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EVALUATING MICROBIAL BIOSTIMULANTS UNDER ABIOTIC STRESSORS IN PLANTS

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Abstract

Abiotic stressors (AS), particularly heat, drought, and salinity have caused notable decreases in crop yield and nutritional quality under changing climatic scenarios. These AS negatively impact the growth of plants, metabolism, and economic yield by seriously disrupting several vital biochemical, physiological, and molecular processes. Plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungus (AMF), endophytes, and certain microalgae are examples of microbial biostimulants, representing innovative approaches to enhance crop resistance to AS. The PGPR work through a variety of processes, including phytohormone regulation, increased nutritional acquisition, osmotic adjustment, antioxidant induction, ion homeostasis, ACC-deaminase activity, and the formation of volatile organic compounds (VOCs) and exopolysaccharides (EPS). This review covers recent advances in microbial biostimulants, including their stress-specific ameliorative effects, challenges in formulation and application, and future research directions needed for their wide-scale application of microbial biostimulants to boost yield and quality of field crops. Future research should concentrate on how the PGPR mediates AS by promoting the biosynthesis of phytohormones such as gibberellins, indole-3-acetic acid, cytokinins, and abscisic acid, as well as enhancing nutrient acquisition .

Key words: Microbial adaptation; Plant growth-promoting microbes; Microbial performance

Introduction

Abiotic stressors (AS) such as drought, salt, severe temperatures, nutrient deficits, and heavy metal toxicity have put agricultural productivity, especially the economic yield and nutritional quality of field crops at risk (Ahmad *et al.,* 2024; Attiq *et al.,* 2024; Ali *et al.,* 2025). These AS are regarded as the principal determinants limiting crop yield globally, with estimates indicating that these can reduce average crop productivity by more than 50% in field crops (Abbas *et al.,* 2024; Hossain *et al.,* 2024). The intensifying climate change has increased the frequency and intensity of such stresses, making the development of long-term crop resilience solutions a global priority (Abbas *et al.*, 2023; Shaddam *et al.*, 2024). Conventional techniques, such as the use of mineral fertilizers, soil amendments, and genetic modification, have so far failed to produce consistent results across diverse pedo-climatic conditions for a variety of field crops (Chowdhury *et al.,* 2021; Sagar *et al.,* 2021).

In the current context of rapidly expanding climate change, microbial biostimulants offer a potential alternative for sustaining plants subjected to abiotic challenges (Santoyo *et al*., 2021; Iqbal *et al*., 2023; EL Sabagh *et al*., 2023). Although recent developments and lab research have demonstrated the beneficial effects of plant-associated microorganisms, field tests have not yet effectively confirmed the effectiveness of microbial biostimulants (Fadiji *et al*., 2022; Li *et al*., 2024). However, their advantages are often variable, and their methods of action are mostly unclear. Therefore, additional research that may result in more precisely targeted goals must be conducted to guarantee the dietary and food security of the world's rapidly growing population. To address climate change-induced stressors such heat/ temperature stress, salt, drought, and disease outbreaks, microbial-based biostimulants have enhanced agricultural innovation (Harsonowati *et al*., 2024).

Recently, biostimulants have emerged as novel and an eco-friendly method of decreasing the harmful effects of abiotic stresses on crop plants (Sadiq *et al*., 2023; Zia *et al.,* 2023). Plant biostimulants, as said by the European Biostimulants Industry Council (EBIC), are the substances, microorganisms, or mixtures thereof that stimulate natural processes in plants to enhance nutrient uptake, stress tolerance, and crop quality, regardless of their nutrient content. Microbial inoculants, which include plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), endophytic bacteria and fungi, and certain cyanobacteria, have received a lot of attention for their multifunctional roles in supporting plant growth and improving stress tolerance in crop plants under varying environmental conditions (Rouphael & Colla, 2020; Backer *et al*., 2018). The importance of bacteria in agriculture is highlighted in the article, especially their recent developments in modulating crops' ability to withstand abiotic stress. It investigates several biologically feasible methods to increase the stress-mitigating effects of microorganisms and critically analyzes the processes by which bacteria give plants stress resilience.

