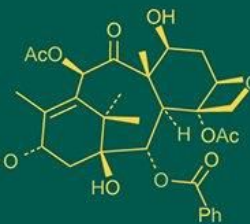
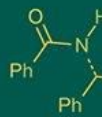


## International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693  
ISSN Online: 2617-4707  
NAAS Rating (2026): 5.29  
IJABR 2026; SP-10(4): 344-357  
[www.biochemjournal.com](http://www.biochemjournal.com)  
Received: 06-01-2026  
Accepted: 09-02-2026

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## Microbial exopolysaccharides as sustainable biopolymers: Production, functional roles, and agricultural significance

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i4Sd.8124>

### Abstract

Microbial Exopolysaccharides (EPS) are structurally diverse biopolymers increasingly recognized as sustainable alternatives to synthetic materials and as key functional mediators in agroecosystems. Beyond their industrial relevance, EPS play critical roles in microbial ecology and plant-microbe interactions, particularly under climate-induced environmental stress. Growing evidence indicates that EPS-producing microorganisms enhance soil aggregation, improve water retention, regulate nutrient dynamics, and stabilize the rhizosphere, thereby promoting plant resilience to drought, salinity, and metal toxicity. This review synthesizes current knowledge on the production, functional roles, and agricultural significance of microbial EPS as sustainable biopolymers. Key aspects of biosynthesis, fermentative optimization, and cost-effective production using agro-industrial substrates are discussed. EPS functional properties and applications are highlighted across industrial, environmental, and biomedical sectors, including emerging roles of probiotic-derived EPS as prebiotic compounds that support beneficial microbiota. Particular emphasis is placed on agricultural applications, including EPS-based biostimulants, bioformulations, and stress-mitigation strategies aimed at enhancing plant growth and resilience. Overall, microbial EPS represent promising biofunctional agents for sustainable and climate-resilient agricultural systems.

**Keywords:** Exopolysaccharides (EPS), biopolymers, biosynthesis, climate resilient, sustainable agriculture

### Introduction

The widespread use of synthetic polymers has resulted in severe environmental consequences, including microplastic accumulation, soil degradation, and ecosystem disruption (Roa *et al.*, 2021) [98]. Due to their high durability and resistance to biodegradation, these materials persist in natural environments, posing long-term ecological risks (Sivakami *et al.*, 2013) [116]. Consequently, there is an urgent need to develop sustainable alternatives that are biodegradable, renewable, and environmentally compatible. In this context, microbial Exopolysaccharides (EPS) have emerged as promising biopolymers capable of addressing these challenges (Fig. 1). The study of bacterial EPS dates back to the mid-19th century, when a viscous polysaccharide was first observed in wine and subsequently identified as dextran, with *Leuconostoc mesenteroides* recognized as the producing organism (Rehm, 2010) [97]. This discovery marked the beginning of extensive research into microbial polysaccharides, leading to the identification of several other EPS such as cellulose, alginate, and xanthan. These advancements significantly contributed to understanding microbial biosynthetic pathways and their industrial relevance. In recent years, EPS have gained considerable attention due to their structural diversity, functional versatility, and wide-ranging applications (Tiwari *et al.*, 2020; Bagnol *et al.*, 2022) [16, 122]. Microbial EPS are high-molecular-weight extracellular carbohydrate polymers secreted into the surrounding environment by a diverse group of microorganisms, including bacteria, fungi, yeast, and microalgae. Structurally, they exhibit remarkable heterogeneity, consisting of monosaccharides such as glucose, galactose, mannose, and rhamnose, along with non-carbohydrate substituents including acetyl, pyruvate, and sulfate groups (Whitfield *et al.*,

2015; Oleńska *et al.*, 2021; Wang *et al.*, 2023) [85, 128, 130]. This compositional complexity underpins their diverse physicochemical and biological properties, such as rheological behaviour, water retention capacity, metal-binding ability, and bioactivity, making them suitable for applications across food, pharmaceutical, and environmental sectors.

In natural ecosystems, EPS play a central role in microbial survival and ecological interactions. They are key components of the biofilm matrix, providing structural stability, facilitating cell-to-cell communication, and protecting microbial communities from environmental stresses such as desiccation, osmotic pressure, and toxic compounds (Karygianni *et al.*, 2020; Costa *et al.*, 2018) [24, 60]. In soil environments, EPS contribute significantly to soil aggregation, improve water retention, and enhance nutrient availability, thereby influencing soil fertility and plant productivity (Bhagat *et al.*, 2021) [18]. These ecological functions position EPS as critical mediators of soil-plant-microbe interactions.

Recent studies emphasize the importance of EPS in sustainable agriculture, particularly in addressing the impacts of climate change. Abiotic stresses such as drought, salinity, and heavy metal contamination continue to limit crop productivity worldwide (Muhammad *et al.*, 2024; Tripathi *et al.*, 2025) [73, 124]. EPS-producing microorganisms can mitigate these stresses by modifying the rhizosphere microenvironment, enhancing soil structure, improving moisture retention, and facilitating plant-microbe interactions that promote stress tolerance (Gantait *et al.*, 2026; Singh and Shivashankar, 2026) [44, 115]. Furthermore, the global transition toward a circular bioeconomy has

intensified interest in EPS as eco-friendly substitutes for petroleum-derived polymers (Liu *et al.*, 2025; Singh *et al.*, 2026) [68, 69, 144]. Their inherent biodegradability, biocompatibility, and non-toxicity, combined with their functional adaptability, position EPS as high-value biomaterials for diverse industrial applications, including bioremediation, drug delivery, and food stabilization (Nguyen *et al.*, 2024; Iqbal *et al.*, 2025) [57, 81].

Despite significant progress, key gaps remain in the understanding and application of microbial Exopolysaccharides (EPSs), particularly regarding the molecular mechanisms governing their biosynthesis and regulation under diverse environmental conditions, especially in complex systems such as the rhizosphere (Deo *et al.*, 2025) [30]. Limited knowledge of structure function relationships further constrains the ability to link compositional variations with ecological roles and stress mitigation potential (Silva and Lambers, 2021) [113]. In addition, challenges related to large-scale production, cost effectiveness, and yield consistency hinder their broader industrial and agricultural adoption, while interactions between EPSs, plant systems, and the rhizosphere microbiome remain insufficiently explored. In this context, the present review provides an integrative perspective by combining insights from microbial physiology, structural characterization, and applied biotechnology, summarizing recent advances in EPS production, functional properties, and applications, with particular emphasis on their relevance in sustainable and climate-resilient agriculture, and highlighting key challenges and future directions to support the development of EPS-based solutions within a sustainable bioeconomy framework.

