EXOPOLYSACCHARIDES: BRIDGING MOLECULAR FRONTIERS, EXTREMOPHILES, AND CLIMATE-RESILIENT AGRICULTURE

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Extreme environments such as hot springs, hydrothermal vents, deep-sea ecosystems, hyper-acidic lakes, acid mine drainage sites, and regions exposed to intense ultraviolet radiation harbour a remarkable diversity of microorganisms. These habitats, once considered inhospitable to life, are dominated by extremophiles that thrive under conditions of high salinity, extreme temperatures, elevated pressure, and highly acidic or alkaline pH (Figure 1). Their survival is enabled by unique biochemical and structural adaptations that allow them to withstand stresses lethal to most other life forms. Among their most significant adaptive strategies is the synthesis of exopolysaccharides (EPS), high molecular weight carbohydrate polymers that form protective extracellular matrices. These polymers play a crucial role in maintaining cellular integrity, facilitating adhesion, and shielding cells from environmental stress. Notably, EPS produced by extremophilic microorganisms exhibit exceptional physicochemical properties, including enhanced thermal stability, viscosity, and resistance to salinity and oxidative stress. Owing to these attributes, extremophile-derived EPS have emerged as promising biomolecules with wide-ranging applications in biotechnology, particularly in the development of climate-resilient and sustainable agricultural systems.

EPS-PRODUCING BACTERIA

Microbial EPS have attracted significant attention in recent years owing to their diverse bioactivities and broad applicability in modern biotechnology (Figure 2). They are increasingly explored in pharmaceutical and medical fields as antiangiogenic and antiviral agents, as well as in targeted drug delivery systems. Compared to plant and algal derived biopolymers, microbial EPS offer distinct advantages due to their unique functional properties, reproducible chemical composition, consistent quality, and cost-effective production at large-scale. Notably, EPS synthesized by halophilic and thermophilic microorganisms exhibit remarkable stability under extreme salinity, temperature, and pH conditions, making them valuable for industrial applications.

EPS production has been widely reported in both halophilic and thermophilic bacterial strains, in their native environments as well as under controlled laboratory conditions. In the context of agriculture, major abiotic stressors such as high temperature, salinity, drought, and heavy metal contamination pose serious challenges to crop productivity worldwide. Under such conditions, microbial communities are increasingly driven to produce EPS as an adaptive response to environmental stress, especially in the face of ongoing climate change. These polymers play a critical role in soil aggregation and help sustain microbial metabolic and physiological functions during stress conditions, particularly drought.

