



Review article

Microbial exopolysaccharides as bioprotective polymers for plant resilience in climate-stressed agroecosystems

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Abstract

Microbial exopolysaccharides (EPS) are multifunctional polymers that play critical roles in supporting plant resilience under climate-induced environmental stress. Increasing evidence shows that EPS secreted by rhizobacteria contribute to water retention, ion chelation, antioxidant activation, immune modulation, biofilm formation and microbe-plant signaling, collectively enhancing plant tolerance to drought, salinity and soil toxicity. Despite the recognized ecological functions of EPS, knowledge of their diversity, mechanisms of action and practical applications in agriculture remains fragmented. This review synthesized current advances in understanding the structural and functional attributes of microbial EPS and highlighted representative microbial producers with plant-protective traits. Emerging applications, including EPS-based biostimulants, bioformulations, and stress-mitigation tools, were examined critically in the context of climate-smart and sustainable crop management. In addition, the discussion considered key challenges, such as variability in EPS production, lack of standardized formulations and limited field validation. By reframing microbial EPS as biologically active shields in the rhizosphere, this review underscored their potential to strengthen crop productivity and agroecosystem stability, as well as further outlining priority directions for research and policy to translate molecular insights into scalable innovations that address the challenges of climate-resilient agriculture.

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Introduction

Globally, agricultural systems are exposed increasingly to the compounded effects of climate-induced stressors such as drought, salinity, extreme temperatures, and soil degradation, resulting in reduced crop productivity and greater volatility in food production (Bibi and Rahman, 2023). According to Food and Agriculture Organization of the United Nations (2023) and Intergovernmental Panel on Climate Change (2022), agricultural systems are threatened increasingly by climate-induced stresses, including prolonged droughts, salinity intrusion in coastal farmlands and temperature extremes that disrupt soil microbiomes and crop productivity. These scenarios underscore the urgent need for resilient bio-based interventions. At the same time, the diminishing returns from agrochemical-based practices, coupled with their ecological externalities such as soil microbiome disruption and resource depletion, highlight the urgent need for more resilient and ecologically compatible approaches to crop management (Mwangi et al., 2023; Anjaria and Vaghela, 2024; Mohanapriya et al., 2025). Enhancing plant tolerance to abiotic stress while preserving soil health and agroecosystem functionality has become a defining challenge in the pursuit of sustainable agriculture.

Among emerging biological solutions, microbial exopolysaccharides (EPS) have attracted growing attention as multifunctional biopolymers that support plant resilience under environmental stress. These high-molecular-weight polysaccharides, secreted into the extracellular milieu by various rhizobacteria, including *Bacillus* spp. (such as *Bacillus cereus* Frankland & Frankland P2, *Bacillus subtilis* B ER-08; Khan and Bano, 2019; Patel et al., 2023), *Rhizobium* spp. (such as *Rhizobium leguminosarum* Frank bv. *trifolii*; Janczarek et al., 2015), *Pseudomonas* spp. (such as *Pseudomonas aeruginosa* Schroeter PF23; Tewari and Arora, 2014) and *Enterobacter* spp. (such as *E. ludwigii*; Aoudi et al., 2024), have a suite of structural and physicochemical properties that allow them to function as adaptive shields in the rhizosphere (Talbi et al., 2023; Mouro et al., 2024; Pham et al., 2024). EPS mediate multiple protective mechanisms, ranging from water retention to stress signaling, that collectively support plant adaptation under harsh environments (Bhagat et al., 2021; Carezzano et al., 2023; Rafique et al., 2024). Beyond their individual biochemical roles, microbial EPS contribute to plant protection through systems-level functions: promoting microbial aggregation, stabilizing soil structure, enhancing stress-responsive pathways in plants and modulating

root–microbiome interactions (Ajijah et al., 2023; Cao et al., 2023; Pham et al., 2024). Increasing evidence has demonstrated that EPS-producing microbes could improve tolerance to drought (Khan and Bano, 2019), salinity (Kim et al., 2024) and toxic ions (Sayyed et al., 2015; Cao et al., 2023). in part by influencing gene expression related to antioxidative defense, osmotic adjustment and hormone signaling (Bharti et al., 2016; Khan and Bano, 2019). These findings suggest that EPS-based strategies offer not only biochemical interventions but also ecological integration points for improving crop performance in climate-challenged agroecosystems.

Although other reviews have addressed the general classification, biosynthesis and ecological roles of EPS (Cao et al., 2023; Pham et al., 2024), few have examined critically their applied potential as bioprotectants in agriculture under intensifying abiotic pressures. With recent advances in microbial genomics, synthetic biology and formulation technologies, there is growing opportunity to harness EPS-producing microbes as core components of climate-smart crop support systems. This review aimed to consolidate current knowledge on microbial EPS with a specific focus on their emerging applications in plant stress mitigation. Specifically, the review aimed: 1) to examine the structural and functional diversity of microbial EPS; 2) to elucidate their roles in modulating plant immunity and abiotic stress responses; 3) to highlight representative microbial producers with agricultural relevance; and 4) assess the technological and ecological pathways for deploying EPS in sustainable, climate-adaptive crop management. By positioning EPS as adaptive shields, it was expected to clarify their role at the interface of microbial function, plant physiology and environmental resilience.