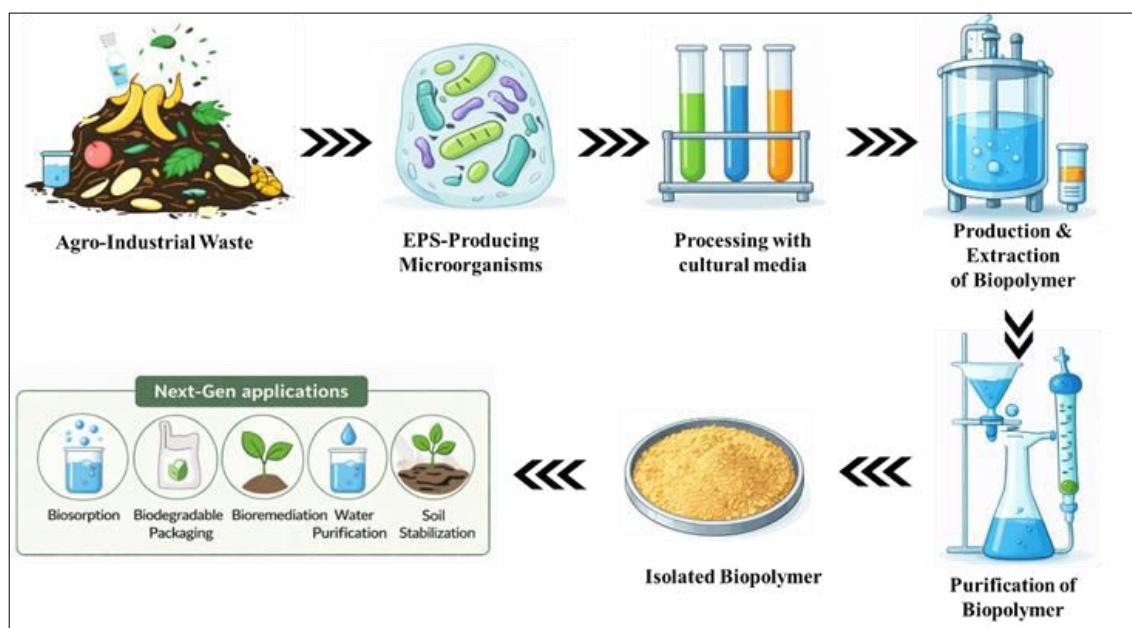


**Fig 1:** Microbial Exopolysaccharide (EPS) production from agro-industrial waste and emergent applications

### Microbial Exopolysaccharides: Chemical Structure, Composition, and Types

Exopolysaccharides (EPSs) are structurally diverse biopolymers synthesized by a wide range of microorganisms, including bacteria, fungi, yeasts, and microalgae (Álvarez *et al.*, 2021; Netrusov *et al.*, 2023) [5, 80]. In addition to microbial EPSs, naturally occurring polysaccharides such as chitin and chitosan, primarily derived from arthropod exoskeletons and fungal cell walls, have gained considerable attention due to their

biocompatibility, biodegradability, and ability to form fibres, films, and membranes (Salimi and Farrokh, 2023) [108]. However, unlike chitin and chitosan, which are largely obtained from marine biomass, EPSs are actively synthesized and secreted by microorganisms in response to environmental stresses such as fluctuations in temperature, salinity, pH, and exposure to chemical agents or radiation. This dynamic mode of production enables EPSs to function directly within biological systems, particularly in the rhizosphere, where they play integral roles in plant-microbe

interactions. In contrast, marine polysaccharides like chitosan primarily act as external amendments or elicitors rather than as active participants in these interactions (Nawaz *et al.*, 2022) <sup>[79]</sup>. Consequently, while chitin and chitosan have been widely explored for applications in biomedical, food, cosmetic, and pharmaceutical industries (Ahuja *et al.*, 2023; Kumari *et al.*, 2023; Younes and Rinaudo, 2015) <sup>[1, 64, 139]</sup>, EPSs offer distinct advantages in ecological and agricultural contexts due to them in situ production and functional adaptability. The structural and compositional diversity of microbial Exopolysaccharides (EPS) underpins their wide-ranging functional properties and applications. Detailed characterization using advanced analytical techniques has revealed that EPS variability arises from differences in monosaccharide composition, molecular weight, glycosidic linkages, functional group substitution, and branching

architecture (Amiri *et al.*, 2019; Schmid *et al.*, 2015) <sup>[8, 109]</sup>. These parameters collectively define EPS classification and functionality in table 1. Based on monomeric composition, EPS are broadly categorized into Homopolysaccharides (HoPS) and Heteropolysaccharides (HePS) (Dong *et al.*, 2025; Nguyen *et al.*, 2024) <sup>[33, 81]</sup>. HoPS are composed of a single monosaccharide unit typically glucose or fructose—and include polymers such as dextran, levan, curdlan, and bacterial cellulose (Razzak *et al.*, 2026; Nabot *et al.*, 2022) <sup>[75, 96]</sup>. In contrast, HePS exhibit greater structural complexity, consisting of repeating units of multiple monosaccharides (e.g., D-glucose, D-galactose, L-rhamnose) often decorated with non-carbohydrate substituents such as acetate, pyruvate, succinate, and phosphate groups (Mouro *et al.*, 2024; Razzak *et al.*, 2026) <sup>[72, 96]</sup>.

