

Review Article

Application of Microbial Exopolysaccharides in the Cereal Products Industry: A Review

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Abstract

Microbial exopolysaccharides (EPS) are high-molecular-weight biopolymers synthesized by various microorganisms, including bacteria, fungi, and algae. These compounds have gained noteworthy attention due to their diverse structural characteristics and functional properties, making them valuable in multiple industries, particularly in food, pharmaceuticals, and environmental applications. This review explores the structure, classification, and biosynthetic pathways of EPS, emphasizing their critical role in improving the texture, stability, and nutritional value of food products. In the cereal industry, EPS contributes significantly to the development of fermented beverages and baked goods by enhancing viscosity, moisture retention, and overall product quality. Additionally, their prebiotic properties offer considerable health benefits, including gut microbiota modulation and immune system enhancement. Despite these advantages, industrial-scale EPS production faces challenges such as high manufacturing costs, structural complexity, and purification difficulties. However, advancements in biotechnology, including strain optimization and the use of alternative carbon sources, present promising solutions for improving EPS yield and cost-effectiveness. This review not only highlights the technological and functional potential of EPS in the cereal products industry but also discusses emerging research trends and opportunities for expanding their application. With growing consumer demand for natural, clean-label ingredients, microbial EPS has the potential to revolutionize food processing by serving as sustainable and health-promoting alternatives to synthetic additives. It is hoped that this article brings more attention to these products as they meet the current and future needs of cereal industry.

Keywords

Biopolymers, Biosynthesis, Biotechnology, Food Industry, Microbial Exopolysaccharides (EPS), Prebiotic Properties, Sustainable Ingredients

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1. Introduction

Microbial exopolysaccharides (EPS) are high-molecular-weight carbohydrate polymers made up of sugar units or their derivatives, biosynthesized by various microorganisms, including bacteria, fungi, yeasts, and algae. These biopolymers are essential for microbial survival, as they protect cells from environmental stresses such as temperature fluctuations, salinity changes, and pH variations. Moreover, EPS contribute to biofilm formation and facilitate microbial adaptation across diverse ecological niches [1-4]. Beyond their biological functions, EPS have gained significant industrial importance due to their diverse structural and functional properties, making them valuable in food, pharmaceutical, and environmental applications. One of the key advantages of EPS is its ability to replace synthetic additives, offering a natural and biodegradable alternative in food formulations. Their role extends beyond improving the rheological properties of food products, as they also exhibit bioactive properties such as antioxidant, antibacterial, anticancer, and immune-boosting effects [4-7]. Among the various EPS-producing microorganisms, lactic acid bacteria (LAB) are particularly significant, as they enhance both the sensory and structural properties of fermented products, contributing to improved texture, stability, and overall product quality. From an industrial standpoint, the application of EPS derived from LAB has facilitated the production of "clean-label" food products—those free from artificial additives and highly favored by modern consumers. These compounds contribute as natural thickeners, emulsifiers, and stabilizers, further en-

hancing their value in the food industry. However, despite their many advantages, large-scale EPS production faces several challenges, including limited industrial yields and structural complexity, which can affect their functional properties. Addressing these challenges requires advancements in microbial fermentation processes, strain optimization, and improved extraction and purification techniques [8-10]. Cereal grains have long been a fundamental component of food and beverage production. In recent years, fermented cereal-based beverages have gained increasing popularity, particularly among consumers seeking non-dairy alternatives due to lactose intolerance, vegan dietary preferences, or a general interest in healthier food choices. The fermentation of cereals using LAB not only enhances their nutritional profile and shelf-life but also improves organoleptic characteristics, making them more appealing to consumers. Additionally, the EPS produced during fermentation positively influences the rheological properties, stability, and texture of these products, highlighting their potential in the development of innovative cereal-based food solutions [9]. This article explores the structural diversity, biosynthetic pathways, and industrial applications of microbial EPS, with a particular focus on their role in cereal-based food production. It is also hoped that this review examines the challenges associated with large-scale EPS utilization to highlight the emerging research perspectives aimed at improving production efficiency and expanding their applications in food technology.

2. Structure of Microbial Exopolysaccharides

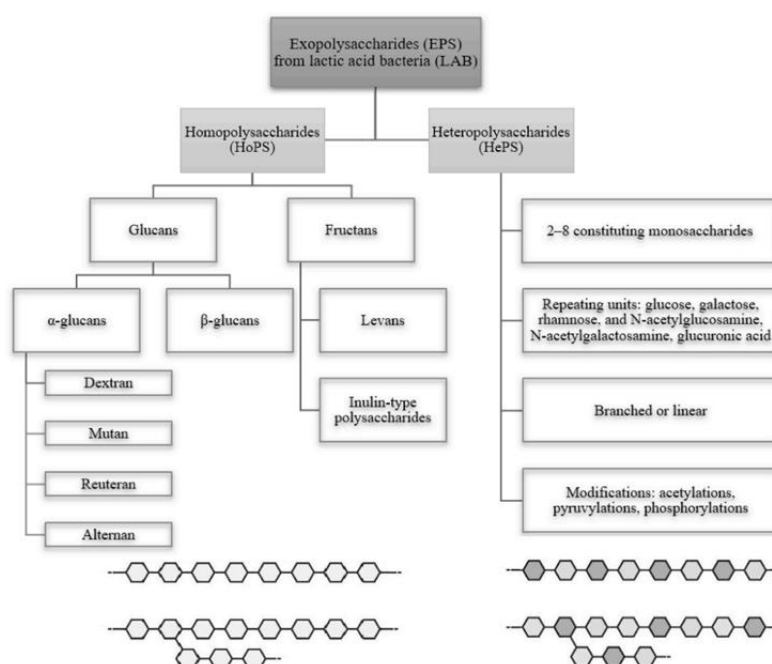


Figure 1. Structure of Exopolysaccharides (EPS).