Classification and characteristics of microbial EPS

Microbial EPS are structurally and functionally diverse biopolymers that can be classified based on their monosaccharide composition and localization relative to the microbial cell surface. Generally, according to composition, EPS are categorized into homopolysaccharides and heteropolysaccharides (Mohd Nadzir et al., 2021). Homopolysaccharides consist of repeating units of a single type of monosaccharide, such as glucose in dextran or fructose in levan, leading to relatively uniform structures. In contrast, heteropolysaccharides are composed of two or more different monosaccharides, including glucose, galactose, rhamnose, mannose and uronic acids (Nguyen and Nguyen, 2024). These heteropolymers tend to be structurally complex, often featuring branched chains and various functional groups,

which endow them with diverse biological properties, including antioxidant activity, ion chelation and immunomodulation (Zhao et al., 2018).

In addition, EPS are distinguished based on their localization as either capsular EPS (closely attached to the microbial cell surface) or secreted EPS (released into the surrounding environment). Capsular EPS form a tight matrix around the cell, contributing to cellular protection, adhesion and immune evasion (Dertli et al., 2015). In contrast, secreted EPS are excreted into the extracellular environment, where they serve critical ecological functions such as biofilm formation, moisture retention and mediation of microbe-plant interactions (Costa et al., 2018). Often, these secreted polymers make up the structural backbone of biofilms, promoting microbial community stability and resistance to environmental stress.

Numerous microbial genera have been identified as prolific EPS producers. For example, *Lactiplantibacillus plantarum* (Orla-Jensen 1919) Zheng et al. 2020 (formerly *Lactobacillus plantarum*) produced EPS with antioxidant and immunomodulatory properties, beneficial in both plant and human systems (Huang et al., 2022). *Pseudomonas* spp. produce EPS such as alginate, which are integral to biofilm formation and root colonization and have been linked to enhanced drought tolerance in plants (Chang et al., 2007). *Bacillus* spp. synthesize levan-type EPS that exhibit both antimicrobial activity and plant growth-promoting effects under abiotic stress (Hamada et al., 2022). *Rhizobium* spp., notable for their symbiotic relationships with legumes, secrete heteropolysaccharides essential for root nodule formation and nitrogen fixation (De Sousa et al., 2021).

The physicochemical characteristics of EPS, including high viscosity, strong adhesiveness and exceptional water-holding capacity, make them highly functional molecules in plant-associated environments. Their adhesive nature facilitates microbial attachment to plant roots, while their hydrophilic properties allow them to retain water and form hydrated matrices, especially under drought conditions (Bhagat et al., 2021). Furthermore, their structural role in biofilm formation provides mechanical stability and creates protective niches for microbial communities (Bhagat et al., 2021). These properties are tied closely to the molecular architecture; the degree of polymerization, branching patterns and the presence of functional groups, such as carboxyl, phosphate or sulfate, that all influence EPS functionality. For example, charged EPS can bind metal ions or toxic compounds, mitigating stress in the rhizosphere, while specific sugar motifs may interact with plant receptors to trigger immune responses or symbiotic signaling (Carezzano et al., 2023).

Altogether, the classification and physicochemical characteristics of microbial EPS offer important insights into their roles in nature and their potential applications in sustainable plant protection. Understanding the structure-function relationships of these biopolymers is essential for developing targeted strategies that harness EPS for improved plant health, resilience and productivity.

Triadic interactions: EPS, microbes and plant systems

The functional role of microbial EPS in agriculture extends beyond their intrinsic physicochemical properties. EPS serve as critical mediators in the tripartite interaction between microorganisms, plant hosts and the surrounding soil environment. These complex interactions encompass molecular signaling, microbial colonization, immune priming and abiotic stress alleviation, ultimately contributing to the establishment of a resilient and beneficial plant-microbe-soil system. Fig. 1 presents the integration of this triad (EPS, microbes and soil-plant interface), showing where EPS act (adhesion, immune priming, ion binding) to stabilize the system. This section of the review integrates previously dispersed mechanisms into a unified framework, emphasizing the central role of EPS in facilitating and stabilizing these interactions.