Applications of microbes in agriculture under climate stress: By improving the plant's capacity to absorb nutrients and build tolerance to environmental stresses, the plant

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microbiome plays a critical role in shielding the host from abiotic stress (Ullah *et al.,* 2025). Agriculture is one of the world's most climate-sensitive industries. Drought, salinity, heat waves, and irregular rainfall patterns are all examples of climate stressors that adversely impact crop development and output, lowering global food production and jeopardizing food security. These abiotic stresses affect water and nutrient intake, cause oxidative stress, and change physiological and biochemical processes in plants. Traditional mitigation strategies, including irrigation, chemical fertilizers, and stress-tolerant variety breeding, have provided some relief, but they are sometimes expensive, environmentally unsustainable, or insufficient in the face of catastrophic weather events (Backer *et al.*, 2018).

A recent study has identified plant-associated beneficial microorganisms as an environmentally favourable and sustainable alternative. Plant growth-promoting microorganisms (PGPMs) include PGPR, AMF, endophytic bacteria and fungi, and cyanobacteria. PGPMs operate as biostimulants, promoting plant growth, stress tolerance, nutrient uptake, and soil health while avoiding the detrimental environmental effects of chemical inputs (Vives-Peris *et al*., 2020; Liu *et al*., 2025).

By increasing soil fertility, boosting biodiversity, and improving nutrient cycling, bioinoculants and microbial biostimulants are examples of microbial-based technologies that provide a means of reducing the environmental impact of farming (Ullah *et al*., 2025). These methods aid in the preservation and regeneration of soil ecosystems in addition to lowering reliance on dangerous agrochemicals (Suman *et al*., 2022). Microbiomes provide a route to more climate-resilient and sustainable farming systems by enhancing soil health, boosting plant resilience, and promoting sustainable farming methods (O'Callaghan *et al*., 2022).

Microbes as natural stress alleviators: Microorganisms in the endosphere rhizosphere of plants interact closely with their hosts, influencing plant physiology and metabolism. Microbial biostimulants respond to abiotic stress in a variety of direct and indirect ways. For example, PGPR such as *Azospirillum*, *Bacillus*, and *Pseudomonas* spp. can produce phytohormones such as auxins, gibberellins, and cytokinins, which promote root system development and increase water and nutrient uptake in drought and nutrient-deficient conditions (Vacheron *et al*., 2013). To alleviate growth inhibition, some bacteria produce 1-aminocyclopropane-1-carboxylate (ACC) deaminase, an enzyme that lowers plant ethylene levels, a stress hormone that builds up in salinity and drought conditions (Glick, 2014).

Similarly, AMF, such as *Glomus* and *Rhizophagus* species, improve plant stress tolerance by increasing root absorptive surface, boosting phosphorus acquisition, and activating antioxidant defense mechanisms. By endorsing the buildup of suitable solutes like proline and soluble carbohydrates, AMF also aids with osmotic adjustment, which supports plants maintain cellular homeostasis under salinity and drought stress (Evelin *et al*., 2019).

Endophytic bacteria, which live within plant tissues without causing illness, are another essential type of microbial biostimulants. These organisms frequently produce secondary metabolites, osmolytes, and antioxidants to maintain membranes and protect photosynthetic machinery from temperature extremes (Santoyo *et al*., 2016). Cyanobacteria and microalgae have also been studied as biostimulants since they not only fix atmospheric nitrogen but also produce polysaccharides and bioactive chemicals that enhance soil structure and plant stress tolerance (Singh *et al.*, 2017).

The combined microbial inoculants, biochar may improve phosphorus availability and efficiency in P-deficient environments. Microbial inoculants not only boost crop productivity and quality but also improve soil health, reduce the need for synthetic fertilizers, and support climate-smart farming methods (Javeed *et al.*, 2020).