Bacterially derived exopolysaccharides (EPS) are classified into two primary categories: homopolysaccharides (HoPS) and heteropolysaccharides (HePS). This classification is based on their monosaccharide composition and structural complexity, which directly influence their physicochemical properties and industrial applications [1]. Accordingly, the structure of the exopolysaccharides (EPS) was shown in Figure 1.

2.1. Homopolysaccharides (HoPS)

Homopolysaccharides (HOPS) consist of repeating units of a single type of monosaccharide, forming linear or branched polysaccharide chains. Examples of this group include dextran, levan, inulin, curdlan, and pullulan, all of which exhibit diverse functional properties suitable for various industrial applications [3, 4]. The classification of HoPS is further refined based on the nature of the glycosidic bonds and the specific carbon atoms involved in linkage formation [9]. The biosynthesis of HoPS primarily occurs extracellularly through the catalytic action of glycosyltransferase enzymes, which facilitate the polymerization of sugar monomers into high-molecular-weight polysaccharides [7, 9]. These polymers often reach molecular weights as high as 10^6 Da, enabling them to serve as effective viscosity enhancers in food and pharmaceutical formulations. Their ability to modify rheological properties makes them valued in enlightening texture, stability, and mouthfeel in diverse products [3]. Mi-

crobial strains are acknowledged for their efficient HoPS production include *Lactobacillus*, *Leuconostoc*, *Streptococcus*, *Weissella*, and *Oenococcus*, each contributing unique biochemical profiles that influence the final characteristics of the synthesized polysaccharide [6, 9].

2.2. Heteropolysaccharides (HePS)

Heteropolysaccharides (HePS), in contrast to HoPS, contain two to eight different monosaccharide units, leading to larger structural diversity and functional versatility. Representative HePS include xanthan, gellan, glucose, and galactose-based polysaccharides, which are widely utilized in food and pharmaceutical industries for their stabilizing, texturizing, and bioactive properties [2, 4]. Due to their branched molecular architecture, which incorporates both α and β glycosidic bonds, HePS exhibit variable molecular weights ranging from 10^4 to 10^6 Da [9]. The biosynthesis of HePS is facilitated by both mesophilic and thermophilic lactic acid bacteria (LAB), including mesophilic species such as *Lactococcus lactis* subsp. *Lactis* and *Lactobacillus rhamnosus*, and thermophilic species such as *Lactobacillus delbrueckii* subsp. *Bulgaricus* and *Streptococcus thermophiles*. Additionally, non-LAB microorganisms contribute to HePS production. Notably, the Gram-negative bacterium *Xanthomonas campestris* is responsible for xanthan biosynthesis, a widely used industrial polysaccharide with thickening and stabilizing properties [6, 3].

3. Properties Structural and Functional Considerations

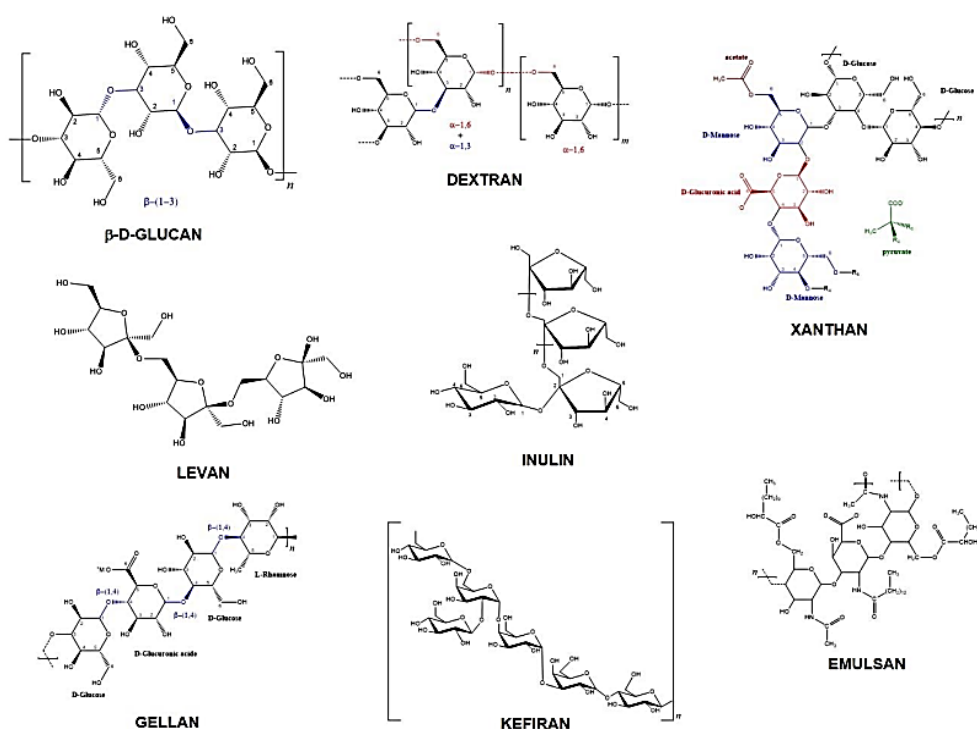


Figure 2. EPS chemical structure examples.