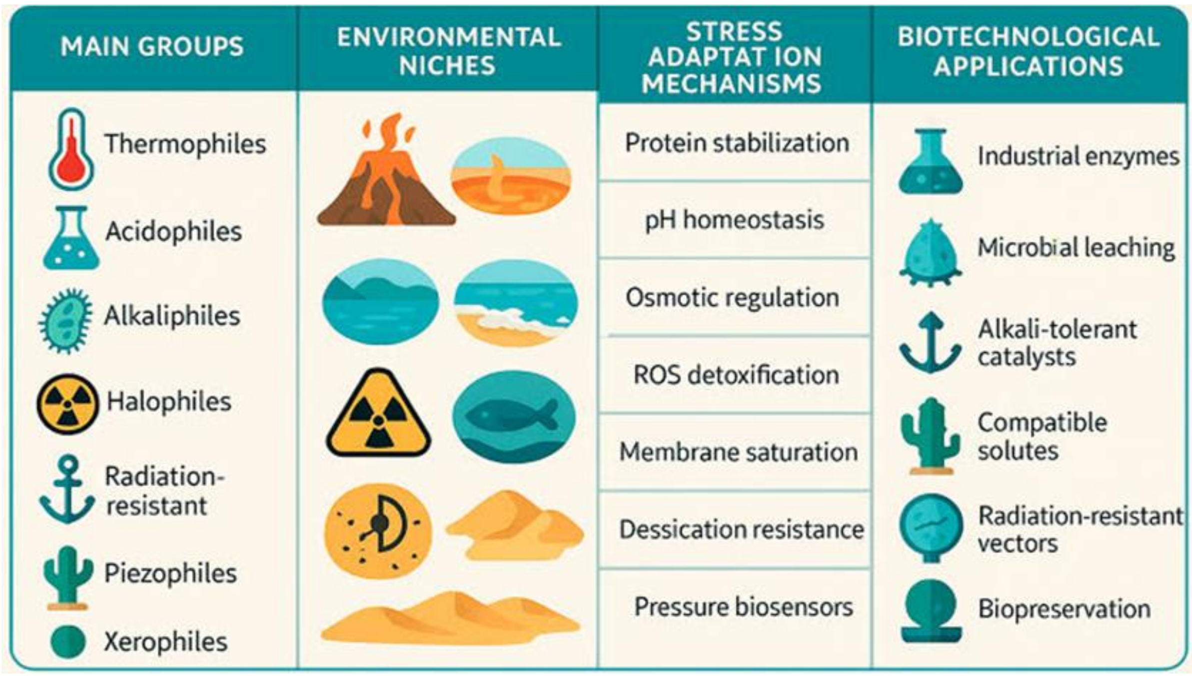

Figure 1 Overview of extremophiles, including their environmental niches, stress adaptation mechanisms, and biotechnological applications (Source: Marzban and Tesei, 2025)

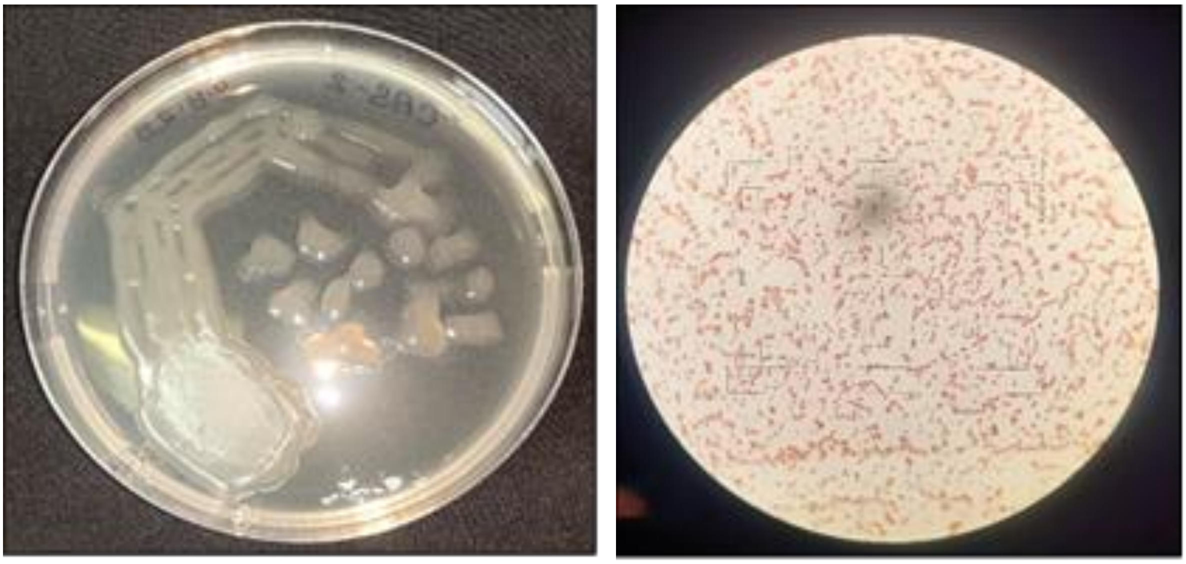

Figure 2 Morphological and microscopic characterization of EPS-producing bacterial isolates. (A) Colony morphology of Isolate on nutrient agar showing mucoid, glistening colonies indicative of exopolysaccharide production. (B) Gram staining of Isolate under light microscopy.