**Table 1:** Classification of microbial exopolysaccharides based on structure, composition, and localization

| Category based on | Type                         | Monosaccharide Composition                                            | Structural Features                                   | Examples                           | Producing Microorganisms                                                             | References                                                                                                                             |
|-------------------|------------------------------|-----------------------------------------------------------------------|-------------------------------------------------------|------------------------------------|--------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Composition       | Homopolysaccharides (HoPS)   | Single monosaccharide (glucose, fructose)                             | Linear or slightly branched; simple repeating units   | Dextran, Levan, Curdlan, Cellulose | <i>Leuconostoc</i> , <i>Bacillus</i> , <i>Komagataeibacter</i>                       | De Vuyst and Degeest (1999) <sup>[29]</sup> ; Razzak <i>et al.</i> (2026) <sup>[96]</sup> ; Nwodo <i>et al.</i> (2012) <sup>[84]</sup> |
|                   | Heteropolysaccharides (HePS) | Multiple sugars (glucose, galactose, rhamnose, mannose, uronic acids) | Branched; complex repeating units; substituted groups | Xanthan, Alginate, Gellan, Kefiran | <i>Xanthomonas</i> , <i>Pseudomonas</i> , <i>Sphingomonas</i> , <i>Lactobacillus</i> | Sutherland (2001) <sup>[119]</sup> ; Freitas <i>et al.</i> (2011) <sup>[41, 43]</sup> ; Mouro <i>et al.</i> (2024) <sup>[72]</sup>     |
| Localization      | Capsular EPS                 | Variable (HoPS/HePS)                                                  | Tightly bound to cell; dense protective layer         | Capsule polysaccharides            | <i>Streptococcus</i> , <i>Klebsiella</i>                                             | Angelin and Kavitha, 2020 <sup>[11]</sup>                                                                                              |
|                   | Secreted (Slime) EPS         | Variable (HoPS/HePS)                                                  | Loosely attached; forms biofilm matrix                | Alginate, Xanthan                  | <i>Pseudomonas</i> , <i>Xanthomonas</i>                                              | Flemming and Wingender (2010); Costa <i>et al.</i> (2018) <sup>[24, 39]</sup>                                                          |
| Charge            | Neutral EPS                  | Neutral sugars                                                        | Non-ionic; stable viscosity                           | Dextran                            | <i>Leuconostoc</i>                                                                   | De Vuyst and Degeest (1999) <sup>[29]</sup> ; Patel <i>et al.</i> (2012) <sup>[87]</sup>                                               |
|                   | Anionic EPS                  | Uronic acids, sulfates, phosphates                                    | Charged; metal binding, gel formation                 | Alginate, Xanthan                  | <i>Pseudomonas</i> , <i>Xanthomonas</i>                                              | Sutherland (2001) <sup>[119]</sup> ; Freitas <i>et al.</i> (2011) <sup>[41, 43]</sup>                                                  |
| Structure         | Linear EPS                   | Repeating units without branches                                      | Straight chains; high crystallinity                   | Cellulose                          | <i>Komagataeibacter xylinus</i>                                                      | Ross <i>et al.</i> (1991) <sup>[102]</sup> ; Klemm <i>et al.</i> (2012) <sup>[62]</sup>                                                |
|                   | Branched EPS                 | Side chains present                                                   | Complex; high viscosity and stability                 | Xanthan, Gellan                    | <i>Xanthomonas</i> , <i>Sphingomonas</i>                                             | Sutherland (2001) <sup>[119]</sup> ; Freitas <i>et al.</i> (2011) <sup>[41, 43]</sup>                                                  |

Structural diversity is further governed by glycosidic linkage patterns and polymer architecture. Variations in linkage type and configuration (e.g.,  $\alpha$ -(1→6),  $\alpha$ -(1→3),  $\beta$ -(1→4)) influence chain conformation and rheological behaviour. For instance, dextran is characterized by  $\alpha$ -(1→6)-linked backbones with variable  $\alpha$ -(1→3) branching, contributing to its high solubility, whereas bacterial

cellulose, a linear  $\beta$ -(1→4)-D-glucan, exhibits exceptional mechanical strength and crystallinity (Li *et al.*, 2020; Ye *et al.*, 2021) <sup>[65, 136]</sup>. Molecular weight, typically ranging from 10<sup>5</sup> to 10<sup>7</sup> Da, further modulates viscosity, gelation, and stability, with representative EPS types and their structural characteristics summarized in table 2.

**Table 2:** Structural Characteristics of Microbial Exopolysaccharides

| Polymer     | Monosaccharide Components         | Non-Sugar Substituents | Linkage Type                              | Molecular Weight (Da)               |
|-------------|-----------------------------------|------------------------|-------------------------------------------|-------------------------------------|
| Xanthan gum | Glucose, mannose, glucuronic acid | Pyruvate, acetate      | $\beta$ -(1→4) backbone with side chains  | $2.0 \times 10^6 - 5.0 \times 10^7$ |
| Dextran     | Glucose                           | —                      | $\alpha$ -(1→6), $\alpha$ -(1→3) branches | $10^3 - 10^7$                       |
| Alginate    | Guluronic acid, mannuronic acid   | Acetate                | $\beta$ -(1→4)                            | $0.3 \times 10^6 - 1.3 \times 10^6$ |

|                     |                                    |                    |                                  |                                     |
|---------------------|------------------------------------|--------------------|----------------------------------|-------------------------------------|
| Bacterial cellulose | Glucose                            | —                  | $\beta$ -(1→4)                   | $\sim 1 \times 10^6$                |
| Levan               | Fructose                           | —                  | $\beta$ -(2→6), $\beta$ -(2→1)   | $\sim 2 \times 10^6$                |
| Gellan              | Glucose, rhamnose, glucuronic acid | Glycerate, acetate | Linear tetrasaccharide repeat    | $5.2 \times 10^5$                   |
| Pullulan            | Glucose (maltotriose units)        | —                  | $\alpha$ -(1→4), $\alpha$ -(1→6) | $4.8 \times 10^4 - 2.2 \times 10^6$ |

Functional group substitution is a critical determinant of the physicochemical properties of microbial Exopolysaccharides (EPS), as the presence of uronic acids, sulfate, or phosphate groups imparts an anionic character that facilitates interactions with cations and enhances metal-binding capacity (Yaşar Yıldız and Radchenkova, 2023) [134]. Additionally, substituents such as pyruvate and succinate improve hydrophilicity and promote hydrogel formation even at low concentrations. EPS also exhibit considerable structural diversity, including uncommon configurations such as oligomeric repeats composed of identical monosaccharide units (e.g., pentameric galactose) and complex heteropolysaccharides containing three to eight different monosaccharide derivatives. Polymers such as kefiran, characterized by nearly equimolar proportions of glucose and galactose, further exemplify this variability (Tan *et al.*, 2020; Schmid *et al.*, 2015) [109, 120]. Overall, the hierarchical organization of EPS, from primary composition to higher-order structural arrangements, governs their functional versatility and supports their wide-ranging applications across industrial, environmental, and biomedical fields (Nadzir *et al.*, 2021; Yildiz *et al.*, 2018) [76, 138].

### Biosynthesis pathways and Genetic regulation

Microbial synthesis of Exopolysaccharides (EPSs) is a tightly regulated and energy-intensive process that proceeds through four major biosynthetic pathways, each distinguished by specific enzymatic systems and polymer translocation mechanisms. These include the Wzx/Wzy-dependent pathway, the ATP-binding cassette (ABC) transporter pathway, the synthase-dependent pathway, and extracellular synthesis mediated by a single glycosyltransferase (Zeidan *et al.*, 2017) [142]. Notably, a single microorganism may harbor multiple EPS biosynthetic pathways simultaneously, enabling the production of structurally diverse polysaccharides. A clear understanding of these pathways is crucial for metabolic engineering strategies aimed at enhancing EPS yield and tailoring their functional and structural properties.

