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REVIEW ARTICLE

Extremophiles as Novel Bioinoculants for Improving Crop Tolerance to Drought and Salinity: Implications for Global Food Security

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ABSTRACT

Drought and soil salinity are major environmental stresses that significantly reduce crop productivity worldwide, and their effects are expected to increase under climate change. Conventional approaches, including breeding stress-tolerant varieties and applying chemical amendments, often face limitations related to cost, time, and environmental sustainability. Extremophilic microorganisms, naturally adapted to harsh environments such as saline soils, deserts, hot springs, and polar regions, have emerged as promising bioinoculants for sustainable agriculture. These microorganisms enhance plant tolerance to drought and salinity through mechanisms such as exopolysaccharide production, ACC deaminase activity, osmolyte accumulation, antioxidant stimulation, and phytohormone synthesis. As a result, they improve plant growth, nutrient uptake, water-use efficiency, and stress resilience. This review highlights the role of halophilic, xerophilic, desert-associated, and polar-adapted plant growth-promoting microorganisms in mitigating abiotic stress. It also discusses current challenges, including inoculant stability, field performance variability, and regulatory issues. Overall, extremophile-based bioinoculants offer an ecofriendly and cost-effective strategy for enhancing climate-resilient agriculture and global food security.

Keywords: extremophiles; bioinoculants; drought tolerance; salinity stress; plant growth-promoting rhizobacteria (PGPR); halophiles; sustainable agriculture; food security

1. Introduction

Drought and soil salinity are among the most serious abiotic stresses limiting agricultural productivity worldwide. These stresses negatively affect plant growth, nutrient uptake, and crop yield, and their impacts are expected to increase under climate change (1–4). Conventional approaches such as breeding stress-tolerant varieties, genetic engineering, and chemical priming have shown positive results, but their application is often constrained by high costs, long development periods, and environmental concerns (5,6).

Beneficial plant growth-promoting microorganisms (PGPMs) have emerged as sustainable alternatives for improving crop resilience under stress conditions. These microorganisms enhance plant growth through nutrient mobilization, phytohormone production, biological nitrogen fixation, and activation of antioxidant defense systems (7,8). Among them, extremophiles are particularly important because they naturally survive in harsh environments such as saline soils, deserts, hot springs, and polar regions. Their unique adaptations enable them to improve plant tolerance to drought and salinity through mechanisms such as exopolysaccharide production, osmotic adjustment, and stress regulation (9,10). Studies have demonstrated that extremophile-associated microorganisms can enhance root growth, water-use efficiency, nutrient uptake, and antioxidant activity in stressed crops (11,12).

2. Extremophiles: Diversity and Adaptive Mechanisms Relevant to Agriculture

Extremophilic microorganisms isolated from desert soils, saline habitats, and polar ecosystems possess unique adaptations that support plant growth under environmental stress (13,14). A key adaptation is the production of compatible solutes such as proline, glycine betaine, and trehalose, which help maintain cellular water balance and improve plant osmotic adjustment under drought and salinity stress (15,16). Many extremophiles also produce exopolysaccharides (EPS), enhancing biofilm formation, soil water retention, and sodium ion sequestration in the rhizosphere (14). In addition, ACC deaminase-producing bacteria reduce stress-induced ethylene levels, thereby promoting root growth and plant development under adverse conditions (17). These microorganisms further enhance stress tolerance by stimulating antioxidant enzymes and synthesizing phytohormones such as indole-3-acetic acid (IAA), gibberellins, and cytokinins, which improve nutrient uptake and plant vigor (6,15). Collectively, these mechanisms make extremophiles promising bioinoculants for improving crop resilience to drought and salinity.