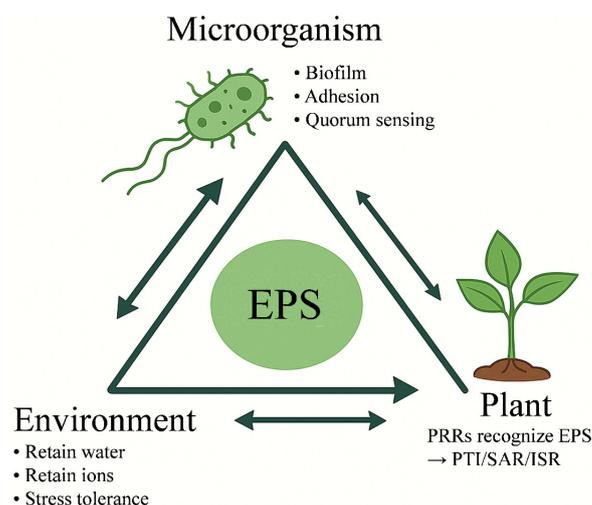


Fig. 1 Triadic interactions among microbial exopolysaccharides (EPS), plant systems and the soil environment, where EPS mediate complex interactions that support plant health, including microbial colonization, immune activation and abiotic stress mitigation, contributing to stable plant-microbe-soil ecosystems, PRRs = pattern recognition receptors, PTI = pattern-triggered immunity, SAR = systemic acquired resistance and ISR = induced systemic resistance

EPS as mediators of plant-microbe communication

Microbial EPS play a vital role in the communication between plants and microorganisms by acting as signaling molecules that can be recognized by plant cells. These EPS molecules are recognized by the plant's pattern recognition receptors (PRRs) located on the surface of root cells, allowing the plant to detect the presence of microorganisms in its vicinity (Jiang et al., 2016). Certain EPS components function as microbe-associated molecular patterns (MAMPs), which are perceived by PRRs to initiate the plant's innate immune responses. The recognition of these MAMPs triggers pattern-triggered immunity (PTI), a defense mechanism in plants that involves complex intracellular signaling cascades. Key events in PTI include the influx of calcium ions into plant cells, phosphorylation of mitogen-activated protein kinases and changes in the transcriptional profile of the plant, leading to the activation of defense genes (Wang et al., 2024). These molecular changes result in the production of various defense-related proteins, including pathogenesis-related proteins, reactive oxygen species (ROS) and antimicrobial compounds (Bigear and Hirt, 2018). Collectively, these responses strengthen the plant's basal immunity and improve its ability to defend against pathogens and environmental stress.

In addition to triggering local defense mechanisms at the site of microbial contact, microbial EPS can prime systemic defense responses in plants; thus, even when only a part of the plant interacts with EPS-producing microbes, the entire plant can benefit from enhanced immunity. There are two major systemic defense mechanisms that EPS can influence. The first is systemic acquired resistance (SAR), where some rhizobacteria that produce EPS can activate the salicylic acid (SA) signaling pathway, which is a key mechanism involved in long-term plant immunity against a broad spectrum of pathogens (Mishra et al., 2024). Upon activation, this pathway leads to the expression of defense-related genes throughout the plant, not just at the site of infection or microbial interaction (Pieterse et al., 2014). In essence, SAR provides the plant with a form of "immune memory," allowing it to mount faster and stronger defenses upon future pathogen attacks. The second systemic defense mechanism is induced systemic resistance (ISR), where EPS can also stimulate jasmonic acid and ethylene signaling pathways, which are primarily involved in defense against necrotrophic pathogens (those that kill host tissue) and herbivorous insects (Beneduzi et al., 2012).

Activation of these pathways enhances the plant's resistance by promoting the production of various defense molecules such as antimicrobial enzymes, pathogenesis-related proteins (PR) and phytoalexins (Haghpanah et al., 2025). Like SAR, ISR provides systemic protection, but it typically operates through a different hormonal signaling network. Fig. 2 details EPS recognition by PRRs and downstream PTI/SAR/ISR signaling cascades that elevate antioxidant and defense responses.

Beyond defense, EPS also influence plant growth and development by modulating phytohormone signaling. Many EPS-producing microbes stimulate the biosynthesis of auxin, a key plant hormone involved in growth regulation (Ansari et al., 2023). By altering auxin levels or distribution within the plant, EPS can promote various developmental processes such as root elongation, lateral root formation and root hair development (Marasco et al., 2024). These growth modifications not only support better plant development but also enhance nutrient uptake by increasing the root surface area, which, in turn, creates a favorable environment for further microbial colonization. This mutualistic relationship between plant roots and beneficial microbes is reinforced, ensuring both plant growth promotion and enhanced defense mechanisms against environmental stresses and pathogens.