Additionally, EPS-producing microorganisms contribute to plant tolerance against salinity by binding sodium ions in the soil, thereby limiting their translocation to plant tissues and reducing ionic toxicity. This process improves nutrient uptake and supports plant growth even in saline environments. In addition, EPS-mediated biofilm formation enhances microbial survival, soil fertility, and plant–microbe interactions under high salinity. Heavy metal stress, often resulting from improper industrial waste disposal, is another critical constraint in agriculture; EPS-producing bacteria can immobilize and biomineralize toxic metal ions, thereby mitigating their harmful effects on plants. Similarly, elevated temperatures adversely affect plant metabolism, seed germination, and seedling development, further underscoring the importance of EPS-mediate stress mitigation mechanisms in sustaining agricultural productivity under changing climatic conditions (Figure 3).

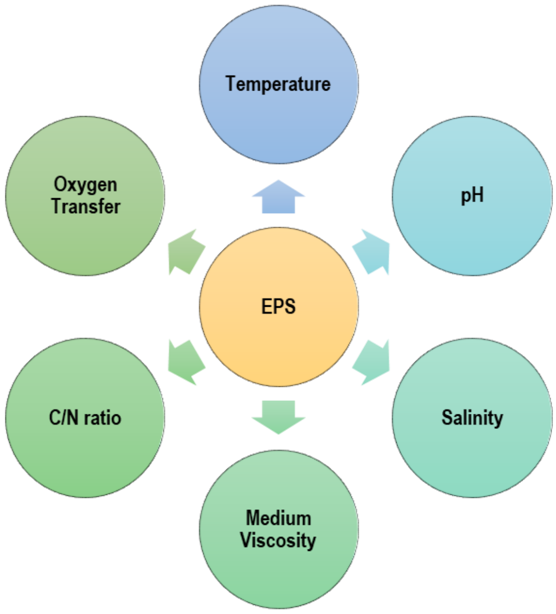

Figure 3 Key environmental & physicochemical factors influencing bacterial exopolysaccharide production.

APPLICATIONS OF EPS

The diverse physicochemical properties of microbial exopolysaccharides (EPS) enable their wide-ranging applications across multiple sectors (Banerjee et al., 2021). The following table highlights key applications of EPS in biotechnology, agriculture, and allied fields (Table 1).

Table 1. Applications of bacterial exopolysaccharides (EPS) in agriculture and environmental management.

Application Area	Mechanism of EPS	Examples / Benefits
Soil Aggregation	EPS binds soil particles	Improves structure, porosity and aeration
Water Retention	Hydrophilic functional groups trap moisture	Reduces drought stress
Salinity-Stress Reduction	EPS binds Na^+; supports biofilm formation	Better K^+/Na^+ ratio; healthier roots
Plant Growth Promotion	EPS supports PGPR colonization and nutrient cycling	Increased biomass and yield
Bioremediation	Metal chelation and pollutant adsorption	Removes Pb, Cr and hydrocarbons
Wastewater Treatment	EPS forms flocs and biofilms	Better sludge settling
Oil Recovery	Viscosity modification	Enhanced oil mobility in reservoirs
Food Industry	Thickening and stabilizing agent	Yogurt, ice-cream and sauces
Pharmaceuticals	Bio-compatible polymer with antioxidant properties	Drug delivery and wound dressings
Industrial Materials	Film-forming and biodegradable	Bioplastics and coatings
Thermo-halophilic EPS Uses	High salt and heat stable	Soil salinity improvement + industrial processing

LIMITATIONS OF EPS PRODUCTION

Despite their immense potential and wide-ranging applications, the large-scale production of EPS faces several technical and economic challenges. Understanding these limitations is essential for optimizing production processes and enhancing their commercial viability:

High Production Cost: EPS production often requires optimized media, controlled conditions, and downstream processing, increasing overall costs. Scaling up from laboratory to industrial level further adds to infrastructure and operational expenses.

Low Yield in Natural Systems: EPS production is often limited in natural settings due to nutrient constraints and environmental variability. This leads to inconsistent and insufficient yields for large-scale applications.

Soil Instability and Degradation: Although EPS improves aggregation, its inconsistent production can sometimes fail to stabilize degraded soils effectively. External disturbances like erosion and poor management can override its beneficial effects.

Strain Survival Failure: Introduced EPS-producing microbes may fail to establish due to competition with native microbiota. Environmental stress and soil conditions may further limit their survival and activity.