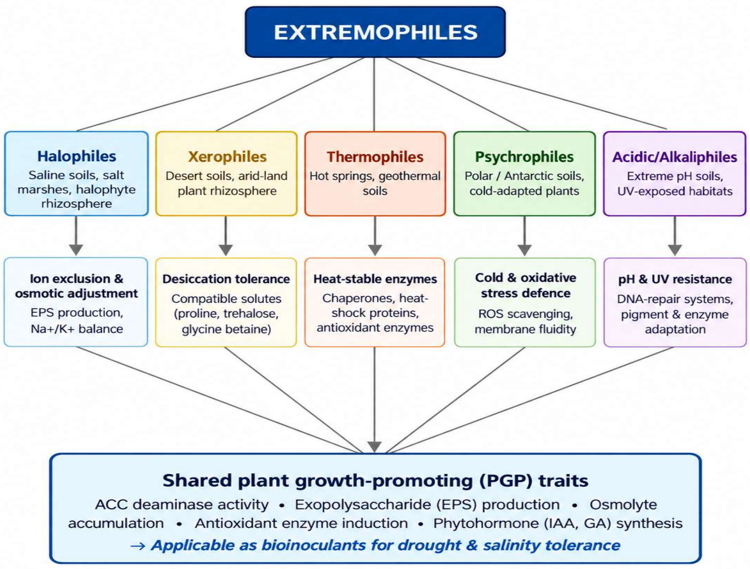

Fig. 1. Classification of extremophiles by habitat of origin and the adaptive traits that overlap with established plant growth-promoting (PGP) mechanisms relevant to drought and salinity tolerance (16).

3. Extremophile Bioinoculants and Drought Tolerance

Extremophile-derived microorganisms can significantly improve crop performance under drought stress by enhancing plant growth, water-use efficiency, and stress tolerance. These microorganisms possess adaptive traits such as phytohormone production, exopolysaccharide synthesis, and osmoprotectant accumulation that support plant survival under water-limited conditions (18). For example, methylotrophic bacteria isolated from drought-prone maize rhizospheres produced IAA, gibberellins, and exopolysaccharides, promoting root development and water retention under osmotic stress (18). Similarly, endophytic and rhizosphere bacteria producing phytohormones and osmoprotective compounds have been recognized as valuable resources for sustainable drought management (19,20). In addition, microbial inoculation with plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) has been shown to improve root architecture, biomass production, and water-use efficiency, particularly when integrated with climate-smart agricultural practices (21). Extremophilic microorganisms from desert ecosystems are especially promising for regions facing multiple stresses such as drought, heat, and salinity because of their broad adaptive capabilities (22). Despite encouraging greenhouse results, large-scale field validation and the development of reliable crop-specific bioformulations remain essential for the successful commercialization of extremophile-based bioinoculants.

Table 1. Adaptive Traits and Crop Benefits of Extremophile-Derived Microorganisms Under Drought Stress

Microbial source / group	Key adaptive traits	Mechanism of action	Effect on crops	Key reference
Extremophile-derived microorganisms	Phytohormone production, EPS synthesis, osmoprotectant accumulation	Enhance osmotic balance, improve root signaling, and support cellular protection under water deficit	Improved plant growth, water-use efficiency, and drought stress tolerance	(18)
Methylotrophic bacteria (maize rhizosphere)	IAA, gibberellins, EPS production	Stimulate root elongation and improve soil water retention under osmotic stress	Enhanced root development and improved drought adaptation	(18)
Endophytic and rhizospheric bacteria	Phytohormones, osmoprotectants	Regulation of plant stress physiology and osmotic adjustment	Improved drought tolerance and sustainable crop growth	(19), (20)
PGPR and AMF (synthetic inoculation)	Symbiotic colonization, nutrient mobilization	Improve nutrient uptake, root architecture, and soil–plant water relations	Increased biomass production and water-use efficiency	(21)
Desert extremophiles	Multi-stress adaptation (heat, drought, salinity tolerance)	Broad physiological resilience and stress cross-protection	Enhanced tolerance under multiple abiotic stresses	(22)
General limitation	Field instability, formulation constraints	Reduced survival and inconsistent colonization in field conditions	Need for large-scale validation and crop-specific formulations	All cited studies

EPS: exopolysaccharides; IAA: indole-3-acetic acid; PGPR: plant growth-promoting rhizobacteria; AMF: arbuscular mycorrhizal fungi. ACC,1-aminocyclopropane-1-carboxylate; EPS, exopolysaccharides; IAA, indole-3-acetic acid; PGP, plant growth-promoting; ROS, reactive oxygen species; SOD, superoxide dismutase.