Homopolysaccharides (HoPSs) are typically synthesized *via* extracellular enzymatic reactions catalyzed by specific glycosyltransferases or fructosyltransferases. In this mechanism, sucrose serves as the primary substrate, undergoing enzymatic hydrolysis followed by the transfer of glucosyl or fructosyl moieties to elongating polysaccharide chains or intermediate oligosaccharides (Donot *et al.*, 2012) [34]. Glycosyltransferases predominantly catalyze the formation of glucans such as dextran, mutan, alternan, and reuteran, whereas fructosyltransferases are responsible for fructan synthesis, including levan and inulin (Badel *et al.*, 2011) [15]. This pathway is energetically efficient as it bypasses intracellular nucleotide sugar intermediates and relies directly on sucrose as both donor and energy source.

In contrast, the Wzx/Wzy-dependent pathway represents a major route for the biosynthesis of structurally complex Heteropolysaccharides (HePSs), particularly in Gram-negative bacteria (Zeidan *et al.*, 2017) [142]. This process begins on the cytoplasmic side of the inner membrane,

where repeating oligosaccharide units are assembled on a lipid carrier, typically undecaprenyl phosphate (C55), through the sequential action of multiple glycosyltransferases. These enzymes utilize Nucleotide Diphosphate (NDP)-activated sugars derived from central metabolic intermediates such as glucose-6-phosphate and fructose-6-phosphate. Once the repeating unit is completed, it is translocated across the membrane by the Wzx flippase. Polymerization of these units occurs in the periplasm *via* the Wzy polymerase, resulting in high structural diversity due to variations in monosaccharide composition and linkage patterns. The mature polysaccharide is subsequently exported to the cell surface through a coordinated system involving Polysaccharide Co-Polymerase (PCP) and outer membrane polysaccharide export (OPX) proteins (Schmid *et al.*, 2015; Nanjani and Soni, 2012) [77, 109].

The ABC transporter-dependent pathway is primarily associated with the production of Capsular Polysaccharides (CPS), which remain attached to the cell surface. In this pathway, the entire polysaccharide chain is synthesized on the cytoplasmic face of the inner membrane before export (Nwodo *et al.*, 2012) [84]. Polymer assembly may involve either a single glycosyltransferase, yielding homopolymers, or multiple enzymes, resulting in heteropolymers. Unlike the Wzx/Wzy system, this pathway does not require periplasmic polymerization. Instead, the fully synthesized polymer is translocated across the cell envelope via a dedicated ATP-driven transport system comprising ABC transporters, along with accessory proteins from the PCP and OPX families. A notable structural feature of polysaccharides produced through this pathway is the presence of a conserved glycolipid moiety at the reducing end, often incorporating linkers such as 2-keto-3-deoxyoctulosonic acid (Kdo) (Poli *et al.*, 2010; Zhang *et al.*, 2011) [88, 143].

The synthase-dependent pathway represents a streamlined mechanism in which polymerization and translocation are carried out simultaneously by a single membrane-bound enzyme complex. This pathway is typically involved in the production of linear homopolysaccharides such as cellulose, curdlan, alginate, and hyaluronic acid. The synthase enzyme utilizes NDP-sugar precursors and extrudes the growing polymer chain directly across the membrane. Regulatory molecules, particularly cyclic di-GMP (c-di-GMP), play a crucial role in activating synthase activity and initiating polymer formation (Czacyk and Myszkowski, 2007; Yates *et al.*, 2018) [27, 135]. This mechanism is highly efficient and is commonly associated with microorganisms capable of producing large quantities of extracellular matrix components.

Across all intracellular biosynthetic pathways, EPS formation relies on nucleotide sugar precursors generated through central metabolic pathways. These precursors originate from glycolytic intermediates, including glucose-6-phosphate and fructose-6-phosphate, and are converted into activated sugar donors such as UDP-glucose, GDP-mannose, or dTDP-rhamnose through multistep enzymatic processes (Rehm, 2010; Andhare *et al.*, 2014) [9, 97]. The

availability and regulation of these precursors are critical determinants of EPS yield and structural composition.

The extracellular (sucrase-mediated) pathway constitutes a specialized mechanism for exopolysaccharide biosynthesis, wherein disaccharide substrates, predominantly sucrose, are enzymatically cleaved and simultaneously utilized for polymer assembly in the extracellular milieu. This process is catalyzed by cell-associated or secreted glycosucrases (e.g., glucansucrases and fructansucrases), which mediate the transfer of glucosyl or fructosyl residues from sucrose directly onto a growing polysaccharide chain. Unlike intracellular biosynthetic routes, this pathway is independent of nucleotide-activated sugar intermediates and central carbon metabolic flux, thereby bypassing the requirement for energy-intensive precursor synthesis. The catalytic mechanism involves a transglycosylation reaction, in which the cleavage of the glycosidic bond in sucrose generates a high-energy intermediate that is subsequently exploited for glycosyl transfer to an acceptor molecule, enabling chain elongation (Kumar *et al.*, 2011; Harutoshi, 2013; Mayer *et al.*, 2020) [52, 63, 71]. This results predominantly in the formation of structurally simpler homopolysaccharides, such as glucans or fructans, with comparatively limited compositional diversity but variable linkage patterns and molecular weights.

### Biotechnological production and Fermentative optimization

The biotechnological production of microbial Exopolysaccharides (EPSs) is achieved through controlled fermentation processes, where metabolic flux is strategically directed toward polymer synthesis. Although the genetic framework of a microorganism determines its intrinsic ability to produce EPS, the overall productivity, yield, and structural characteristics of the polymer are strongly influenced by fermentation conditions and process optimization strategies (Salimi and Farrokh, 2023; Freitas *et al.*, 2011; Suresh Kumar *et al.*, 2007) [41, 43, 108, 118]. Consequently, the integration of physiological, biochemical, and engineering approaches is essential for efficient large-scale EPS production.

A key principle in fermentative optimization is the establishment of nutrient imbalance, particularly the provision of excess carbon source in combination with the limitation of other essential nutrients such as nitrogen, phosphorus, or oxygen (Xiao *et al.*, 2024; Freitas *et al.*, 2014; Torres *et al.*, 2014) [42, 123, 131]. This imbalance shifts cellular metabolism away from biomass accumulation toward the synthesis of secondary metabolites, including EPSs. High carbon-to-nitrogen ratios are commonly employed to enhance polysaccharide production, as excess carbon is redirected into nucleotide sugar precursors required for polymer biosynthesis (Rath *et al.*, 2022) [95].

Oxygen transfer is another critical parameter that significantly affects EPS production. Most bacterial EPSs are synthesized under aerobic conditions, where sufficient oxygen availability supports energy generation and precursor synthesis. However, the oxygen requirement is highly strain-specific. For example, high aeration and agitation rates are essential for maximizing xanthan gum production by *Xanthomonas* spp., whereas reduced oxygen levels favour alginate synthesis in *Pseudomonas* spp. (García *et al.*, 2022; Yang *et al.*, 2025) [46, 133]. Such differences highlight the importance of optimizing dissolved

oxygen levels and bioreactor configurations to match the metabolic requirements of the producing organism.