The functional properties of EPS are strongly influenced by their molecular weight, glycosidic bond type, and the presence of functional side groups, such as sulfate, acetyl, phosphate, and pyruvate moieties. These structural variations affect solubility, viscosity, and interaction with other food or pharmaceutical components, determining their suitability for specific applications [10, 3]. EPS exists in two distinct forms of capsular EPS and viscous EPS. Capsular EPS remains attached to the microbial cell surface, forming a protective layer that shields the cell from environmental stressors, including temperature fluctuations, osmotic pressure, and desiccation. Viscous EPS, on the other hand, is secreted freely into the surrounding environment, where it enhances the rheological properties of the medium, contributing to viscosity, gelation, and emulsion stability [3]. The structural complexity of EPS (Figure 2), coupled with their ability to modulate texture and stability in diverse formulations, emphasizes their significance in both natural and engineered biotechnological applications. Further research into optimizing microbial production and tailoring EPS composition will enhance their functionality across various industries [11].

4. Common Exopolysaccharides in the Cereal Industry

EPS play an essential role in the cereal industry, contributing to the enhancement of overall product quality, specifically texture and stability. These biopolymers are primarily used in baked goods, breakfast cereals, and gluten-free products, where they improve structural integrity, extend shelf life, and offer efficient health benefits. The following sections provide an overview of the most common EPS utilized in cereal-based products, detailing their microbial producers, structural characteristics, and industrial applications.

4.1. Dextran

Dextran is synthesized by *Leuconostoc mesenteroides* and various *Lactobacillus* species, both of which are known for their part in the fermentation of cereal-based products. Dextran is classified as a homopolysaccharide composed of glucose monomers linked predominantly by α -1,6 glycosidic bonds, with additional α -1,3 branch points that influence its functional properties (Figure 3). Its industrial applications in cereal products are dough rheology enhancement by improving its elasticity, making it more resistant to mechanical stress, volume expansion by increasing bread volume and leading to a lighter and more aerated texture, and shelf-life extension by retaining moisture and preventing hardening over time. Dextran serves as a natural alternative to synthetic dough conditioners and emulsifiers, reducing the need for chemical additives while improving softness and overall bread quality [12, 11].

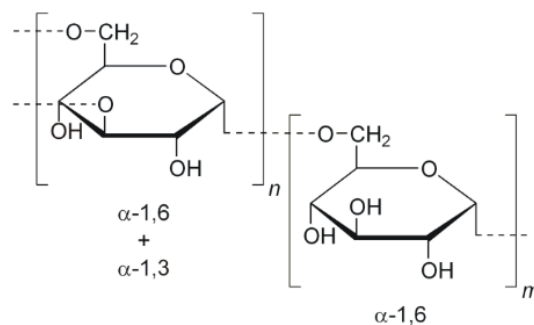


Figure 3. Dextran Structure.

4.2. Beta-Glucan (β -Glucan)

β -Glucan is synthesized by various fungi and bacteria, including *Lactobacillus* species, which are frequently utilized in cereal fermentation processes. This linear or branched homopolysaccharide consists of glucose monomers linked by β -1,3 and β -1,4 glycosidic bonds, contributing to its high solubility and gel-forming capacity (Figure 4). Its industrial applications in cereal products works based on its nutritional enhancement. It increases fiber content in bread and breakfast cereals, and applies glycemic control by lowering the glycemic index, making cereal products more suitable for individuals with diabetes. β -Glucan additionally improves gut microbiota by acting as a prebiotic and reducing cholesterol. β -Glucan is widely recognized for its prebiotic potential, making it a valuable ingredient in functional foods designed to support digestive and cardiovascular health [11, 7].

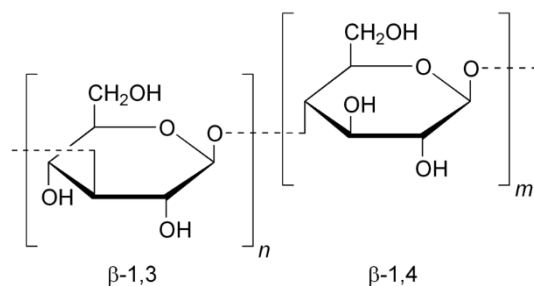


Figure 4. Beta-Glucan Structure.

4.3. Xanthan

Xanthan is produced by the Gram-negative bacterium *Xanthomonas campestris*, which is widely used in food biotechnology. As a HePS, xanthan consists of glucose, mannose, and glucuronic acid. Its unique structure imparts high viscosity and stability, even under varying temperature and pH conditions (Figure 5). In cereal products sector, it's used in gluten-free formulations as a gluten substitute to improve texture and elasticity. It also prevents phase separation in

cereal-based beverages and dough systems and applies rheological modifications by enhancing uniformity and consistency in dough formulations. Xanthan is particularly val-

uable in gluten-free product development, providing structural integrity and enlightening mouthfeel for individuals dealing with celiac disease or gluten intolerance [1, 11].

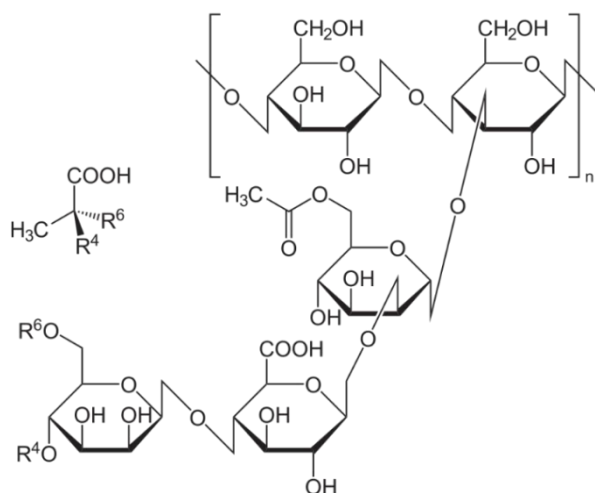


Figure 5. Xanthan Structure.