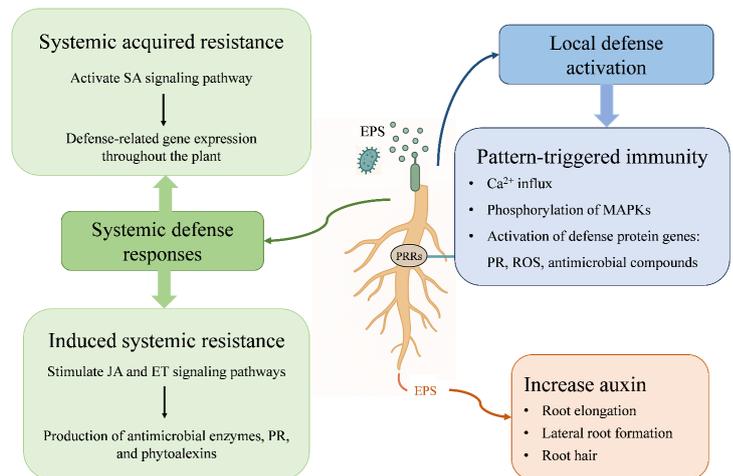


Fig. 2 Mechanisms by which microbial exopolysaccharides (EPS) modulate plant immunity and signaling, where EPS are recognized by pattern recognition receptors (PRRs) on plant root cells to trigger pattern-triggered immunity and prime systemic responses such as systemic acquired resistance and induced systemic resistance, enhancing plant resistance to pathogens and environmental stress, ET = ethylene, JA = jasmonic acid, MAPKs = mitogen-activated protein kinases, PR = pathogenesis-related proteins, ROS = reactive oxygen species and SA = salicylic acid

EPS in microbial colonization and biofilm formation

A key ecological role of microbial EPS is to support the colonization and long-term persistence of beneficial microbes in the rhizosphere. EPS function as adhesion mediators, enhancing the attachment of microbial cells to root surfaces and initiating the development of complex biofilm structures. These hydrated EPS matrices envelop microbial communities and plant tissues, serving as a physical barrier that protects microbes from environmental stressors such as fluctuations in pH, temperature, desiccation and antimicrobial compounds produced by plants (Costa et al., 2018). This matrix forms the structural basis of biofilms, which are three-dimensional microbial assemblies that foster spatial stability and mediate microbe-plant interactions by modifying the immediate root environment. Fig. 3 highlights how a thin EPS-rich biofilm sheath supports root surface colonization and protects microcolonies from desiccation and ionic stress.

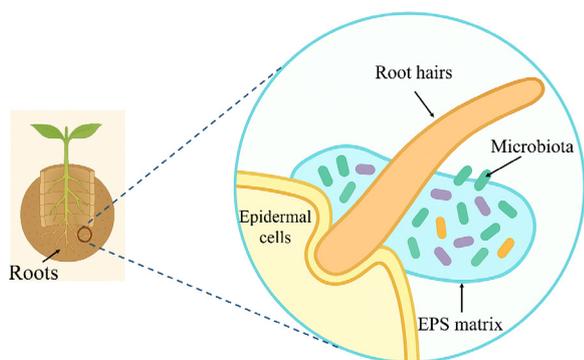


Fig. 3 Role of microbial exopolysaccharides (EPS) in biofilm formation and rhizosphere colonization, where EPS facilitate microbial adhesion to plant roots, biofilm matrix development and protection against environmental stressors, supporting the establishment of beneficial microbial communities

EPS-driven biofilm formation is essential for plant growth-promoting rhizobacteria to establish and maintain stable populations in the rhizosphere (Rafique et al., 2024). This stability enables continuous microbial functions such as nitrogen fixation, phosphate solubilization and phytohormone production. Within the biofilm microenvironment, microbial cells benefit from nutrient gradients and quorum sensing mechanisms, which enhance cooperation and coordination. At the same time, plants are protected from pathogens through physical exclusion, niche competition and suppression mechanisms (Ajijah et al., 2023). Additionally, EPS contribute to the selective recruitment and spatial organization of microbial consortia in the rhizosphere by modulating the physicochemical properties of both root surfaces and the surrounding soil. These modifications create specific

ecological niches that favor the proliferation of beneficial microbial taxa, facilitating the development of a plant-associated microbiome that promotes nutrient cycling, disease resistance and stress resilience (Ajijah et al., 2023).

EPS in plant abiotic stress tolerance

Microbial EPS play a central role in enhancing plant tolerance to abiotic stresses such as drought, salinity and heavy metal toxicity (Morcillo and Manzanera, 2021). Due to their highly hydrophilic nature and complex polysaccharide structure, EPS can retain substantial amounts of water, forming gel-like matrices that envelop root systems (Chang et al., 2007; Janczarek et al., 2015). These hydrated matrices improve soil moisture retention, reduce water loss through evaporation and maintain a favorable water status in the rhizosphere under drought conditions. Additionally, EPS enhance the soil structure by binding soil particles into aggregates, thereby increasing porosity and facilitating better aeration and water infiltration, which in turn supports root growth and nutrient uptake. In saline environments, the anionic functional groups in EPS, such as carboxyl and sulfate groups, can bind excess sodium ions (Na^+), forming stable complexes that reduce ion mobility and limit Na^+ uptake by plant roots (Bhagat et al., 2021). This ion-chelating property mitigates salt-induced toxicity and helps maintain ionic homeostasis, particularly the crucial Na^+/K^+ ratio, which is essential for cellular membrane integrity, enzyme activity and metabolic regulation. By maintaining this balance, plants are better equipped to sustain physiological processes under salt stress conditions. Fig. 4 summarizes abiotic-stress mitigation: water-holding gels, Na^+ sequestration, osmolyte accumulation and antioxidant enzyme upregulation.