Medium composition plays a crucial role in both microbial growth and EPS synthesis. In addition to carbon and nitrogen sources, supplementation with vitamins, amino acids, and metabolic precursors can enhance enzyme activity and stimulate biosynthetic pathways (Radchenkova *et al.*, 2014) [93]. These additives often function as cofactors or regulatory signals, leading to increased polymer yield in systems producing gellan, welan, bacterial cellulose, and curdlan. Furthermore, trace elements such as magnesium, calcium, and iron may influence enzyme stability and polymer assembly, thereby affecting overall productivity (Radchenkova and Yaşar Yıldız, 2025) [92].

While the fundamental carbohydrate backbone of most EPSs remains relatively conserved, fermentation conditions can significantly influence the degree and pattern of substitution with functional groups such as acetyl, pyruvyl, or succinyl residues (Ali *et al.*, 2020) [3]. These modifications directly impact the physicochemical and rheological properties of the polymer, including viscosity, solubility, and gel-forming ability. In certain microbes, such as *Rhizobium* and *Pseudomonas*, environmental conditions can even alter the monomer composition of the EPS, enabling the tailored production of polymers with desired functional attributes.

Another important aspect of fermentative optimization is the management of metabolic flux distribution. In many microorganisms, carbon substrates may be diverted toward the synthesis of intracellular storage compounds such as glycogen or Polyhydroxyalkanoates (PHAs), thereby reducing EPS yield (Poli *et al.*, 2011) [89]. Strategies to minimize such competing pathways either through strain selection or metabolic engineering are critical for improving process efficiency. Notably, *Xanthomonas* spp. exhibit minimal accumulation of storage polymers, allowing efficient conversion of substrate into xanthan gum and making them highly suitable for industrial applications (Rosalam and England, 2006) [101].

The kinetics of EPS production relative to microbial growth also plays a significant role in process design. EPS synthesis can be categorized as growth-associated, non-growth-associated, or partially growth-associated. Growth-associated production occurs during the exponential phase, as observed in gellan gum and bacterial cellulose synthesis, whereas non-growth-associated production occurs predominantly during the stationary phase, as in curdlan production (Zhou *et al.*, 2018) [144]. Many industrially relevant systems exhibit mixed kinetics, where EPS production initiates during active growth and continues even after growth deceleration, as seen in xanthan production by *Xanthomonas* spp. (Rosalam and England, 2006) [101]. Understanding these kinetic patterns is essential for optimizing fermentation time, feeding strategies, and reactor operation modes.

Substrate selection is a major determinant of both process economics and sustainability. Conventional fermentation processes utilize refined sugars such as glucose, sucrose, or fructose due to their high purity and predictable metabolic pathways. However, the high cost of these substrates has driven the exploration of alternative, low-cost carbon sources, including agro-industrial wastes and byproducts such as molasses, cheese whey, lignocellulosic hydrolysates, and crude glycerol from biodiesel production (Sharma *et al.*,

2022) <sup>[112]</sup>. These substrates have demonstrated significant potential for EPS production, including the synthesis of polymers such as GalactoPol and FucoPol, thereby contributing to cost reduction and waste valorization (Ranaei Siadat *et al.*, 2024) <sup>[94]</sup>.

Despite their advantages, the use of low-cost substrates presents several challenges. The variability in composition and presence of inhibitory compounds can lead to inconsistent fermentation performance and the activation of alternative metabolic pathways, resulting in the formation of undesired byproducts. Additionally, impurities may accumulate during fermentation and complicate downstream processing, particularly in applications requiring high product purity (Castillo *et al.*, 2015) <sup>[21]</sup>. Therefore, careful substrate pretreatment, process optimization, and efficient purification strategies are necessary to ensure consistent product quality.

Advancements in biotechnological tools, including metabolic engineering, systems biology, and process intensification, have further enhanced the efficiency of EPS production. Genetic modifications aimed at overexpressing key biosynthetic enzymes, eliminating competing pathways, and improving precursor availability have shown promising results in increasing yield and productivity (Dixon *et al.*, 1996) <sup>[32]</sup>. Similarly, optimization of bioreactor design, including fed-batch and continuous fermentation systems, has enabled better control over nutrient supply, oxygen transfer, and process scalability (Flevaris and Chatzidoukas, 2021) <sup>[40]</sup>. Overall, efficient EPS production requires an integrated approach combining microbial physiology, metabolic regulation, and bioprocess engineering. Advances in fermentation technology and metabolic engineering continue to enhance yield, reduce costs, and enable the production of tailor-made polysaccharides for diverse industrial applications.

### Analytical methodologies for characterization of exopolysaccharides

Comprehensive characterization of microbial Exopolysaccharides (EPSs) is essential for elucidating their

structure-function relationships and determining their suitability for diverse industrial and biomedical applications (Alves *et al.*, 2011) <sup>[6]</sup>. Analytical methodologies for EPS characterization encompass the evaluation of chemical composition, molecular structure, molecular weight distribution, and physicochemical behavior in solution.

The determination of chemical composition primarily involves the identification of constituent monosaccharides, repeating units, and functional substituents such as acetyl, pyruvyl, and phosphate groups (Nouara *et al.*, 2019) <sup>[83]</sup>. Conventional approaches based on acid hydrolysis followed by derivatization to alditol acetates and subsequent Gas Chromatography (GC) analysis have been widely used (Hallack *et al.*, 2010) <sup>[50]</sup>. However, more advanced techniques such as high-performance anion-exchange chromatography coupled with pulsed amperometric detection (HPAEC-PAD) enable direct carbohydrate analysis without derivatization, offering improved sensitivity and efficiency (Grünewald *et al.*, 2021; Arruda *et al.*, 2025) <sup>[12, 48]</sup>. Capillary electrophoresis has also emerged as a rapid and high-resolution method for monosaccharide profiling.

Structural characterization of EPSs is particularly challenging due to the diversity of monosaccharide linkages, branching patterns, and stereochemical configurations. Methylation analysis remains a standard technique for elucidating glycosidic linkage patterns, involving permethylation of hydroxyl groups followed by hydrolysis, reduction, and acetylation to generate partially methylated alditol acetates, which are subsequently analyzed by Gas Chromatography-Mass Spectrometry (GC-MS). Gas Chromatography-Mass Spectrometry (GC-MS) remains one of the most widely used and reliable techniques for determining monosaccharide composition. Due to the non-volatile nature of sugars, analysis requires a multistep derivatization procedure to convert monosaccharides into volatile derivatives, typically in the form of alditol acetates. This process involves sequential hydrolysis, reduction, and acetylation steps prior to chromatographic analysis table 3.