However, obstacles persist in the large-scale use of microbial biostimulants. Variability in field performance, formulation stability issues, and interactions with natural microbial communities can all restrict their efficacy. New potential to comprehend plant-microbe-environment interactions and create customized microbial consortia that may produce consistent outcomes across a variety of agroecosystems is being created by developments in systems biology and omics technologies (genomics, transcriptomics, and metabolomics) (Vives-Peris *et al.*, 2020). To improve agricultural resilience, sustainability, and productivity and support global food security in the face of climate change, microbial biostimulants present a viable strategy for reducing the detrimental effects of abiotic stress on crops.

Plant growth-promoting microbes (PGPMs) for stress mitigation: The AS such as drought, salt, nutrient inadequacy, and severe temperatures, are reducing agricultural productivity. These stresses impair plant physiology, metabolic balance, and yield stability, and are expected to reduce crop productivity by more than 50% worldwide (Mittler, 2006). Conventional treatments, such as genetic improvement and chemical inputs, have provided some remedies, but they are frequently unsustainable and environmentally detrimental (Backer *et al.*, 2018).

PGPMs have recently emerged as long-term biostimulants that improve plant resistance to AS. PGPMs are PGPR, AMF, endophytes, and cyanobacteria. These microorganisms inhabit the rhizosphere or internal tissues and promote plant growth by releasing phytohormones, including indole-3-acetic acid, gibberellins, and cytokinins, which improve root architecture and water/nutrient intake (Vacheron *et al*., 2013; Liu *et al*., 2025). Many PGPR cells produce the enzyme ACC deaminase, which reduces stress-induced ethylene levels and prevents growth inhibition under drought and salinity (Glick, 2014).

Similarly, AMF enhances phosphorus uptake, regulates osmotic balance, and activates antioxidant enzyme systems that protect plants from oxidative stress and membrane damage in salt or drought conditions (Evelin *et al*., 2019; Jiang *et al.*, 2023). Endophytic bacteria and PGPR also boost osmolyte accumulation (such as proline and trehalose) and antioxidant activity, increasing drought tolerance in crops like wheat and rice (Salem *et al.*, 2024).

Recent reviews confirm that PGPMs play a key role in ion homeostasis, maintaining a favorable K^+/Na^+ ratio during salinity stress and upregulating stress-responsive genes (Vives-Peris *et al*., 2020; Kibret *et al*., 2024;). Dual inoculation with PGPR and AMF has been shown to have synergistic benefits, including increased biomass, nutrient absorption, and stress tolerance (Al-Turki *et al*., 2023).

Overall, PGPMs are a viable technique for lessening abiotic stress via physiological, biochemical, and molecular mechanisms, contributing not only to crop resilience but also to sustainable and climate-smart agriculture.

Mechanisms of microbial action in plants under climatic stress

Improved water and nutrient uptake: PGPMs increase root architecture and plant absorptive ability, which is especially important in drought and nutrient-limited environments. AMF forms vast hyphal networks, which improve phosphorus and micronutrient uptake. Nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and cyanobacteria provide critical nutrients, lowering the need for synthetic fertilizers (Evelin *et al.*, 2019; Salem *et al.*, 2024). By releasing protons and organic anions, PGPMs improve the solubility of metals, according to several earlier investigations (Becerra-Castro *et al.*, 2011). PGPR promote plant growth by enhancing nutrient uptake, improving soil structure, and promoting nutrient cycling. In addition to increasing the availability of essential nutrients, the use of PGPR as bio-inoculants lessens the need for synthetic fertilizers, thereby reducing environment pollution and promoting more environmentally friendly agricultural practices (Jabborova *et al.*,2021). By Enhancing root growth and expanding root surface area, biostimulants promote soil exploration and resource absorption, which improves water and nutrient uptake. Through mechanisms including chelation and microbial activity, they increase the availability of nutrients and boost the efficiency of nutrient consumption. Better plant growth, yield, and stress tolerance result from this, particularly in dry and sandy soils (Rouphael & Colla, 2020).