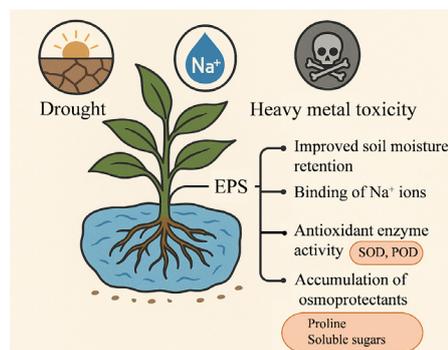


Fig. 4 Microbial exopolysaccharides (EPS)-mediated enhancement of plant tolerance to abiotic stresses, where EPS improve plant adaptation to drought, salinity and heavy metal stress conditions through water retention, ion chelation, antioxidant enzyme activation and osmolyte accumulation, POD = peroxidase and SOD = superoxide dismutase

Beyond their physical and chemical roles in the rhizosphere, EPS also contribute to activating plant antioxidant defense mechanisms. Plants treated with microbial EPS often have elevated levels of antioxidant enzymes, such as superoxide dismutase, catalase and peroxidase, which play vital roles in detoxifying ROS and protecting plant cells from oxidative damage under stress conditions (Ilyas et al., 2020). This enzymatic upregulation helps to prevent lipid peroxidation, protein denaturation and damage to nucleic acids, thereby preserving cellular function and vitality. Simultaneously, EPS can promote the accumulation of compatible solutes such as proline and soluble sugars (Bharti et al., 2016). These osmoprotectants help to stabilize cellular proteins and membranes and to regulate osmotic pressure within cells, enabling plants to adapt to osmotic stress caused by drought or salinity (Khan and Bano, 2019). The accumulation of these solutes represents a key biochemical strategy that allows plants to sustain metabolic activity and cellular integrity in hostile environments.

Collectively, these mechanisms demonstrate that microbial EPS are not merely extracellular byproducts, but active biological agents that assist plants in coping with environmental extremes. Their multifunctional properties highlight their potential as valuable allies in the development of climate-resilient agriculture, offering sustainable solutions to enhance crop productivity and stability under changing environmental conditions.

Functional applications of microbial EPS for plant stress resilience

Microbial EPS offer broad functional versatility that can be harnessed in multiple agricultural contexts. Their physicochemical properties and ecological functions make them valuable biological tools in supporting plant stress tolerance and promoting agroecosystem sustainability. Based on current evidence, the practical roles of microbial EPS can be grouped into four key domains.

Biostimulants for abiotic stress alleviation

Microbial EPS-producing strains have demonstrated considerable capacity to improve plant responses to drought, salinity and oxidative stress. Their beneficial effects are attributed largely to stress-alleviating mechanisms that

stabilize the rhizosphere and enhance plant adaptive capacity. These outcomes have been illustrated across crops and environments. For example, EPS from *Planomicrobium chinense* Dai et al. P1 and *Bacillus cereus* Frankland & Frankland P2 improved wheat drought tolerance by enhancing osmotic adjustment and antioxidative defenses (Khan and Bano, 2019). Likewise, *Dietzia natronolimnaea* Duckworth et al. STR1 activated abscisic acid-related and salt over-sensitive-related pathways in wheat under salt stress, increasing antioxidant enzyme activity and proline accumulation (Bharti et al., 2016). Furthermore, transcriptomic analyses revealed that EPS treatments upregulated genes involved in ROS scavenging and ion transport, supporting stress mitigation in crops (Kruasuwan et al., 2023; Aoudi et al., 2024). In rice, EPS-producing *Enterobacter ludwigii* Brenner et al. increased chlorophyll values measured based on soil plant analysis development, with improvements of 90% under drought and 59% under salinity, while shoot and root biomass increased by 14% and 27%, respectively (Aoudi et al., 2024). Similarly, Kim et al. (2024) demonstrated that purified EPS from *Pseudomonas liriopsis* Kim et al. had strong antioxidant potential, leading to substantial increases in carrot biomass and stress tolerance compared to controls. Collectively, these findings highlight the potential of EPS as core biostimulants for climate-resilient agriculture.

Bioformulation and delivery platforms

EPS serve as natural polymers in microbial formulations, where their adhesive and gel-forming properties enhance the stability, survival and field performance of bioinoculants (Netrusov et al., 2023). They protect microbes against desiccation, UV radiation and temperature extremes, which are critical factors in open-field applications (Yin et al., 2019). In addition, EPS facilitate microbial adherence to plant roots, improving colonization efficiency and promoting long-term rhizosphere persistence (Morcillo and Manzanera, 2021). For example, co-inoculation with EPS-producing *Bacillus* and *Azotobacter* increased wheat shoot and root development by approximately 20–25% compared with the non-inoculated controls (Çam, 2024). Probably, these growth benefits arose from a combination of mechanisms: EPS contributed to improved root colonization and moisture retention, while *Azotobacter* simultaneously enhanced nitrogen availability through biological nitrogen fixation and other plant growth-promoting traits. Therefore, the observed effect

reflects synergistic action rather than EPS activity alone. These developments suggest that EPS could be integrated functionally into next-generation biofertilizers and seed-coating platforms.