Variation in EPS Properties: EPS composition and functionality vary significantly between microbial strains and growth conditions. This variability can affect consistency and performance in industrial and agricultural applications.

Difficult Purification: EPS extraction and purification involve complex, multi-step procedures that are time-consuming. Contaminants such as proteins and salts make the process more challenging and costly.

Poor Shelf-life of Inoculants: Microbial inoculants producing EPS often have limited storage stability under field conditions. Loss of viability during storage reduces their effectiveness upon application.

Risk of Biofilm Overgrowth: Excessive EPS production can lead to unwanted biofilm formation in industrial systems. This may clog equipment, reduce efficiency, and require additional maintenance.

Limited Field Trials: Most EPS research is confined to laboratory or greenhouse conditions with limited real-field validation. Lack of large-scale trials restricts confidence in their widespread agricultural use.

Biosafety Concerns: Some EPS-producing microbes may pose ecological or health risks if not properly evaluated. Their release into the environment requires strict regulatory assessment and monitoring.

USE OF EPS IN AGRICULTURE

The study of the crucial function that thermophilic microbial species play in the composting and organic waste decomposition processes is one of the main topics of interest (Figure 4). These microorganisms' capacity to tolerate high temperatures and display enzymatic activity allows them to efficiently break down organic materials, producing nutrient-rich compost. The innate ability of thermophiles to produce enzymes with remarkable temperature stability, which makes them ideal for agricultural uses, is another significant factor that merits consideration. These enzymes can be used to boost a variety of activities, including bioconversion of biomass and production of various bioformulations.

When exposed to a salt concentration of 2.5 M (Amoozegar et al., 2019), the organisms under study show a maximum growth rate of 15%. Microorganisms require certain modifications in their cellular and enzymatic machinery to maintain osmotic balance in settings with high salt concentrations. Both the creation of osmo-protectants utilizing appropriate organic solutes and the control of salt concentrations inside the cell and its surroundings can lead to cellular changes. Many tactics have been used to improve survivability in high-salinity situations. These tactics include cutting back on salt consumption, using organic solutes, and developing high salt tolerance mechanisms.

By encouraging the growth of halophytic plants and aiding in the removal of excess salt from the soil, the microorganisms in question have the capacity to improve soil quality across regions impacted by salinity. It has been discovered that these halophiles generate a wide range of bioactive chemicals that have been demonstrated to significantly improve plant growth and stress tolerance. As a result, the utilization of these bioactive substances as biofertilizers and bio-stimulants has attracted a lot of curiosity in both agricultural practices and scientific research. These include hormones that stimulate plant development, osmo-protectants (Costa and Martins, 2022), and enzymes. Utilizing these innate traits may help develop biofertilizers and bio-stimulants made from extremophiles, which can significantly increase agricultural productivity (Table 2).