4.4. Levan

Levan is synthesized by a diverse range of bacterial species, including both Gram-negative bacteria such as *Acetobacter*, *Gluconobacter*, *Komagataeibacter*, *Pseudomonas*, *Halomonas* and *Erwinia*, and Gram-positive bacteria such as *Bacillus subtilis*, *Bacillus licheniformis*, *Paenibacillus polymyxa*, *Lactobacillus reuteri* and *Leuconostoc citreum* [6]. Levan is a fructan-based homopolysaccharide, primarily composed of β -2,6 glycosidic linkages, which contribute to its high solubility and stability under various processing conditions (Figure 6). Its applications in cereal products are texture enhancement, fat reduction in baked goods and shelf-life improvement. Levan improves dough consistency and softness in industrial bread production and acts as a fat replacer to reduce lipid content in bakery formulations. It also retains moisture and enhances freshness in bread products. Levan's water retention capacity and heat resistance make it an effective ingredient for maintaining product stability while reducing reliance on synthetic stabilizers [7].

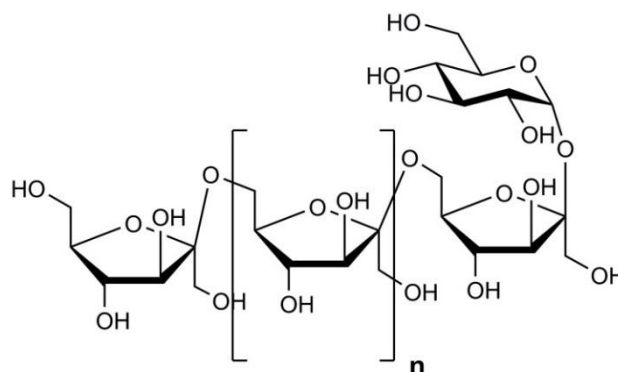


Figure 6. Levan Structure.

Paenibacillus polymyxa is capable of producing levan. In Figure 7 shows the morphological characteristics and purification medium of the bacteria capable of producing this product.

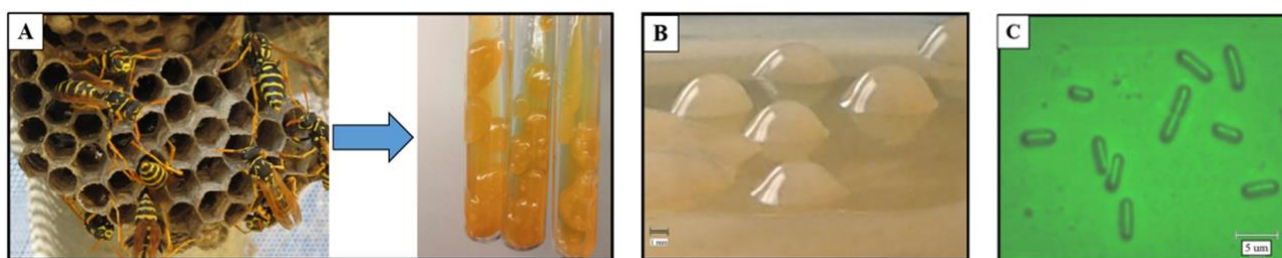


Figure 7. *Pa. polymyxa*; first isolated from wasp honeycombs (A), Colony morphology (B), Cell morphology (C).

4.5. Curdlan

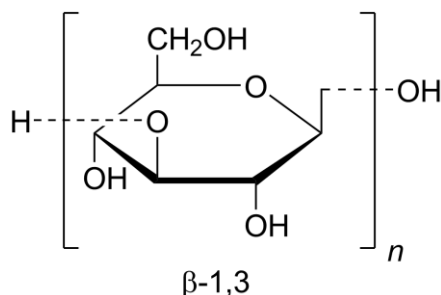


Figure 8. Curdlan Structure.

Curdlan is produced by *Alcaligenes faecalis*, a bacterium known for its ability to synthesize thermos-reversible gel-forming polysaccharides. Curdlan is a β -1,3 glucan homopolysaccharide, characterized by its ability to form strong, heat-induced gels at high temperatures (Figure 8). Its role in cereal products industry is enhancing structural stability in semi-prepared and frozen cereal products and preventing structural damage by protection against textural degradation in frozen baked goods. Curdlan's unique gelation properties allow it to withstand harsh processing conditions, making it an essential stabilizer in high-temperature food applications [2].

4.6. Pullulan

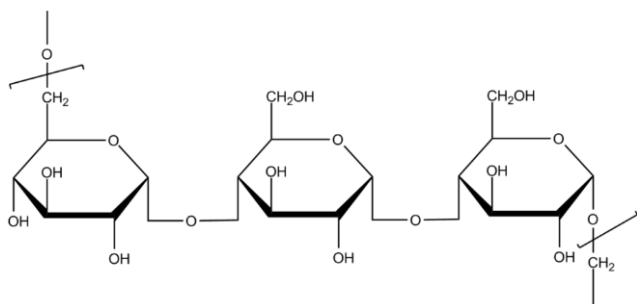


Figure 9. Pullulan Structure.

Pullulan is synthesized by the fungal species *Aureobasidium pullulans*, a well-known producer of biodegradable polysaccharides. This trisaccharide homopolysaccharide consists of glucose monomers linked by α -1,4 and α -1,6 glycosidic bonds, forming a highly adhesive and flexible polymer (Figure 9). Pullulan takes role in edible packaging and dough integrity enhancement as it's used to create biodegradable films for cereal product preservation and increase adhesion and uniformity in specialized baking applications. Pullulan is environmentally friendly, and this specialty makes it a promising candidate for sustainable food packaging solutions that align with the growing demand for eco-friendly materials [3].