Enhancement of biological nitrogen fixation

Rhizobial EPS are essential for successful legume-rhizobium symbiosis, contributing to root nodule formation and nitrogen fixation (Yu and Zhu, 2024). EPS help mediate root recognition and compatibility through specific glycan structures, while also protecting rhizobia from plant immune responses and abiotic stress during colonization (Marczak et al., 2017). Studies have shown that exogenous application of *Rhizobium*-derived EPS can accelerate nodule initiation and enhance nitrogen assimilation. For example, in EPS-deficient mutants, only about 50% of the plants formed nodules even after 4 weeks, whereas the wild-type or EPS-supplemented treatments restored nodule formation rates to near-complete levels (Janczarek et al., 2015). These findings are particularly relevant in low-input agricultural systems, where synthetic nitrogen fertilizers are costly or environmentally unsustainable.

Bio-remediation and stress mitigation in degraded soils

The ion-binding capacity of EPS, mediated by functional groups such as carboxyl and sulfate, enables them to immobilize toxic ions (Na^+ , Pb^{2+} , Cd^{2+}) in polluted or saline soils (Dhanya et al., 2021; Yang et al., 2024). EPS-producing bacteria, such as *Enterobacter* sp. RZS5, have demonstrated effective remediation properties by tolerating heavy metal concentrations in the range 100–2,000 μM . Notably, EPS production increased 2-fold upon supplementation with Ca^{2+} , Fe^{2+} and Mg^{2+} (Sayyed et al., 2015) and EPS-rich broth substantially promoted seed germination, shoot and root elongation, leaf number and chlorophyll content in wheat and peanut seedlings. However, evidence for EPS effects in *Pseudoalteromonas agarivorans* Romanenko et al. remains more qualitative at present, lacking specific numerical metrics of improvement (Sayyed et al., 2015; Cao et al., 2023). In saline environments, EPS not only mitigated ionic toxicity but also stabilized soil moisture and porosity, creating favorable conditions for root growth and microbial colonization (Zhang et al., 2024). These benefits could be explored for rehabilitating marginal agricultural lands and enhancing crop productivity in degraded areas.

Field trials and practical applications

Most studies on EPS-mediated stress tolerance have been carried out under controlled laboratory or pot conditions, providing valuable insights into the physiological, biochemical and molecular mechanisms underlying plant resilience. Consistently, these experiments have demonstrated improvements in the chlorophyll content, osmolyte accumulation, antioxidant enzyme activities and biomass across diverse crops, thereby establishing EPS as potent biostimulants under abiotic stress. Such controlled studies form the mechanistic foundation for understanding how EPS stabilize the rhizosphere and prime plant defenses. Representative laboratory and pot-scale findings are summarized in [Table 1](#).

By contrast, an increasing number of field trials and practical applications have highlighted the agronomic potential of EPS under real-world conditions. In rainfed wheat, inoculation with EPS-producing *Bacillus* strains improved the chlorophyll content, photosynthetic efficiency and grain yield by 20–25% under drought stress (Khan and Bano, 2019). In semi-arid regions of India, application of EPS-producing *Rhizobium* strains substantially enhanced soybean and maize yields by 44–58%, while also increasing soil organic carbon (15.5%), available nitrogen (70.0%) and enzymatic activity (214.5%), underscoring dual benefits for crop productivity and soil fertility (Chaudhary et al., 2024). Hydrogel-based matrices mimicking EPS water-retention functions improved maize growth and yield by up to 29% in drought-prone soils (Thejesh et al., 2024), whereas cross-linked superabsorbent polymers enhanced crop survival and marketable yield in sandy soils by 15–20% (Bublitz et al., 2025). Furthermore, long-term agroecosystem studies revealed that EPS-producing microbes contributed to soil aggregate stability, water retention and improved resilience under contrasting tillage regimes (Costa et al., 2018). In addition, salt-tolerant EPS strains have improved seed germination and growth under saline conditions by enhancing soil aggregation and maintaining Na^+/K^+ balance (Ilyas et al., 2020). More recently, EPS from *L. plantarum* encapsulated in chitosan nanoparticles promoted the growth and antioxidant activity in mint under semi-field conditions, suggesting novel delivery strategies for sustainable agriculture (Huang et al., 2022). Collectively, these examples confirm that EPS and EPS-inspired materials can deliver measurable agronomic benefits, bridging laboratory insights with applied outcomes. Representative field-based evidence and application strategies are summarized in [Table 2](#).