4. Extremophile Bioinoculants and Salinity Tolerance

Soil salinity is a major constraint to agricultural productivity, particularly in arid and semi-arid regions. Excess salts cause osmotic stress, ion toxicity, and nutrient imbalances, adversely affecting plant growth and yield. Halophilic and halotolerant microorganisms have emerged as promising bioinoculants because of their natural ability to survive and function under saline conditions (23,24). These microorganisms, commonly isolated from saline soils, coastal ecosystems, and halophyte rhizospheres, possess adaptive mechanisms such as ion regulation, osmotic adjustment, and phytohormone production that enhance plant salinity tolerance (19).

Several studies have demonstrated the effectiveness of halotolerant bacteria, including species of *Bacillus*, *Pseudomonas*, and *Salinicola*, in improving crop growth under salt stress through ACC deaminase activity, nitrogen fixation, and plant growth regulator production (25). Exopolysaccharide (EPS) production is considered a key mechanism, as EPS-producing bacteria form protective biofilms around roots, improve water retention, bind excess sodium ions, and reduce salt toxicity (26,27). Inoculation with such microorganisms has been shown to enhance plant growth, chlorophyll content, antioxidant activity, and osmotic balance under saline conditions. Furthermore, biofilm-forming microbial consortia often provide greater benefits than individual strains by improving nutrient acquisition and membrane stability (28). In addition, psychrotolerant and halotolerant microorganisms from Antarctic environments have shown considerable potential for salinity management. These extremophiles improve K^+/Na^+ homeostasis, stimulate antioxidant defenses, and regulate phytohormone production, thereby enhancing crop tolerance to salt stress (29). Collectively, saline, desert, and polar ecosystems represent valuable sources of extremophilic microorganisms for developing next-generation bioinoculants to improve crop resilience in salt-affected soils.

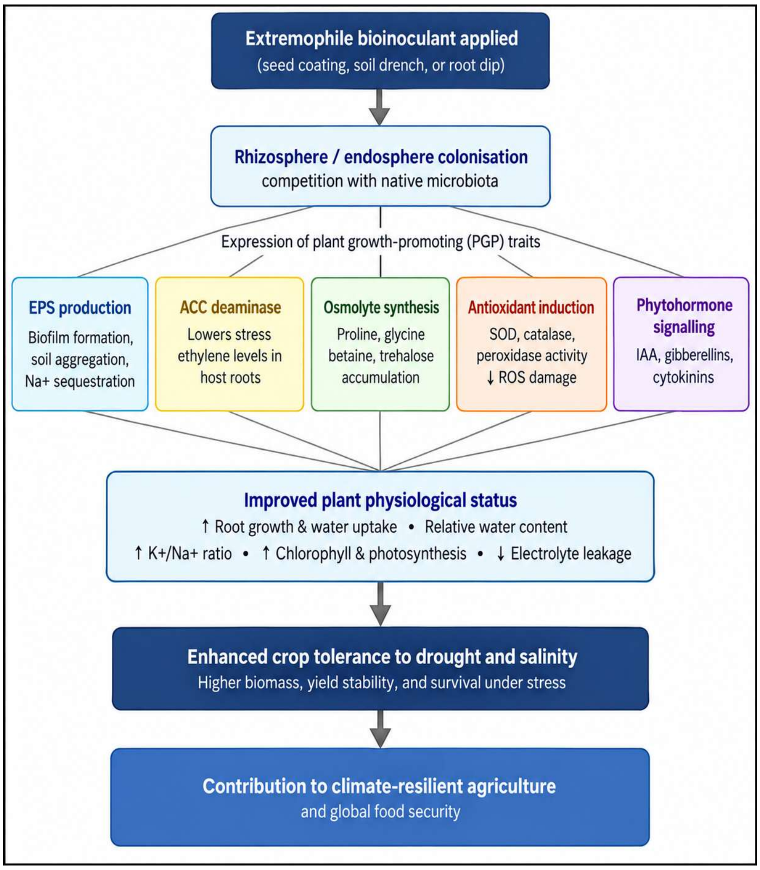

Fig. 2. Integrated model showing the role of extremophile-derived microbial inoculants in stress mitigation. Microbial functional traits improve water relations, nutrient balance, antioxidant defense, and hormonal regulation, ultimately enhancing crop performance under drought and salinity conditions (26).

