell lines derived from colorectal, hepatic, and gastric tumors. These effects may involve the induction of programmed cell death (apoptosis), inhibition of cancer cell proliferation, and activation of immune components such as tumor-associated macrophages. While *in vitro* and animal studies are promising, the clinical translation of these findings remains in its early stages, necessitating more human trials for validation [14].

5. Industrial and Biomedical Applications of Exopolysaccharides from Lactic Acid Bacteria

Exopolysaccharides (EPS) synthesized by lactic acid bacteria (LAB) have garnered increasing attention for their multifunctional properties and excellent safety profile. These naturally derived polymers are biodegradable, non-toxic, and Generally Recognized as Safe (GRAS), making them highly suitable for various applications across the food, pharmaceutical, cosmetic, and environmental sectors.

5.1 Utilization in the Food Industry

One of the most established applications of LAB-EPS is in the food industry, where they function as natural alternatives to synthetic stabilizers, thickeners, and texturizers. Their roles include:

- Fermented dairy products: Enhancing creaminess, reducing syneresis, and increasing viscosity in products such as yogurt, cheese, and kefir.
- Fat-reduced formulations: Acting as fat mimetics in low-fat or fat-free foods by contributing to mouthfeel and richness.
- Gluten-free and plant-based products: Improving texture and structural integrity in dairy and gluten substitutes.

In sourdough bread systems, EPS produced by *Weissella* and *Lactobacillus* species have been shown to increase loaf volume, enhance crumb softness, and extend shelf life by mitigating starch retrogradation and microbial spoilage [15].

5.2 Biomedical and Pharmaceutical Potential

Due to their biocompatibility, immunomodulatory effects, and structural versatility, LAB-derived EPS are emerging as promising agents in biomedical innovation:

- Drug delivery: EPS-based hydrogels and nanoparticle systems offer controlled release profiles for encapsulated therapeutics.
- Wound healing: Certain EPS promote fibroblast proliferation and tissue regeneration, accelerating wound closure.
- Tissue engineering: The porous and hydrated nature of EPS scaffolds supports cell adhesion, proliferation, and matrix formation.

Moreover, the biofilm-forming capacity of some LAB strains is being investigated for use as bioactive coatings on medical implants and antimicrobial surfaces [16].

5.3 Applications in Cosmetics and Personal Care

The hydrating and antioxidant activities of LAB-EPS have made them valuable ingredients in cosmetic and skincare formulations:

- Moisturizers and serums: To enhance skin hydration and provide a protective barrier against oxidative stress.
- Anti-aging products: Contributing to wrinkle reduction, inflammation control, and improved skin elasticity.

EPS derived from *Lactobacillus plantarum* and *Lactobacillus rhamnosus* have demonstrated potential in protecting skin against UV-induced damage and in reinforcing the skin's barrier function [17].

5.4 Environmental and Packaging Innovations

In response to the growing demand for eco-friendly materials, LAB-EPS are being explored as components of sustainable packaging and encapsulation systems:

- Biodegradable films and edible coatings: Offering protection against moisture loss and oxidation, while extending shelf life of perishable goods.
- Encapsulation matrices: Used for protecting probiotics or flavor compounds during storage and enabling their targeted release during digestion.

When combined with other biopolymers such as chitosan or starch, LAB-derived EPS demonstrate excellent film-forming properties, offering a viable and sustainable alternative to petroleum-based plastic packaging [18].

6. Recent Advances and Future Perspectives in LAB-Derived Exopolysaccharide Research

The field of lactic acid bacteria (LAB)-derived exopolysaccharide (EPS) research is evolving rapidly, driven by innovations in molecular biology, systems-level omics technologies, and industrial bioprocessing. LAB continue to attract considerable attention as sustainable producers of bioactive and multifunctional EPS, with promising applications spanning food, biomedical, and material sciences. However, key challenges remain in enhancing production efficiency, unraveling structure–function relationships, and translating laboratory-scale successes into commercially viable solutions.