**Table 3:** Standard derivatization protocol for GC-MS-based monosaccharide analysis

| Step        | Process                           | Reagents                              | Conditions               |
|-------------|-----------------------------------|---------------------------------------|--------------------------|
| Hydrolysis  | Depolymerization                  | 2 M Trifluoroacetic Acid (TFA)        | 121 °C, 2-3 hours        |
| Reduction   | Conversion of aldoses to alditols | NaBH <sub>4</sub> or KBH <sub>4</sub> | Room Temperature, 1 hour |
| Acetylation | Formation of alditol acetates     | Acetic Anhydride, Pyridine            | 100 °C, 30-60 minutes    |
| Extraction  | Recovery of derivatives           | Chloroform/Water                      | Liquid-liquid extraction |

Recent advancements in derivatization techniques, particularly Trimethylsilyl-Dithioacetal (TMSD) methods, enable simultaneous detection of neutral sugars, uronic acids, and amino sugars with improved resolution. These approaches generate a single derivative peak per monosaccharide, significantly simplifying chromatographic interpretation and enhancing analytical throughput. Complementary methods such as Smith degradation and controlled hydrolysis (chemical or enzymatic) are employed to generate smaller oligosaccharide fragments for detailed structural analysis (Hallack *et al.*, 2010) <sup>[50]</sup>. These fragments can then be characterized using GC-MS, matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF-MS), and nuclear magnetic resonance (NMR) spectroscopy (Ali *et al.*, 2023; Ventorino *et al.*, 2019) <sup>[4, 126]</sup>. Advanced NMR techniques, including

two-dimensional methods such as COSY, TOCSY, NOESY, and HSQC, provide detailed insights into atomic connectivity, linkage positions, and spatial conformation (Liu *et al.*, 2025; Dutta *et al.*, 2023) <sup>[68, 69]</sup>. The determination of molecular weight and polydispersity is crucial for understanding EPS functionality and performance. High-Performance Size-Exclusion Chromatography (HPSEC), particularly when coupled with Multi-Angle Laser Light Scattering (MALLS), allows accurate estimation of absolute molecular weight and distribution profiles, offering significant advantages over conventional gel permeation chromatography (Sabaté, 2017) <sup>[103]</sup>.

Physicochemical characterization in solution provides critical information regarding polymer behavior under application-relevant conditions. Properties such as intrinsic

viscosity, hydrodynamic volume, molecular conformation, and critical overlap concentration are typically assessed using dilute solution viscometry (Nickerson *et al.*, 2008; Hilliou *et al.*, 2009) <sup>[53, 82]</sup>. The presence of ionizable groups often imparts polyelectrolyte behaviour, significantly influencing intermolecular interactions and solution dynamics (Ikeda *et al.*, 2019) <sup>[56]</sup>. Advanced techniques such as Atomic Force Microscopy (AFM) enable direct visualization of three-dimensional molecular architecture and aggregation phenomena, while rheological analyses are essential for evaluating viscosity, viscoelasticity, and gel-forming properties in concentrated systems (Yiasmin *et al.*, 2024; Ata *et al.*, 2025) <sup>[13, 137]</sup>. Overall, the integration of chromatographic, spectroscopic, and physicochemical techniques provides a comprehensive framework for EPS characterization, facilitating the correlation between molecular structure and functional performance, and enabling the rational design of tailored biopolymers for specific applications.

### Functional properties and applications

The functional behaviour of microbial Exopolysaccharides (EPSs) in aqueous systems is primarily determined by their molecular architecture, including chain conformation, branching, and the presence of functional substituents (Khan *et al.*, 2007) <sup>[61]</sup>. These structural features govern key physicochemical properties such as viscosity, gelation, and intermolecular interactions, which are critical for their industrial applicability. Representative polymers such as gellan and xanthan highlight the influence of molecular organization on functionality. Linear EPSs can undergo conformational transitions from disordered coils to ordered double-helical structures, leading to gel formation through intermolecular associations (Jindal and Khattar, 2018; Tiwari *et al.*, 2020) <sup>[58, 122]</sup>. In contrast, branched EPSs typically form highly viscous, shear-thinning solutions due to molecular entanglement, making them suitable as viscosity modifiers rather than gelling agents.

The functional properties of EPSs can be further enhanced through synergistic interactions with other biopolymers and through chemical modifications such as crosslinking or substitution, enabling the tailoring of mechanical strength, stability, and responsiveness to environmental conditions. Owing to these versatile properties, EPSs are widely used across food, pharmaceutical, and biomedical sectors as thickeners, stabilizers, emulsifiers, and structuring agents (Wao *et al.*, 2023; Amer *et al.*, 2025) <sup>[7, 129]</sup>. Additionally, their ability to form films, hydrogels, and encapsulation systems has enabled their application in drug delivery, tissue engineering, and controlled release systems (Bibi *et al.*, 2021; Coutinho *et al.*, 2010) <sup>[19, 20, 26]</sup>. Certain EPSs also exhibit intrinsic bioactivities, including antimicrobial and anti-inflammatory effects, further expanding their functional scope. Importantly, beyond these physicochemical and industrial roles, microbial EPSs also exhibit significant biological functions that contribute to human health and environmental sustainability, particularly through their roles in probiotic systems and agricultural applications.

### Probiotic derived exopolysaccharides

Exopolysaccharide (EPS)-producing probiotic bacteria are widely distributed across diverse ecological niches, including both dairy and non-dairy environments. Dairy-associated sources primarily include milk and fermented

dairy products, whereas non-dairy sources encompass fruits, vegetables, cereals, and a variety of traditionally fermented foods (Gao *et al.*, 2025) <sup>[45]</sup>. In addition, EPS-producing strains have also been isolated from animal-derived sources such as meat, fish, and gastrointestinal microbiota. A wide range of Lactic Acid Bacteria (LAB) have been identified as efficient EPS producers (Sakoui *et al.*, 2024; Xu, 2019) <sup>[106, 132]</sup>. For instance, *Lactobacillus plantarum* strains have been isolated from fermented plant-based foods such as pickled cabbage, kimchi, and traditional pickles, while *Lactobacillus helveticus* has been reported from fermented dairy products like kefir (Gustaw *et al.*, 2021; Fan and Hansen, 2012) <sup>[36, 49]</sup>. Similarly, *Lactobacillus delbrueckii* subsp. *bulgaricus* is commonly associated with yogurt fermentation (Hao *et al.*, 2011) <sup>[51]</sup>. Other notable EPS-producing bacteria include *Leuconostoc citreum* from fermented cheese products, as well as strains isolated from diverse sources such as camel milk, durian fruit pulp, and traditional fermented fish products (Bibi *et al.*, 2021) <sup>[19, 20]</sup>. Furthermore, species such as *Enterococcus faecium* and *Lactobacillus gasseri* have been identified from animal-associated environments, including fish gut and poultry systems (Suphoronski *et al.*, 2021; Sahoo *et al.*, 2015) <sup>[105, 117]</sup>.