Hormone regulation and stress signalling: Auxins, gibberellins, and cytokinins are few of phytohormones produced by PGPR that accelerate the growth of roots and shoots in crop plants under normal and stressful environments. Additionally, the ACC deaminase enzyme lowers ethylene rates in plants under stress, reducing the growth inhibition brought on by salinity or drought (Glick, 2014; Vacheron *et al.*, 2013). The usage of these advantageous microbes in agriculture to increase crop yields is growing. Numerous functions, including as the biological fixation of atmospheric nitrogen, organic matter decomposition, pesticide detoxification, plant disease suppression, and the synthesis of different bioactive chemicals, plant hormones, and enzymes, are greatly aided by them (Sagar *et al.*,2021). In the previous two decades, research has shown that plant hormones are essential for both launching defense responses and sensing and communicating environmental information (Thilakarathne *et al.*,2025). Through phytohormone modulation and stress-signaling pathway activation, biostimulants improve plant growth and stress responses. They have an impact on hormones that control photosynthesis and root architecture, including as auxins and gibberellins. Furthermore, biostimulants increase stress signaling through antioxidant systems and gene expression, enhancing resistance to abiotic stresses including salinity and drought, which improves crop quality and production stability under challenging circumstances (Rouphael & Colla, 2020). For plants to react to environmental stressors such drought, salinity, heat, cold, and heavy metal toxicity, hormone regulation is essential. Under these circumstances, plants sense external cues and initiate complex hormonal signaling networks that control defense systems, growth, and metabolism (Waadt *et al.*, 2022).

Oxidative stress mitigation: Excessive reactive oxygen species (ROS) produced by AS have the potential to injury DNA, proteins, and cell membranes. By improving the activity of the enzymes superoxide dismutase (SOD), catalase (CAT), and peroxidases (POD), PGPMs strengthen antioxidant defense systems. Additionally, they promote the buildup of osmolytes (proline, trehalose), which stabilize proteins and membranes under stress (Salem *et al.*, 2024). These osmolytes are essential for preventing plant cells from becoming dehydrated and preserving cellular function in the face of water stress. Furthermore, drought stress causes the production of ROS, which can oxidatively harm biological components such proteins, lipids, and nucleic acids (Ullah *et al.*, 2025). An imbalance between oxidants and antioxidants causes oxidative stress, which is a major factor in the development of many diseases. It is thought to be a successful tactic to reduce oxidative stress by counteracting oxidants (Muscolo *et al.*,2024). By lowering reactive oxygen species (ROS) under abiotic stress, biostimulants strengthen the plant antioxidant defense system and mitigate oxidative stress. They activate non-enzymatic antioxidants such ascorbate and phenolic compounds as well as enzymatic antioxidants like catalase and superoxide dismutase. During environmental challenges like salinity and drought, this response supports photosynthesis and metabolic balance, enhances redox homeostasis and membrane stability, and shields cellular structures from oxidative damage (Lakhdar *et al.*, 2023). Abiotic stressors promote the buildup of reactive oxygen species (ROS) and reduce photosynthesis in plants. Through DNA damage, lipid peroxidation, and protein oxidation, these hazardous substances can harm cells and perhaps trigger plant cell death (Hasanuzzaman & Fujita, 2022).