5. Microorganisms Producing Exopolysaccharides

Microbial EPS are synthesized by a diverse range of microorganisms, including bacteria, fungi, and algae. These organisms produce EPS with varying molecular structures and functional properties, making them treasured in multiple industrial applications, particularly in food, pharmaceuticals, and environmental sciences. The physicochemical characteristics of EPS such as molecular weight, polymer branching, and solubility are largely influenced by the microbial source, which dictates their potential applications. Bacteria represent one of the most significant EPS-producing microbial groups due to their metabolic diversity and ability to generate structurally varied polysaccharides. Among these, lactic acid bacteria (LAB) are particularly well known for their role in fermentative EPS production. Some key bacterial producers include: *Lactopantibacillus plantarum*, *Streptococcus thermophilus* and *Leuconostoc* spp. [3, 11]. These bacteria primarily synthesize heteropolysaccharides (HePS), although some species are capable of producing homopolysaccharides (HoPS). The molecular weight of bacterial EPS generally ranges from 10^4 to 10^6 Daltons, influencing their rheological and functional properties in industrial formulations. These bacterially derived EPS are widely utilized in the food industry due to their ability to modify the physicochemical properties of various products. Their technical functionalities include viscosity enhancement, phase stability and protein interaction. EPS contribute to the thickening and stabilization of products such as yogurt, fermented beverages, and bread. These polysaccharides reduce syneresis in both dairy and non-dairy products, improving texture and shelf stability. EPS interact with proteins to form stable matrices, particularly in low-fat formulations, enhancing product consistency and mouthfeel. Beyond their role as texturizing agents, bacterial EPS exhibit significant bioactive properties that contribute to health and wellness. Bacterial EPS have prebiotic effects as they promote the growth of beneficial gut microbiota and facilitate the production of short-chain fatty acids, supporting digestive health. They have also shown some immunomodulatory activity. Certain EPS, such as dextran and β -glucan, have been shown to enhance immune function and lower cholesterol by breaking down bile salts, contributing to cardiovascular health [11].

6. EPS Production by Fungal Species

Numerous fungal species knows as producers of EPS with unique structural and functional characteristics. *Aureobasidium pullulans* is recognized for its ability to synthesize pullulan and curdlan, two widely studied fungal polysaccharides. Fungal EPS are typically branched heteropolysaccharides with molecular weights ranging from 10^5 to 10^7 Da, resulting in enhanced gelling, stabilizing, and bioactive properties. The

distinctive physicochemical properties of fungal EPS contribute to their extensive use in industrial applications. Certain fungal EPS exhibit strong gelation, particularly in the presence of metal ions, which makes them suitable for thickening applications and gives them high gelling capacity. Fungal EPS can also be applied as edible films and coatings, extending the shelf life of food products. These polysaccharides maintain their functionality across a wide range of environmental conditions. Their thermal and pH stability makes them more resilient during food processing [11]. Fungal EPS also possess bioactive properties, contributing to their application in functional foods and pharmaceuticals. Certain fungal EPS exhibit free radical scavenging properties, reducing oxidative stress and lipid peroxidation. Additionally, studies suggest that EPS such as curdlan have anti-tumor activity, highlighting their potential in biomedical applications. Last but not least, fungal EPS have been linked to improved blood pressure and cholesterol regulation, contributing to overall metabolic health.

7. EPS Production by Algal Species

Algae, particularly red and green microalgae, as well as cyanobacteria, are noteworthy producers of EPS with unique high-molecular-weight structures. Notable algal EPS include alginate and carrageenan, which are commonly applied in the food and pharmaceutical industries. The molecular weight of algal EPS can range from 10^6 to 10^8 Daltons, making them highly effective in applications requiring high viscosity and gel stability. Algal EPS possess distinct physicochemical characteristics that contribute to their functional versatility. These polysaccharides form stable gels, even at low concentrations, making them valuable in food hydrocolloid applications. They also serve as natural emulsifiers and viscosity modifiers, particularly in plant-based and dairy-free formulations and unlike many microbial polysaccharides, algal EPS exhibit high thermal and pH resistance, ensuring stability in various processing environments. In addition to their technical functions, algal EPS offer significant biological benefits. Certain algal polysaccharides enhance immune responses, contributing to overall health and disease prevention. They have also been linked to reductions in both systemic and localized inflammation, making them valuable in functional food formulations. Moreover, some EPS produced by algae exhibit metal-binding properties, enabling them to adsorb and remove heavy metals and environmental toxins, thus contributing to ecological sustainability [11].

8. Steps of EPS Biosynthesis

8.1. Synthesis of Monosaccharide Units

The initial stage of EPS production involves the synthesis of fundamental monosaccharides, which serve as the building blocks of polysaccharides. This process occurs through cen-

tral metabolic pathways, including glycolysis and the pentose-phosphate pathway, where precursors such as glucose-1-phosphate and fructose-6-phosphate are generated. These intermediates are essential for subsequent activation and polymerization processes [1, 11].

8.2. Activation of Monosaccharides

Before polymerization can occur, the monosaccharide units must be transformed into their activated forms, such as uridine diphosphate-glucose (UDP-glucose) and guanosine diphosphate-mannose (GDP-mannose). This activation is catalyzed by specific enzymes that facilitate the formation of high-energy sugar nucleotides, which serve as substrates for polymerization [9].

8.3. Synthesis of Repeating Units

Following activation, individual monosaccharide units are enzymatically assembled into oligosaccharide repeating units by glycosyltransferase enzymes, which are situated in the cytoplasmic membrane. These repeating units vary in composition depending on the type of EPS being synthesized, influencing their functional properties and industrial applications.