6.1 Advances in Synthetic Biology and Metabolic Engineering

Emerging tools in synthetic biology, particularly CRISPR-Cas9 genome editing, have enabled the precise manipulation of EPS biosynthetic pathways in LAB. Modulating the expression of glycosyltransferase genes can alter EPS composition, chain branching, and molecular weight, allowing the tailoring of functional properties. For instance, engineered *Lactobacillus plantarum* strains have demonstrated improved EPS yield and targeted structural features [19].

Moreover, transferring EPS gene clusters into robust heterologous hosts like *Escherichia coli* or *Bacillus subtilis* is under exploration to boost production efficiency and facilitate tighter process control in industrial systems.

6.2 Systems Biology and Omics Integration

High-throughput genomics, transcriptomics, proteomics, and metabolomics are being employed to dissect the regulatory mechanisms of EPS biosynthesis under various environmental and nutritional conditions. The integration of multi-omics data within systems biology frameworks allows for the prediction and selection of high-performing LAB strains and optimization of culture conditions [20].

Genome mining from traditional fermented foods has further broadened the diversity of known EPS-producing LAB strains, offering novel candidates beyond conventional dairy-associated isolates.

6.3 Bioprocess Engineering and Production Optimization

While LAB-EPS hold significant industrial promise, scalable and cost-effective production remains a critical barrier. Strategies to enhance yield include:

- ✓ Fed-batch and continuous fermentation systems
- ✓ pH-controlled bioreactor operations
- ✓ Utilization of agro-industrial residues (e.g., whey permeate, molasses, fruit peels).

These approaches not only increase EPS output but also contribute to environmental sustainability and circular bioeconomy models by valorizing food industry waste streams [21].

6.4 Commercialization and Regulatory Considerations

Despite mounting evidence of their functional and health benefits, the regulatory landscape for LAB-derived EPS remains complex. Clear guidelines regarding EPS purification, compositional standardization, and substantiation of health claims are essential for market acceptance.

Technical hurdles, such as the high cost of large-scale EPS isolation, structural characterization, and performance consistency in real-world food matrices, also limit commercial viability.

6.5 Future Directions

The next frontier in LAB-EPS research focuses on multifunctional and application-specific development, including:

- Tailor-made EPS for defined applications in food texture enhancement, dermatological care, or wound healing
- Advanced hybrid biomaterials combining EPS with proteins, nanoparticles, or bioactive enzymes
- Integration into personalized nutrition platforms, using LAB strains selected based on individual gut microbiota profiles

Realizing the full potential of LAB-EPS will require interdisciplinary collaboration among microbiologists, materials scientists, biotechnologists, food engineers, and regulatory bodies. As these collaborative efforts mature, LAB-derived EPS are poised to become pivotal ingredients in next-generation bio-based innovations.

7. Conclusion

Exopolysaccharides (EPS) synthesized by lactic acid bacteria (LAB) constitute a dynamic and multifunctional group of natural polymers with wide-ranging applications across the food, health, and industrial sectors. Their distinct physicochemical attributes enable them to improve the texture, viscosity, and overall sensory quality of fermented products, while their diverse biological activities—including prebiotic, antioxidant, immunomodulatory, and lipid-lowering effects—highlight their potential as ingredients in functional foods and nutraceuticals. Recent progress in genetic engineering, systems biology, and fermentation technology has significantly enhanced our understanding of EPS biosynthesis and regulation in LAB. These advancements have opened avenues for the rational design of EPS with tailored structures and specific functional attributes. Concurrently, the discovery of novel EPS-producing LAB strains from diverse fermented sources continues to enrich the available microbial toolbox for EPS production.

Nonetheless, important challenges remain. The transition from laboratory-scale research to industrial-scale application requires improvements in production efficiency, consistency in EPS isolation and characterization, and the establishment of regulatory frameworks for health claims. In addition, further *in vivo* studies and human clinical trials are necessary to confirm the safety and efficacy of LAB-derived EPS.

Looking to the future, multidisciplinary collaboration and environmentally conscious bioprocessing strategies will be crucial for fully realizing the potential of LAB-EPS. Their natural origin, biodegradability, and functional versatility make them promising candidates not only for food and pharmaceutical use but also for emerging areas such as sustainable packaging and cosmetic formulations.

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