Osmotic and ion homeostasis: Microbes help to maintain osmotic balance and ion homeostasis under salinity and drought. Kibret *et al.* (2024) found that microbes improve plant tolerance to salt stress by compartmentalizing or excluding harmful ions like Na^+ and boosting uptake of K^+ and Ca^{2+}. These functions are necessary for maintaining metabolic activity and turgor pressure in adverse settings. By generating phytohormones, enhancing nutritional availability, lowering oxidative stress, and controlling gene expression linked to stress tolerance, these bacteria aid in minimizing the negative consequences of stress. PGPR enhance plant resilience to stress by improving nutrient absorption, scavenging excess ROS, decreasing osmotic stress, and increasing photosynthetic efficiency (Zhang *et al.*, 2023). Small amounts of chemical molecules called phytohormones are created by plants to assist them deal with a variety of stressful situations. In addition to causing plant growth, the coordination of several phytohormones affects the physiological and morphological development of plants when faced with obstacles (Chakraborty *et al.*, 2025). Significant pre-harvest and post-harvest losses are caused by acute biological, environmental, and climate change challenges that negatively impact plant survival by reducing photosynthetic efficiency and shortening longevity. As signaling molecules, phytohormones work together to reduce these signs of stress (Chakraborty *et al*., 2025). Phytohormones have a crucial role in controlling how plants react to abiotic stressors such drought, excessive salt, and harsh temperatures (Salvi *et al*., 2021).

Molecular and genetic regulation: PGPMs can influence the expression of stress-response genes, involving those linked to drought, salinity, and heat tolerance. Microbial inoculation activates systemic tolerance mechanisms, analogous to systemic acquired resistance in biotic stress, hence improving plant resilience at the molecular rate (Vives-Peris *et al*., 2020; Al-Turki *et al*., 2023). Phytohormone modulation, osmoregulation, the synthesis of exopolysaccharides and antioxidants, and the activation of host stress-tolerant genes are frequent ways that microorganisms reduce stress (Sharma & Kaur, 2024). Using plant growth-promoting rhizobacteria (PGPR) increases a plant's resistance to stressors such as salt, drought, infections, and nutrient shortages. Through processes including nutrient solubilization, phytohormone synthesis, and systemic resistance induction, these helpful bacteria enhance plant growth and stress tolerance. The review highlights recent research findings and explores how PGPR increases resilience through defense induction, hormone modulation, and nutrition absorption (Al-Turki *et al*., 2023). By altering the expression of genes linked to growth, nutrient transport, and stress tolerance, biostimulants improve plant performance. They trigger signaling pathways that control stress-responsive genes and transcription factors, including those related to hormone balance and antioxidant defense. Biostimulants enhance metabolic efficiency and resilience against abiotic stress by upregulating genes for nutrient transporters, photosynthesis, and secondary metabolite production. This eventually results in improved growth, yield stability, and quality under challenging circumstances (Zhang *et al.*, 2025). Recent developments in plant molecular biology have revealed intricate regulatory networks that control how plants react to abiotic stressors such salt, drought, low temperatures, and nutrient shortages. Improving crops' ability to withstand stress requires an understanding of these networks. Important stress-responsive genes, transcription factors, and signaling pathways that improve plant resilience have been found via research, offering useful targets for breeding and biotechnological methods targeted at creating climate-resilient crops (Rouphael & Colla, 2020).

Adaptation for improved microbial performance: PGPR, AMF, and endophytes are examples of beneficial microbes that are being extensively used to increase agricultural productivity and lessen AS. However, their field performance is frequently unpredictable because of environmental variations, soil heterogeneity, competition with local microbiota, and exposure to climatic pressures (Bashan *et al*., 2014). Improving microbial survival, colonization, and functional activity is thus essential for successful agricultural applications. Natural selection, stress preconditioning, formulation technologies, genetic engineering, and microbial consortia are examples of adaptation strategies used to improve microbial performance in adverse conditions (Ngumbi & Kloepper, 2016; Tiwari *et al*., 2020). Adaptive laboratory evolution, stress preconditioning, sophisticated formulation technologies, genetic and metabolic engineering, and the use of microbial consortia are some adaptation tactics targeted at enhancing microbial performance under stress. Together, these tactics improve plant-microbe interactions, ecological fitness, and microbial robustness, which improves crop production and stress reduction in difficult agroecosystems (Tiwari *et al*., 2020).