8.4. Transfer of Repeating Units to the Cell Surface

Once synthesized, the repeating oligosaccharide units are transported to the cell surface by specialized transporter proteins. The transport mechanism is primarily governed by two distinct pathways:

8.4.1. Wzx/Wzy-Dependent Pathway

In this mechanism, repeating units are translocated across the cytoplasmic membrane and subsequently polymerized on the cell surface.

8.4.2. ATP-Binding Cassette (ABC) Transporter Pathway

This system directly transports fully synthesized polymeric chains from the cytoplasm to the extracellular environment.

8.5. Polymerization and Secretion

The final stage of EPS production involves polymerization of the repeating units into high-molecular-weight polysaccharides, followed by secretion into the extracellular space. The polymerization process is mediated by specific enzymes that regulate the chain length, branching, and overall structural characteristics of the polysaccharide. This step is critical for determining the functional properties of the EPS, such as viscosity, gelation capacity, and bioactivity [11].

9. Major EPS Production Pathways in Bacteria

Bacterial EPS biosynthesis occurs via three primary pathways: Wzx/Wzy-dependent pathway, ABC transporter pathway, and the synthase pathway (Figure 10). These pathways differ in their transport mechanisms and enzymatic processes, influencing the structural diversity of the EPS produced [6, 11].

9.1. Wzx/Wzy-Dependent Pathway

The Wzx/Wzy-dependent pathway is commonly found in Gram-positive bacteria and is primarily responsible for the production of heteropolysaccharides (HePS) such as gellan. This pathway consists of three major steps:

- 1) Synthesis: The repeating units of EPS are first synthesized in the cytoplasm through the action of glycosyl-transferase enzymes.
- 2) Transport: These units are translocated across the inner membrane to the periplasmic space by the Wzx protein system.
- 3) Polymerization and Secretion: Polymerization occurs at the cell surface through the activity of Wzy proteins, resulting in the extracellular accumulation of EPS.

Some noteworthy key features in this pathway are the facts that it requires sequential translocation and polymerization steps and allows for structural diversity due to variations in sugar composition.

9.2. ATP-Binding Cassette (ABC) Transporter Pathway

The ABC transporter pathway is predominant in Gram-negative bacteria and is primarily responsible for the

synthesis of capsular polysaccharides (CPS) and certain EPS such as xanthan. This pathway is characterized by:

- 1) Direct Transport: Unlike the Wzx/Wzy pathway, fully polymerized EPS are directly transported from the cytoplasm to the extracellular environment via ABC transporter proteins.
- 2) Polymerization: The polymerization process occurs within the cytoplasm, before export.

Some key features considering this pathway is its efficient transport mechanism and the fact that it's suitable for the production of structurally uniform EPS. ABC method is generally observed in xanthan biosynthesis, contributing to its role as a stabilizer in industrial applications.

9.3. Synthase Pathway

The synthase pathway is unique in that both EPS synthesis and polymerization occur directly at the cell membrane. This pathway is primarily observed in Gram-negative bacteria and is responsible for the production of homopolysaccharides (HoPS), such as dextran, curdlan, cellulose, and alginate. Some key steps in this pathway are:

- 1) Direct Polymerization: Unlike other pathways, the polymerization of sugar units occurs simultaneously with synthesis at the cell membrane, eliminating the need for intermediate transport steps.
- 2) Extracellular Secretion: Once synthesized, the EPS is secreted into the surrounding medium for immediate functionality.

The synthase pathway enables high-speed EPS production, making it industrially efficient. This pathway is primarily associated with the biosynthesis of homopolysaccharides and is common in dextran-producing LAB strains, which are widely used in the food industry [6, 11].

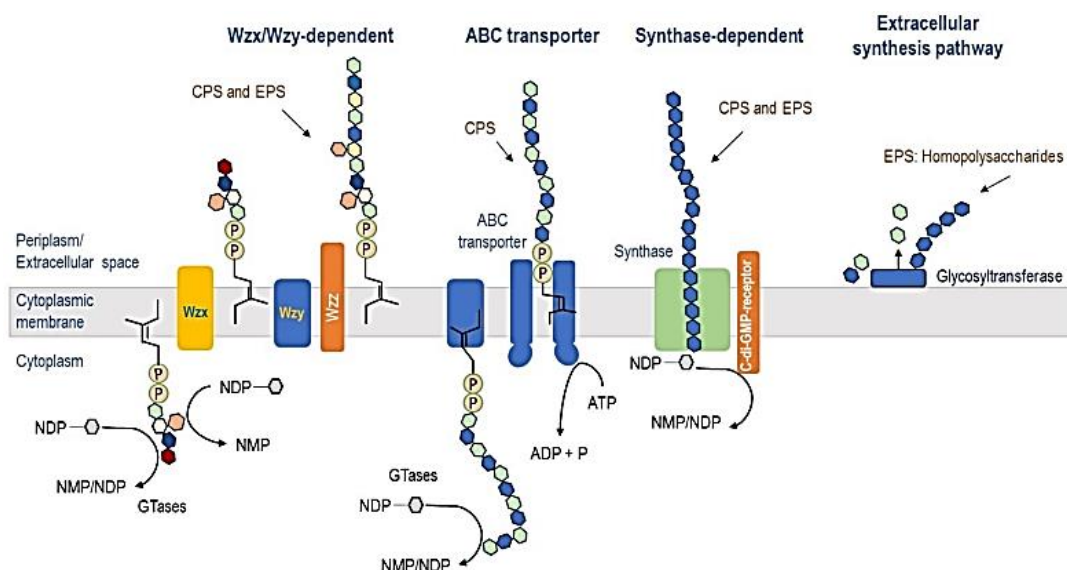


Figure 10. Biosynthesis of polysaccharides in microorganisms.