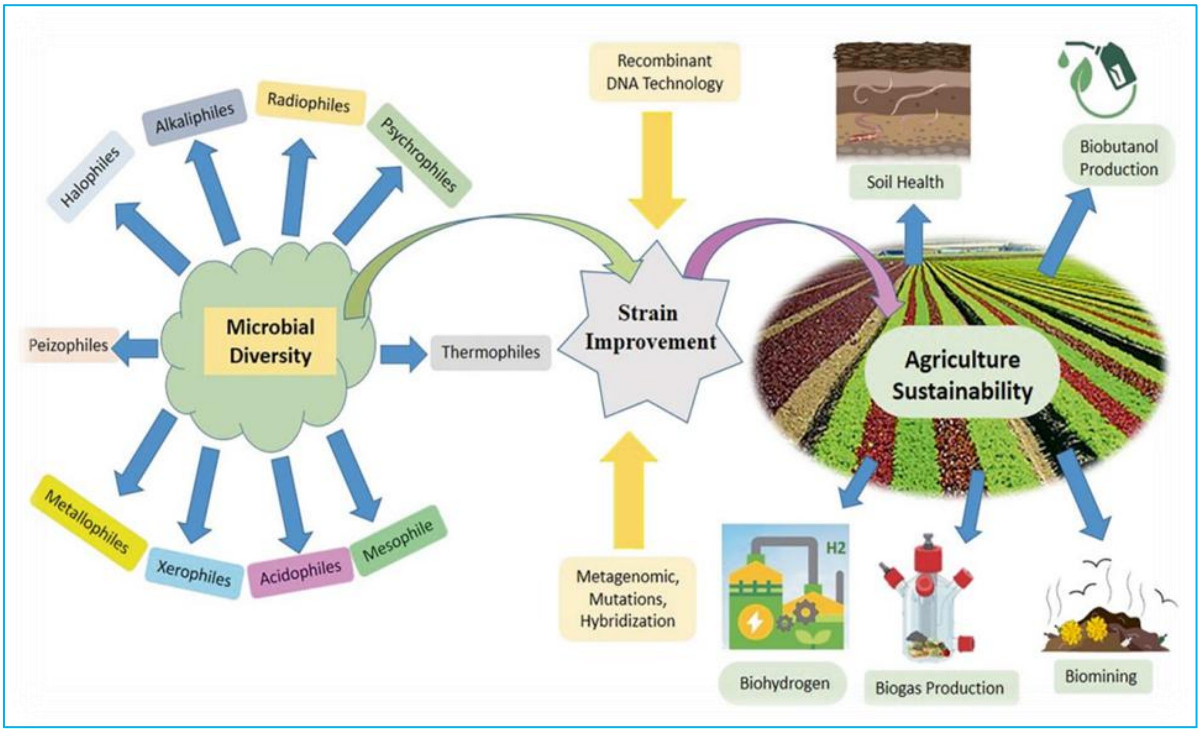

Figure 4 Microbial diversity and approaches used in sustainable agriculture practices (Kaur et al. 2022)

Table 2. Role of Extremophilic Bacterial Exopolysaccharides (EPS) in Soil Health and Plant Growth Promotion

Category	Details
Source Microbes	Halophiles, Thermophiles, Psychrophiles, Acidophiles and Polyextremophiles
Key EPS Properties	Water retention, Soil particle binding, Na^+/metal chelation, High thermostability, Viscosity and Biofilm formation
Soil Benefits	Improved soil aggregation, better aeration, Higher water-holding capacity (WHC) and Reduced compaction
Salinity Benefits	Na^+ binding, Reduced EC, Lower osmotic stress and Protection of root membranes
Plant Growth Promotion	Phosphate solubilization, Nitrogen fixation, Siderophore production, IAA synthesis and ACC deaminase activity
Microbial Survival Advantage	Better persistence in drought/salinity, Biofilm-mediated protection and Higher inoculant shelf-life

Agricultural Uses	Seed coating, Soil drenching, Biofertilizer formulation, Reclamation of saline/degraded soils and Enhancement of plant stress tolerance
Recent Evidence (2023–2025)	Improved wheat and rice growth under salinity, increased biomass, Reduced soil EC and Enhanced microbial colonization

REFERENCES

Kaur T, Kour D, Pericak O, Olson C, Mohan R, Yadav A et al. 2022. Structural and functional diversity of plant growth promoting microbiomes for agricultural sustainability. J Appl Biol Biotech Nol 10(1):70–89

Marzban G, Tesei D. 2025. The Extremophiles: Adaptation Mechanisms and Biotechnological Applications. Biology (Basel). 14(4):412. doi: 10.3390/biology14040412. PMID: 40282277; PMCID: PMC12024854.

Banerjee, S., Sarkar, P., Govil, T., et al. 2021 Extremophilic exopolysaccharides: Biotechnologies and wastewater remediation. Frontiers in Microbiology, 12, 721365. https://www.frontiersin.org/articles/10.3389/fmicb.2021.721365/full

Costa, M. S., & Martins, L. L. 2022. Bacterial osmo-protectants: A way to survive in saline conditions and potential crop allies. FEMS Microbiology Reviews.

Amoozegar MA, Safarpour A, Noghabi KA, Bakhtiary T and Ventosa A. 2019. Halophiles and Their Vast Potential in Biofuel Production. Front. Microbiol. 10:1895. doi: 10.3389/fmicb.2019.01895.

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