Drought and salinity tolerance: Two of the most prevalent and severe abiotic factors that impair plant growth, development, and crop productivity globally are salinity and drought. These stresses frequently take place in similar settings (such as semi-arid and arid regions), and they have some similar physiological consequences on plants (Zhang *et al*., 2025). Drought and salinity stress are common challenges for PGPMs, limiting their survival and functional activity. Adaptive techniques include pre-exposing microorganisms to stress conditions or choosing naturally adaptable strains. For example, repeated desiccation cycles or osmotic stress during laboratory culture have been demonstrated to promote drought resistance in PGPR, increasing colonization efficiency and stress mitigation in crops (Ngumbi & Kloepper, 2016). Similarly, salt-tolerant AMF strains greatly improve plant development in saline circumstances as compared to non-adapted strains (Estrada *et al*., 2013). Nevertheless, little is recognized about the exact processes by which PGPR increases crop tolerance to drought. It is known that rhizosphere microorganisms react to the abrupt changes in environmental circumstances when crops are exposed to drought stress in the short term (Li & Iqbal, 2024). By controlling phytohormones, increasing nutrient uptake, and triggering antioxidant defenses, plant growth-promoting microorganisms (PGPMs), such as rhizobacteria and beneficial fungi, improve crops' resistance to drought and salinity. They have ACC deaminase activity to reduce stress-induced ethylene levels and create substances like indole-3-acetic acid (IAA) that encourage root growth. PGPMs enhance ion homeostasis by regulating Na^+ and K^+ levels and increase osmotic adjustment through proline buildup. Additionally, they stimulate antioxidant enzymes to reduce oxidative damage, which eventually enhances crop development, yield stability, and stress tolerance in arid environments (Kaushal & Wani 2016 and Etesami & Beattie, 2018).

Temperature and pH adaptations: Plant growth-promoting microorganisms (PGPMs) help plants adapt to severe pH soils by altering the rhizosphere. Through the formation of ammonia, proton extrusion, or organic acid secretion, they change the pH of the soil, increasing the availability and solubility of nutrients. Microbial exopolysaccharides (EPS) promote root-soil interactions and shield roots from pH-induced stress, while PGPMs enhance nutrient uptake, especially phosphorus, iron, and micronutrients. Under challenging circumstances, this control of hormone balance, nutrition availability, and stress signaling improves plant growth and productivity (Vurukonda *et al*.,2016; Ma *et al.*, 2020). Extreme conditions, such as high temperatures or acidic/alkaline soils, can impair microbial viability. Selecting thermotolerant or pH-adapted strains or gradually introducing microorganisms to target settings increases field performance. This technique is particularly crucial for bacteria that live in dry, tropical, or semi-arid climates (Malusá *et al*., 2016). When plants are under cold or heat stress, PGPR helps them absorb nutrients and produce hormones, improves the activity of antioxidant enzymes, protects the photosynthetic system, maintains ion homeostasis, and promotes necessary amino acid and gene modifications (Zhang *et al*., 2023). In addition to strengthening stress responses and overcoming survival constraints, adaptation can increase microorganisms' tolerance to stressful situations on a variety of scales (Tan *et al.*, 2022). Plant growth-promoting microorganisms (PGPMs) improve a plant's ability to withstand high temperatures and pH shifts in the soil. Under heat stress, they enhance antioxidant defenses, trigger stress-responsive genes, and regulate phytohormone levels. Additionally, PGPMs protect cellular integrity by upregulating heat shock proteins (HSPs) and encouraging the accumulation of osmoprotectants. Additionally, PGPMs with ACC deaminase activity boost root growth and stability under temperature stress by lowering ethylene levels (Vurukonda *et al*., 2016; Ma *et al*., 2020).

Formulation and carrier-based adaptations: Microbes are protected from harmful environmental conditions during storage and field application by formulation techniques. Encapsulation in alginate beads, charcoal, or polymer-based carriers improves life during UV radiation, desiccation, and temperature variations (Malusá *et al*., 2016). Carriers may also supply nutrients or microhabitats to help microbial establishment and activity in soil. For example, seed coating with PGPR and protective polymers improves germination and drought tolerance when compared to uncoated seeds (Ngumbi & Kloepper, 2016). Despite advancements in microbial biofertilizers, their field effectiveness is hindered by significant flaws in current formulation methods. These issues primarily stem from poor compatibility and stability of the carriers used for microbial inoculants. Such limitations impact the overall efficacy and reliability of biofertilizers in agricultural applications (Fadiji *et al*., 2024).