### Prebiotic potential of bacterial exopolysaccharides

Prebiotics are non-digestible dietary components that resist degradation in the upper gastrointestinal tract and selectively stimulate the growth and metabolic activity of beneficial gut microbiota, thereby contributing to host health. Upon fermentation by intestinal microorganisms, these compounds generate Short-Chain Fatty Acids (SCFAs), which serve as an essential energy source for colon epithelial cells and play a key role in maintaining gut homeostasis (Fernández *et al.*, 2016) <sup>[37]</sup>.

Exopolysaccharides (EPSs) synthesized by probiotic bacteria have emerged as promising functional prebiotics due to their resistance to gastrointestinal digestion and selective utilization by beneficial microbes. Among probiotic groups, species belonging to *Lactobacillus* and *Bifidobacterium* are particularly significant, as many strains are capable of producing EPS with diverse health-promoting properties (Pourjafar *et al.*, 2023) <sup>[90]</sup>. Homoexopolysaccharides produced by Lactic Acid Bacteria (LAB) often exhibit structural features similar to conventional prebiotic carbohydrates, enabling their efficient fermentation in the gut (Harutoshi, 2013) <sup>[52]</sup>. For example, certain strains such as *Lactobacillus sanfranciscensis* produce fructan-type EPS with demonstrated prebiotic activity, while EPS derived from sourdough-associated bacteria, including levan-type polymers, have been shown to exert bifidogenic effects (Salazar *et al.*, 2016) <sup>[107]</sup>. These polymers can stimulate the growth of *Bifidobacterium* populations at levels comparable to established prebiotics such as inulin (Teferra, 2021) <sup>[121]</sup>. Additionally, dextran synthesized by LAB serves as a fermentable substrate for commensal bacteria, including *Lactobacillus* and *Bifidobacterium*, further supporting gut microbial balance (Turroni *et al.*, 2014) <sup>[125]</sup>. Similarly, levan, a soluble and non-digestible polysaccharide, is widely recognized for its prebiotic functionality (Chavan *et al.*, 2023) <sup>[22]</sup>. EPS produced by *Lactobacillus plantarum* has demonstrated notable prebiotic potential, characterized by selective enhancement of beneficial gut microbiota and

strong resistance to digestive processes (Wang *et al.*, 2018)<sup>[127]</sup>. These attributes ensure its effective delivery to the colon, where it can exert its functional role.

### Potential applications of exopolysaccharides in sustainable agriculture

Bacterial Exopolysaccharides (EPSs) have emerged as promising biopolymers for enhancing agricultural productivity, although their full potential is yet to be fully exploited. Structurally, EPS share similarities with industrially relevant polysaccharides such as alginates, which underpins their functional versatility (Saha *et al.*, 2020; Nguyen *et al.*, 2024)<sup>[81, 104]</sup>. In agricultural systems, EPS find applications in plant tissue culture, enzyme immobilization, and the formulation of artificial seeds (Hussain *et al.*, 2019)<sup>[54]</sup>. These polymers provide protective functions by reducing seed desiccation and shielding against microbial attack, while also influencing the uptake and mobility of antimicrobial compounds and toxic metals (Palza, 2015; Hussain *et al.*, 2019)<sup>[54, 86]</sup>. EPS play a critical role in improving soil physicochemical properties and promoting plant growth. Their high water-retention capacity and adhesive nature facilitate soil aggregation and stabilization, thereby enhancing soil structure (Costa *et al.*, 2018; Dar *et al.*, 2021)<sup>[24, 28]</sup>. Through biofilm formation in the rhizosphere, EPS regulate the availability and movement of water and nutrients, ultimately improving nutrient uptake efficiency and plant productivity (Naseem *et al.*, 2018)<sup>[78]</sup>. Additionally, EPS contribute to the protection of nitrogenase enzymes from oxygen-induced inactivation, thereby supporting biological nitrogen fixation and beneficial plant-microbe interactions.

Under abiotic stress conditions, EPSs serve as important protective agents for plants. They mitigate salt stress by limiting sodium (Na<sup>+</sup>) accumulation in plant tissues and enhance plant tolerance to drought and water deficit conditions (Bhagat *et al.*, 2021)<sup>[18]</sup>. EPS-producing Plant Growth-Promoting Rhizobacteria (PGPR) have been shown to improve plant growth, increase nitrogen assimilation, and enhance nodulation, particularly under stress environments (Alhoqail, 2026)<sup>[2]</sup>. Furthermore, EPS enhance root adhesion to soil particles, improve soil permeability, and maintain higher moisture levels in the rhizosphere, thereby sustaining plant water status during adverse conditions. A strong correlation has also been observed between EPS production and desiccation tolerance in certain rhizobial strains, such as *Bradyrhizobium* species associated with leguminous crops (Naseem *et al.*, 2018; Primo *et al.*, 2020; Roohi *et al.*, 2025)<sup>[78, 91, 100]</sup>. These findings highlight the potential of EPS-producing microorganisms in improving plant resilience to environmental stress. Overall, the incorporation of EPS-producing bacteria into agricultural systems represents a sustainable strategy for enhancing soil health, improving crop productivity, and supporting climate-resilient agriculture.

### Integration strategies of exopolysaccharides producing bacteria

The effective incorporation of EPS-producing bacteria into sustainable agricultural systems requires a combination of strategic approaches, including seed-based applications, development of microbial consortia, and scalable production methodologies. These strategies exploit the functional attributes of EPS, such as their ability to improve soil

structure, facilitate biofilm formation, and enhance plant tolerance to environmental stresses, thereby contributing to sustainable intensification of agriculture (Bhagat *et al.* 2021)<sup>[18]</sup>.

### Seed biopriming with exopolysaccharides producing PGPR consortia

Seed biopriming is a widely adopted technique that involves treating seeds with consortia of EPS-producing Plant Growth-Promoting Rhizobacteria (PGPR), typically including genera such as *Pseudomonas* and *Bacillus* (Deshmukh *et al.*, 2020)<sup>[31]</sup>. In this approach, seeds are immersed in a microbial suspension for a defined period, allowing efficient bacterial colonization and adhesion mediated by EPS. This process enhances seed germination, root development, and early seedling establishment. The application of EPS-producing PGPR through biopriming has been shown to significantly improve seedling vigour, particularly under abiotic stress conditions. The beneficial effects are attributed to improved microbial colonization, enhanced nutrient availability, and increased stress resilience. For instance, microbial consortia comprising species such as *Enterobacter aerogenes* and *Pseudomonas fluorescens* have demonstrated the potential to reduce nitrogen fertilizer inputs while simultaneously improving phosphorus solubilization, phytohormone production (e.g., indole-3-acetic acid), and drought tolerance in crops such as maize (Zahir *et al.*, 2012)<sup>[141]</sup>.