10. Impact of EPS on Cereal-based Beverages

Cereal-based beverages, derived from grains such as barley, wheat, corn, quinoa, and rice, are nowadays gaining popularity due to their nutritional value and potential as non-dairy alternatives. The incorporation of EPS in these beverages enhances viscosity, stability, and overall sensory quality, making them more appealing to consumers [9, 16].

10.1. Enhancement of Rheological Properties

EPS contribute to increased viscosity and improved texture, ensuring a more uniform and pleasing mouthfeel. This characteristic is particularly beneficial for diluted beverages or formulations that lack natural viscosity due to processing techniques.

10.2. Phase Stabilization

Beverages containing suspended solids, proteins, or fiber components often experience phase separation over time. EPS functions as a natural stabilizer, preventing the settling of insoluble particles and maintaining product homogeneity.

10.3. Reduction of Artificial Additives

Consumer demand for "clean label" products those free from synthetic additives is increasing. EPS serves as natural thickeners and stabilizers, reducing reliance on artificial emulsifiers and aligning with industry trends toward minimally processed ingredients.

10.4. Improved Stability in Fermented Cereal-based Beverages

In fermented cereal-based products, EPS helps prevent syneresis (water separation) and enhance texture uniformity, particularly in oat- and quinoa-based formulations that mimic dairy yogurt alternatives [9, 17].

10.5. Application of EPS in Specific Cereal-based Beverages

- 1) Oat-Based Beverages: The incorporation of *Lactopantibacillus plantarum*-derived EPS enhances viscosity and improves product stability.
- 2) Quinoa-Based Beverages: EPS from *Weissella confusa* contributes to improved consistency and reduced water separation, making these high-protein beverages more structurally stable.
- 3) Rice-Based Beverages: EPS improves the texture and sensory attributes of rice-based beverages, enabling the production of yogurt-like plant-based alternatives with

enhanced mouthfeel and stability.

11. Role of EPS in Bread and Baked Products

EPS play a crucial role in bread and baked product formulations, where they influence dough rheology, texture, and shelf life. Dextran, produced by lactic acid bacteria (LAB) such as *Weissella* and *Leuconostoc mesenteroides*, enhances dough elasticity and increases loaf volume. EPS also contribute to crumb softness and ensures a uniform air cell distribution in the final baked product and help retain moisture, thereby delaying the staling process and extending product shelf-life. This effect is particularly beneficial for whole-grain and gluten-free breads, which have a higher tendency to dry out rapidly. In gluten-free formulations, EPS serve as a structural enhancer, compensating for the absence of gluten by improving elasticity, loaf volume, and softness. Dextran and other EPS create a more cohesive dough matrix, resulting in higher-quality gluten-free baked goods and generally contribute to moisture retention and texture enhancement, reducing cracking and improving shelf life. EPS also stabilize semi-prepared doughs, ensuring quality retention after freezing and thawing. Their presence help prevent syneresis, maintaining product integrity over time. Last but not least, dextran and other EPS act as prebiotic compounds, promoting gut microbiome health and enhancing the nutritional profile of cereal-based products [2, 17].

12. Challenges in EPS Production

Despite the significant industrial potential of EPS, their large-scale production presents several technical and economic challenges. These limitations include high production costs, low microbial yields, structural complexity, and competitive market conditions. Addressing these challenges is essential for making EPS a viable alternative to synthetic polymers in various industries.

12.1. High Production Costs at an Industrial Scale

The commercial-scale production of EPS requires precisely controlled fermentation conditions and high-purity nutrient sources such as sucrose or glucose, leading to increased operational expenses. The cost of carbon sources, which constitute a major component of microbial growth media, remains one of the primary economic barriers to large-scale EPS manufacturing.

12.2. Low Yields in Certain Microbial Strains

Many naturally occurring EPS-producing microorganisms

exhibit low polysaccharide productivity, limiting their industrial viability. The efficiency of microbial EPS synthesis is influenced by strain-specific metabolic pathways, carbon source utilization rates, and environmental conditions. Therefore, optimizing microbial strains through metabolic engineering and adaptive evolution is necessary to improve yields [14, 15].

12.3. Structural Diversity and Regulatory Complexity

EPS exhibit significant structural heterogeneity, which makes it difficult to predict their application, tailor it for specific industrial usages, and standardize their functional properties.

12.4. Complex and Costly Purification Processes

The downstream extraction and purification of EPS involve multiple processing steps, including:

- 1) Precipitation and centrifugation to remove microbial biomass.
- 2) Filtration and ultrafiltration to isolate high-purity polysaccharides.
- 3) Chromatographic separation to refine the final product.

These processes are time-consuming, labor-intensive, and expensive, making large-scale production financially challenging.

12.5. Sensitivity to Environmental Conditions

EPS biosynthesis is highly dependent on external factors, such as:

- 1) Temperature fluctuations, which affect microbial enzymatic activity.
- 2) pH variations, which influence polysaccharide yield and molecular composition.
- 3) Nutrient availability, which regulates EPS production rates.

Maintaining consistent fermentation conditions at an industrial scale remains a significant challenge, requiring precise bioprocess optimization strategies.

12.6. Competition with Synthetic Polymers

Despite their biodegradability and functional benefits, EPS must compete with synthetic polymers, which are often:

- 1) Lower in production cost, due to established manufacturing processes.
- 2) Highly customizable, offering predictable and uniform properties.
- 3) Widely available, making them the preferred choice for many industries.

To establish EPS as a viable alternative, improvements in cost-efficiency, functionality, and scalability are necessary.