5. Implications for Global Food Security

Extremophile-based bioinoculants offer a promising, sustainable, and cost-effective approach to improving crop productivity under drought and salinity stress, thereby contributing to global food security. Compared with irrigation infrastructure, chemical amendments, or transgenic crop development, microbial inoculants are generally less expensive and more accessible, particularly for smallholder farmers in resource-limited regions (22,24). They also provide a faster route to application, as effective microbial strains can be developed and deployed more rapidly than conventional stress-tolerant crop varieties (19).

Rather than replacing existing technologies, extremophile bioinoculants are most effective when integrated with complementary strategies such as improved irrigation, soil management, and stress-tolerant cultivars, thereby enhancing overall system resilience (21). Their importance is particularly evident in climate-vulnerable regions such as sub-Saharan Africa, South Asia, the Middle East and North Africa (MENA), Australia, and parts of the United States, where drought and salinity increasingly threaten agricultural productivity (22,24,23). Beyond yield improvement, these microorganisms can enhance nutrient-use efficiency, reduce dependence on synthetic inputs, and support climate adaptation goals aligned with Sustainable Development Goals (SDGs) 2 (Zero Hunger), 13 (Climate Action), and 15 (Life on Land) (19). Overall, extremophile-derived bioinoculants represent an important component of climate-smart agriculture, offering a complementary tool for strengthening food-system resilience under increasing environmental stress.

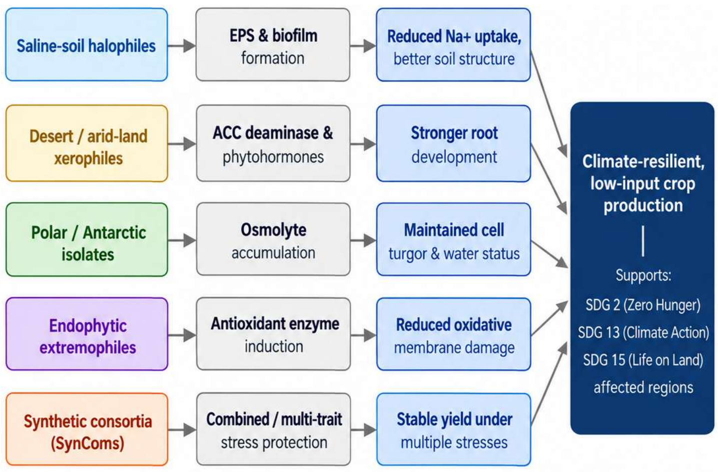

Fig. 3. Conceptual model demonstrating how extremophile-associated microorganisms enhance crop stress tolerance through specialized functional traits, contributing to climate-resilient and sustainable agricultural production (22).

6. Challenges and Limitations

Despite their strong potential, extremophile-derived bioinoculants face several challenges that limit large-scale agricultural adoption. One major constraint is the inconsistency of their performance under field conditions. Unlike controlled greenhouse environments, field systems involve complex interactions among soil properties, climate variability, crop genotype, management practices, and native microbial communities, all of which can affect inoculant survival and efficacy (24,19). Consequently, strains that perform well under experimental conditions may show reduced effectiveness in real agricultural systems, highlighting the need to improve ecological adaptability and field stability.