Table 1 Laboratory and pot-scale evidence of microbial exopolysaccharides (EPS) in plant stress resilience

Microbial source	EPS function	Target crop/system	Key findings	Reference
<i>Bacillus cereus</i> Frankland & Frankland, <i>Pseudomonas aeruginosa</i> Schroeter	Increased water retention	Maize (<i>Zea mays</i> L.)	Improved soil water retention and plant growth	Naseem et al., 2024
<i>Pseudomonas azotoformans</i> Kämpfer et al. JRBHU5, <i>Burkholderia seminalis</i> Vanlaere et al. JRBHU6	EPS production, biofilm matrix formation, phosphate solubilization, IAA and enzyme production	Wheat (<i>Triticum aestivum</i> L.)	Enhanced germination, growth and yield; EPS as key PGP trait	Prasad et al., 2022
<i>Pseudoscherichia liriopsis</i> Kim et al. L3T	Drought/salinity tolerance	Carrot (<i>Daucus carota</i> subsp. <i>sativus</i> (Hoffm.) Schübl. & G. Martens)	Improved growth and tolerance	Kim et al., 2024
<i>Enterobacter Hormaeche</i> & Edwards sp. RZS5	Heavy metal tolerance, root colonization	Wheat (<i>Triticum aestivum</i> L.), Groundnut (<i>Arachis hypogaea</i> L.)	Enhanced growth and root adherence under metal stress	Sayyed et al., 2015
<i>Bacillus</i> Cohn spp., <i>Azotobacter</i> Beijerinck spp.	EPS production, biofilm	Wheat (<i>Triticum aestivum</i> L.) in nutrient-limited soil	Co-inoculation improved shoot and root development by ~20–25%	Çam, 2024
<i>Bacillus subtilis</i> Ehrenberg ER-08	EPS production, stress tolerance	Fenugreek (<i>Trigonella foenum-graecum</i> L.)	Enhanced growth and tolerance to salt/drought	Patel et al., 2023
<i>Pseudoalteromonas agarivorans</i> Romanenko et al.	EPS production, Pb immobilization	Pakchoi (<i>Brassica chinensis</i> L.)	EPS immobilized Pb and altered rhizosphere microbiome	Cao et al., 2023
<i>Pseudomonas aeruginosa</i> Schroeter PF23	EPS production, biocontrol, stress amelioration	Sunflower (<i>Helianthus annuus</i> L.)	Improved growth, pathogen control, alleviated salt stress	Tewari and Arora, 2014
<i>Enterobacter ludwigii</i> Brenner et al.	Abiotic stress alleviation, ROS detoxification	Rice (<i>Oryza sativa</i> L.)	SPAD ↑90% (drought), 59% (salt); biomass ↑14–27%; ROS-scavenging DEGs upregulated	Aoudi et al., 2024
<i>Dietzia natronolimnaea</i> Duckworth et al. STR1	Salt stress alleviation, gene modulation	Wheat (<i>Triticum aestivum</i> L.)	Upregulated ABA/SOS pathway genes, antioxidant enzymes and proline	Bharti et al., 2016

ABA = abscisic acid; DW = dry weight; IAA = indole-3-acetic acid; PGP = plant growth-promoting; ROS = reactive oxygen species; SOS = salt overly sensitive; SPAD = soil plant analysis development; ↑ = increase compared with control plants.

Table 2 Field trials and practical applications of microbial exopolysaccharides and EPS-inspired materials

Microbial source / formulation	Application	Target crop/system	Key findings	Reference
<i>Bacillus</i> Cohn spp.	Rainfed field trial under drought	Wheat (<i>Triticum aestivum</i> L.)	Improved chlorophyll, photosynthetic efficiency and yield by 20–25%	Khan and Bano, 2019
<i>Rhizobium</i> Frank spp.	Semi-arid field application	Soybean (<i>Glycine max</i> (L.) Merr.), Maize (<i>Zea mays</i> L.)	Yield ↑44–58%; SOC ↑15.5%; N ↑70%; enzymatic activity ↑214%	Chaudhary et al., 2024
Hydrogel-based formulations	EPS-mimicking water retention	Maize (<i>Zea mays</i> L.) under drought	Growth and grain yield ↑29%	Thejesh et al., 2024
Cross-linked superabsorbent polymers	EPS-inspired stress mitigation	Crops in sandy soil	Survival and marketable yield ↑15–20%	Bublitz et al., 2025
EPS-producing bacteria	Soil aggregation under field tillage	European cropping systems	EPS stabilized soil aggregates and enhanced resilience	Costa et al., 2018
Salt-tolerant EPS-producing strains	Salinity stress mitigation	Wheat (<i>Triticum aestivum</i> L.) and other crops in saline soils	Improved germination, growth, Na ⁺ /K ⁺ homeostasis	Ilyas et al., 2020
EPS nanoparticles (<i>Lactiplantibacillus plantarum</i> (Orla-Jensen) Zheng et al.)	Novel delivery platform	Mint (<i>Mentha</i> sp.) semi-field	Promoted growth and antioxidant activity	Huang et al., 2022

SOC = soil organic carbon; SPAD = soil plant analysis development and ↑ = increase compared with control plants.