### Bacterial exopolysaccharides as biostimulants and industrial biopolymers

Polysaccharides are increasingly recognized as effective plant biostimulants owing to their eco-friendly nature, high water-binding capacity, and ability to interact with soil and plant systems. Although algal derived polysaccharides have traditionally been utilized for such purposes, their commercial application is often limited by low productivity and scalability constraints (Selvaraj *et al.*, 2025)<sup>[110]</sup>. In comparison, bacterial exopolysaccharides (EPSs) offer a more efficient and sustainable alternative, as they can be produced in higher yields under controlled fermentation conditions (Bibi *et al.*, 2021)<sup>[19, 20]</sup>. In addition to their role in agriculture, bacterial EPSs are well established in industrial applications, particularly within the food and healthcare sectors, where they serve as essential agents for thickening, emulsification, and gel formation (Mouro *et al.*, 2024)<sup>[72]</sup>. Furthermore, EPS synthesized by bacterial genera such as *Pseudomonas* and *Burkholderia* contribute to enhanced microbial adaptability by improving resistance to antibiotics and environmental stresses, thereby supporting microbial survival in harsh conditions (Ferreira *et al.*, 2010; Bhagat *et al.*, 2021)<sup>[18, 38]</sup>.

The production of EPS is highly dependent on environmental and operational parameters, including pH, temperature, oxygen levels, nutrient composition, and the carbon-to-nitrogen ratio (Babiak and Krzemińska, 2021)<sup>[14]</sup>. Careful optimization of these factors is crucial for achieving high productivity. However, the economic feasibility of large-scale EPS production remains a challenge, primarily due to the reliance on expensive substrates such as refined sugars (Mouro *et al.*, 2024)<sup>[72]</sup>. To address these limitations, alternative production strategies have been explored, including the use of mixed microbial cultures, which have demonstrated improved EPS yields and process robustness

compared to monocultures (Rodrigues *et al.*, 2024) <sup>[99]</sup>. These developments highlight the growing potential of bacterial EPSs as sustainable biopolymers with wide-ranging applications in both agricultural and industrial domains.

### **Sustainable production of exopolysaccharides using agro industrial wastes**

Agro-industrial residues have emerged as cost-effective and sustainable substrates for Exopolysaccharide (EPS) production, addressing both economic and environmental challenges. Generated in large quantities worldwide, these wastes serve as valuable feedstocks for microbial bioconversion, reducing production costs while supporting waste valorization and resource recovery (Liguori *et al.*, 2013) <sup>[66]</sup>. Their utilization also aligns with circular bioeconomy principles by converting low-value residues into high-value bioproducts. Agro-industrial by-products have been successfully employed for the production of EPS and other biopolymers such as bioflocculants, polyhydroxyalkanoates, and cellulose-based materials (Sharma *et al.*, 2014; Muniyasamy *et al.*, 2019) <sup>[74, 111]</sup>. Among production strategies, solid-state fermentation (SSF) has gained prominence due to its low moisture requirement, reduced energy and water consumption, higher productivity, and minimal waste generation compared to submerged fermentation, making it suitable for sustainable large-scale production (Mansour *et al.*, 2016) <sup>[70]</sup>.

The efficiency of SSF-based EPS production depends on the selection of appropriate substrates and microbial strains. Lactic acid bacteria, particularly *Leuconostoc mesenteroides*, are widely recognized EPS producers in SSF systems (Yu *et al.*, 2025) <sup>[140]</sup>. Other effective strains include *Azotobacter beijerinckii* and *Burkholderia cepacia*, known for their adaptability and EPS-producing capabilities (Garcia-Muchart *et al.*, 2025) <sup>[47]</sup>. Additionally, extremophiles such as *Geobacillus thermodenitrificans* and acidophilic bacteria expand production potential under specialized conditions (Bera *et al.*, 2022) <sup>[17]</sup>. The application of SSF-derived EPS in agriculture supports the development of sustainable biostimulants and environmentally friendly crop management practices. Overall, these approaches enhance circular agri-food systems and contribute to sustainable agricultural development.

### **Future perspectives and challenges in exopolysaccharide research**

Despite their broad applications, the large-scale production and commercialization of microbial Exopolysaccharides (EPSs) remain constrained by variability in yields, process inefficiencies, and high production costs. Standardization of fermentation and downstream processing is essential to ensure reproducibility and scalability.

A deeper understanding of EPS biosynthetic pathways across bacteria, fungi, and microalgae is required to enable targeted metabolic engineering for improved yield and tailored functionality. Additionally, challenges in process scale-up, including oxygen transfer and nutrient control, necessitate the development of optimized fermentation strategies and advanced bioreactor systems (Liu *et al.*, 2021; Chavan *et al.*, 2021) <sup>[23, 67]</sup>. Economic feasibility remains a key concern, which can be addressed through the use of low-cost substrates such as agro-industrial wastes,

supporting sustainable production and circular bioeconomy approaches (Ibrahim *et al.*, 2022) <sup>[55]</sup>. Furthermore, ensuring safety, biocompatibility, and regulatory compliance is critical for applications in food and biomedical sectors. Future research should focus on exploring novel microbial sources, particularly extremophiles, and expanding the biological applications of EPSs, including antimicrobial and therapeutic uses. Advances in material processing techniques such as 3D printing and nanofabrication, along with the development of EPS-based composites, will further enhance their application potential.

### **Conclusion**

Microbial Exopolysaccharides (EPSs) are versatile and sustainable biopolymers with diverse structures and multifunctional roles across industrial, biomedical, and agricultural sectors. Their unique physicochemical properties, along with biocompatibility, biodegradability, and non-toxicity, position them as promising alternatives to synthetic materials. In agriculture, EPSs play a crucial role in improving soil structure, enhancing plant stress tolerance, and promoting sustainable crop productivity, while in biotechnology and medicine they serve as functional biomaterials, bioactive compounds, and formulation agents. Despite their potential, challenges related to high production costs, low yields, and process variability continue to limit large-scale applications. Addressing these issues requires optimization of fermentation processes, adoption of low-cost and renewable substrates, and deeper insights into biosynthetic pathways through advanced omics and metabolic engineering approaches. Furthermore, emerging technologies such as advanced bioprocessing, nanostructuring, and material engineering are expected to expand the functional scope of EPSs. Their integration into circular bioeconomy frameworks and sustainable agricultural practices further enhances their relevance in addressing global environmental and food security challenges. Overall, continued interdisciplinary research and technological innovation will be essential to fully exploit microbial EPSs as next-generation sustainable biopolymers with broad societal and industrial impact.

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