Another key challenge is maintaining microbial viability and functional traits during production, storage, and application. Although techniques such as encapsulation, freeze-drying, and carrier-based formulations have improved shelf life, loss of microbial activity and stress-adaptive functions during storage remains a concern (30). Regulatory and quality control limitations further complicate commercialization, as lack of standardized global guidelines leads to variability in product quality, microbial purity, and performance consistency (31). Research limitations also persist, with most studies focused on a narrow range of crops (e.g., maize, wheat, rice) and well-characterized bacterial genera such as *Bacillus*, *Pseudomonas*, and *Rhizobium* (28). In contrast, extremophilic fungi, archaea, cyanobacteria, and complex microbial consortia remain underexplored despite their potential functional advantages. In addition, long-term persistence of introduced strains in the rhizosphere is often limited due to competition with native microbiota, reducing sustained field benefits (32). Advances in multi-omics approaches have further revealed that plant–microbe interactions are highly complex, and the molecular mechanisms underlying stress tolerance under field conditions are still not fully understood (21).

7. Future Directions

The growing interest in extremophile-based bioinoculants for mitigating drought and salinity stress highlights their potential in developing climate-resilient agriculture. However, major research gaps must be addressed before large-scale commercialization. A key priority is the conduct of long-term, multi-location field trials across diverse soils, climates, and cropping systems to evaluate consistency, stability, and adaptability under real agricultural conditions (24). Future development should also shift from single-strain inoculants to synthetic microbial consortia (SynComs), reflecting natural microbial community interactions. Combining strains with complementary traits such as ACC deaminase activity, exopolysaccharide production, nitrogen fixation, phosphate solubilization, and phytohormone synthesis may enhance stress tolerance and improve rhizosphere stability (19).

Advances in multi-omics approaches (genomics, transcriptomics, proteomics, and metabolomics), integrated with machine learning and artificial intelligence, offer powerful tools for identifying key stress-tolerance traits such as osmolyte production, ion regulation, and antioxidant activity. These technologies can accelerate the discovery of novel extremophiles and enable development of targeted, crop-specific bioinoculants (21).

Improved formulation technologies are also essential to ensure microbial viability during production, storage, and application. In parallel, standardized protocols for strain identification, quality control, and product regulation are required to ensure consistency and build stakeholder confidence (31). Expanding research beyond commonly studied bacteria toward extremophilic fungi, archaea, cyanobacteria, and endophytes from deserts, saline soils, and polar ecosystems may further enhance functional diversity (22). Finally, extremophile bioinoculants should be integrated into broader climate-smart agricultural systems rather than used as standalone solutions. Their effectiveness can be maximized when combined with stress-tolerant cultivars, conservation agriculture, precision irrigation, and sustainable nutrient management (23). Overall, interdisciplinary collaboration across microbiology, agronomy, biotechnology, and policy will be essential to transform extremophiles into reliable tools for sustainable, climate-resilient food production.

8. Conclusion

Drought and soil salinity remain among the most significant constraints to agricultural productivity and global food security, and their impacts are expected to intensify under changing climatic conditions. In this context, extremophilic microorganisms have emerged as promising bioinoculant candidates due to their ability to survive under harsh environments and confer stress tolerance to crop plants. Through mechanisms such as exopolysaccharide production, ACC deaminase activity, osmolyte accumulation, phytohormone synthesis, and antioxidant regulation, these microorganisms enhance plant growth, nutrient acquisition, and physiological resilience under drought and salinity stress. Recent advances demonstrate that extremophile-derived bioinoculants can improve crop performance and resource-use efficiency under adverse environmental conditions. However, challenges related to field performance, microbial persistence, formulation stability, and regulatory standardization continue to constrain their widespread agricultural adoption. Future research should prioritize multi-environment field validation, synthetic microbial consortia, microbiome engineering, and omics-assisted discovery of novel stress-adaptive microorganisms. Expanding investigations to include extremophilic fungi, archaea, and complex microbial communities may further enhance the effectiveness of bioinoculant technologies. Overall, extremophile-based bioinoculants represent a sustainable and environmentally sound strategy for strengthening climate resilience in agriculture and have considerable potential to contribute to long-term food security in drought- and salinity-affected regions worldwide.

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