Current challenges and future perspectives

The implementation of these benefits into scalable agricultural solutions, particularly in tropical and subtropical regions, remains in its early stages, despite the growing body of evidence supporting the multifunctionality of microbial EPS in plant protection. Compared with other biofertilizer strategies, such as nitrogen-fixing rhizobia, phosphate-solubilizing bacteria, or arbuscular mycorrhizal fungi, EPS-based applications offer unique advantages in enhancing soil aggregation, water retention and ionic balance under stress (Alami et al., 2000). Unlike classical biofertilizers that primarily improve nutrient availability, EPS act as physicochemical protectants that stabilize the rhizosphere environment. However, EPS-based approaches are less mature in terms of formulation and field deployment compared with commercial PGPR inoculants or synthetic biological-derived microbial consortia (Srivastava et al., 2024). This highlights the need for integrative strategies where EPS-producing microbes are combined with nutrient-enhancing biofertilizers to achieve synergistic benefits for crop resilience.

Several practical and technical challenges must be addressed to enable effective deployment of EPS-based strategies in the field. One of the foremost limitations is the variability in EPS yield and composition across microbial strains and environmental conditions. Factors, such as carbon source, pH, osmolarity and incubation time, can substantially affect both the quantity and bioactivity of EPS produced (Arayas et al., 2023; Wang et al., 2023). To mitigate this, future work should focus on genetic and metabolic engineering of native tropical strains (such as *Bacillus*, *Rhizobium* and *Enterobacter*) to enhance EPS biosynthesis under resource-constrained conditions (Kong et al., 2022).

A second key need is the development of robust, low-cost formulation technologies that can stabilize EPS for field applications. Given that EPS are prone to enzymatic degradation and environmental variability (for example, temperature, pH and moisture), formulation techniques such as nanoencapsulation, chitosan-based carriers, or hydrogel matrices offer promising solutions for improving stability and delivery (De Sousa et al., 2021). These systems not only protect the EPS molecules but also extend their residence time in the rhizosphere, thus enhancing their bioavailability and efficacy under field conditions (Latif et al., 2022). Additionally, EPS-based applications can be optimized by integrating them with existing biofertilizer and biostimulant products,

for example, seed coatings containing EPS-producing consortia have enhanced early-stage root colonization, water retention and stress resistance in crops such as wheat, rice and maize (Khan and Bano, 2019; Patel et al., 2023; Kim et al., 2024). In addition, synergistic effects could be provided by incorporating EPS into multifunctional microbial inoculants, based on traits such as phosphate solubilization, auxin production and biofilm formation (Prasad et al., 2022; Çam, 2024).

Perhaps most critically, long-term field trials under diverse tropical agroecological zones are essential to validate the reproducibility, scalability and economic viability of EPS-based solutions. Such trials should assess performance across multiple crop types, soil conditions and climate regimes, while evaluating indicators such as yield stability, soil health improvement and microbial community shifts (Saha et al., 2023; Aoudi et al., 2024). Furthermore, policy and regulatory frameworks will need to evolve to accommodate the commercialization of microbial EPS. Establishing standards for EPS content, purity, microbial viability and field efficacy will support both quality assurance and farmer adoption.

Conclusion

Microbial EPS are multifunctional biopolymers that enhance plant resilience to drought, salinity, and soil toxicity by mediating water retention, ion sequestration, antioxidant regulation and immune signaling. EPS-producing rhizobacteria, including *Bacillus* spp. (*Bacillus cereus* Frankland & Frankland P2 and *Bacillus subtilis* Ehrenberg ER-08), *Rhizobium* spp. (*Rhizobium leguminosarum* Frank bv. *trifolii*), *Pseudomonas* spp. (*Pseudomonas aeruginosa* Schroeter PF23) and *Enterobacter* spp. (*Enterobacter ludwigii* Brenner et al.) enhance plant tolerance to drought, salinity and heavy metal stress, while stabilizing rhizosphere microbial communities and sustaining nutrient cycling, thereby underscoring their dual ecological and agronomic importance as candidates for nature-based agricultural interventions. Beyond advancing physiological benefits, a future research agenda should focus on optimizing high-EPS-producing strains, clarifying molecular signaling pathways in plants and testing consortia that integrate EPS producers with other plant growth-promoting microbes. Equally important is the development of stable, low-cost delivery systems, such as seed coatings, hydrogels and encapsulated formulations, validated through multi-season

and multi-location field trials. On the policy side, standardized guidelines for EPS-based biostimulants are urgently needed, covering product quality, efficacy testing and safety evaluation. Public-private partnerships could accelerate scaling by linking research institutions, industry and farmers, while subsidies or green financing mechanisms may reduce adoption barriers for smallholders. Integrating EPS technologies into national climate-smart agriculture strategies, alongside training and extension services, will ensure that the benefits reach diverse agroecosystems. By combining targeted research with enabling policy measures, microbial EPS can move from promising laboratory findings to actionable solutions that enhance crop productivity, soil health and resilience under climate stress.

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