13. Opportunities for EPS Development and Application

While microbial EPS face production challenges, emerging research and technological advancements present significant opportunities to expand their use in food, pharmaceutical, environmental, and biomedical industries.

13.1. Utilization of Low-cost Resources and Waste-derived Substrates

One of the most promising cost-reduction strategies is the use of alternative carbon sources, including:

- 1) Agricultural residues, such as wheat straw and corn stover.
- 2) Food industry byproducts, such as molasses and dairy whey.
- 3) Lignocellulosic biomass, which can be enzymatically converted into fermentable sugars.

These approaches lower production costs while promoting sustainable and circular bioeconomy models.

13.2. Genetic Engineering and Strain Optimization

Advancements in synthetic biology and metabolic engineering offer opportunities to enhance EPS yield and tailor their functional properties. Strategies include:

- 1) Gene editing techniques (e.g., CRISPR-Cas9) to improve biosynthetic pathways.
- 2) Strain selection and adaptive evolution to enhance microbial productivity.
- 3) Recombinant technology to introduce desirable traits in EPS-producing microorganisms.

By modifying bacterial metabolism, researchers can improve yield efficiency and functional diversity of EPS.

13.3. Expansion in Functional Food and Health-promoting Products

With increasing consumer demand for functional foods, EPS holds potential in:

- 1) Prebiotic formulations, supporting gut microbiota health.
- 2) Low-fat and sugar-replacement applications, improving the texture of reduced-calorie products.
- 3) Gluten-free bakery formulations, enhancing dough elasticity and structure.

These applications position EPS as valuable bioactive ingredients in the nutraceutical and health-oriented food sectors.

13.4. Natural Alternative to Synthetic Food Additives

The growing demand for clean-label and natural food in-

redients presents an opportunity for EPS as substitutes for synthetic stabilizers, emulsifiers, and thickeners. Their functional benefits in:

- 1) Dairy alternatives (e.g., oat and almond milk) for improved mouthfeel.
- 2) Bakery products to enhance moisture retention.
- 3) Fermented beverages to prevent phase separation.

EPS can provide manufacturers with natural solutions to improve food texture and stability.

13.5. Environmental Applications and Sustainability

As biodegradable and eco-friendly polymers, EPS offer innovative solutions in:

- 1) Biodegradable packaging materials, reducing plastic waste.
- 2) Heavy metal removal from wastewater, acting as bio-sorbents.
- 3) Soil stabilization and bioremediation, supporting sustainable agriculture.

These applications align with global sustainability goals and create new commercial pathways for EPS utilization.

13.6. Expanding Applications in Pharmaceuticals and Biomedicine

EPS possess antioxidant, antimicrobial, and immune-modulating properties, making them valuable in pharmaceutical and biomedical sectors, including:

- 1) Drug delivery systems, where EPS functions as bio-compatible carriers.
- 2) Wound healing applications, leveraging their gel-forming and moisture-retention properties.
- 3) Tissue engineering, where EPS-based hydrogels support cell adhesion and regeneration.

Such applications demonstrate the multifunctionality of EPS beyond traditional food uses.

14. Functional Roles of EPS

EPS serve as non-digestible fibers, undergoing fermentation by gut microbiota to produce short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate, which support intestinal health. EPS also selectively promote the growth of beneficial probiotic strains (*Bifidobacterium*, *Lactobacillus*), while inhibiting harmful bacteria (*Clostridia*). Their ability to enhance probiotic adhesion strengthens gut barrier function [3]. Certain EPS possess immunomodulatory properties, reducing systemic and localized inflammation. Some have been identified for anti-mutagenic and anti-tumor effects [9]. EPS directly bind to cholesterol molecules, facilitating their excretion. Additionally, they stimulate the production of bile salt-degrading enzymes, which contribute to lower blood cholesterol levels. Many EPS function as anti-

oxidants, neutralizing free radicals and reducing lipid peroxidation, thus protecting against oxidative stress. Moreover, certain EPS exhibit direct antimicrobial activity, disrupting pathogenic bacterial membranes and inhibiting viral replication, making them potential candidates for natural antimicrobial agents [11, 13, 16].

15. Conclusion

Microbial EPS hold great promise across various industries thanks to their biodegradability, unique functional properties, and health advantages. However, large-scale commercialization faces challenges such as high production costs, complex purification processes, and competition with synthetic polymers. To fully realize their potential, advancements in strain engineering, fermentation optimization, and cost-effective bioprocessing are essential. Despite these challenges, the global rising demand for sustainable and natural ingredients presents significant opportunities for EPS expansion in food, pharmaceutical, and environmental applications. The use of low-cost substrates, genetic modifications, and novel bioprocessing technologies will be instrumental in overcoming current limitations. By harnessing these advancements, EPS can play a crucial role in sustainable development, functional food innovation, and environmentally friendly material production. As industries move toward eco-conscious solutions, microbial EPS are poised to become key components in next-generation bio-based technologies.

Abbreviations

EPS	Exopolysaccharides
HMW	High-Molecular-Weight
LAB	Lactic Acid Bacteria
BP	Biosynthetic Pathways
HPP	High-Purity Polysaccharides
CBB	Cereal-Based Beverages
SCFAs	Short-Chain Fatty Acids
GFB	Gluten-Free Bakery
HPLC	High-Performance Liquid Chromatography
Lpb	<i>Lactopantibacillus plantarum</i>
GC	Gas Chromatography
GDP-mannose	Guanosine Diphosphate-mannose
UDP-glucose	Uridine Diphosphate-glucose

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

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Fatemeh Jalili: Food Technology.

Fatemeh Abbaszadeh: Gluten free bread and cake, Pickering emulsion, Solid colloidal particle-stabilized emulsions.