Genetic and metabolic engineering: Modern biotechnology enables the manipulation of microbial genomes to improve features like: Researchers can synthesize high-value chemicals, optimize microbial production systems, and improve crop resilience. In addition to addressing pressing global issues like climate change, the energy crisis, and food security, these technologies likewise promote sustainable industrial practices and personalized health (Ramakrishnan *et al.*, 2025). For example, PGPR modified to overexpress ACC deaminase decreases ethylene buildup in plants, improving drought and salinity tolerance (Glick, 2014). Similarly, microorganisms modified to produce osmoprotectants such as trehalose or proline perform better in water-stressed environments (Tiwari *et al*., 2020).

Co-inoculation and microbial consortia: Using microbial consortia rather than single strains replicates natural ecosystems and provides functional redundancy, which improves reliability under changing conditions. These microbes are important for improving plant development, growth, and resistance to heavy metal stress. Choosing appropriate plant families, such as Fabaceae, Brassicaceae, and Poaceae, which are recognized for their distinct qualities that aid in heavy metal mitigation, is essential to the success of phytoremediation techniques (Hnini *et al*., 2024). Disease Resistance Co-inoculation of PGPR and AMF in wheat increased drought tolerance, antioxidant activity, and grain yield when compared to single inoculants (Berendsen *et al*., 2012). With consortium members carrying out complementary tasks like nitrogen fixation and phytohormone synthesis, co-inoculation has been successful in increasing tolerance to abiotic challenges including drought and nutrient deficits. Additionally, by strengthening biocontrol against diseases and improving soil structure and nutrient dynamics, they support rhizosphere engineering. All things considered, microbial consortia offer a viable and efficient way to boost plant output in the face of various environmental difficulties (Compant *et al*., 2019; Trivedi *et al*., 2020).

Adaptive laboratory evolution (ALE): It is the long-term culture of microorganisms under precise stress conditions to select stress-adapted populations. ALE has successfully created microorganisms that are resistant to severe salinity, oxidative stress, and temperature fluctuations while retaining their beneficial qualities in field circumstances (Dragosits & Mattanovich, 2013). This technology offers a regulated way to increase microbial robustness without introducing foreign genes. An experimental technique called Adaptive Laboratory Evolution (ALE) selects for improved stress resistance by growing microorganisms under controlled stress. Continuous passaging allows populations to preserve important functional features while accumulating mutations that increase fitness against certain stressors such as salinity, oxidative damage, severe temperatures, and food constraints. This genetic material-free, regulatory-friendly method is useful for creating strong microbial strains that can be used in industrial, agricultural, and environmental settings (Dragosits & Mattanovich, 2013; Lenski, 2017). Through tissue culture, specific stress-adapted cell lines can be regenerated into entire plants, increasing their resistance to a variety of conditions like heat, drought, and salinity without introducing foreign genes. This strategy is consistent with non-transgenic and regulation-friendly methods, such as *In vitro* selection (Al-Mayahi, 2014).

Table 1. Strategies to improve microbial performance for mitigating abiotic stressors in field crops.

Strategy	Mechanism	Benefits	Reference
Stress Preconditioning	Expose microbes to drought, salinity, or heat *In vitro*	Enhanced tolerance, improved colonization	Ngumbi & Kloepper, 2016
Formulation & Carriers	Encapsulation in polymers, biochar, or beads	Protection from UV, desiccation, longer shelf-life	Malusá *et al*., 2016
Genetic/Metabolic Engineering	Overexpression of ACC deaminase, osmolytes, and phytohormones	Improved stress tolerance and plant growth	Glick, 2014; Tiwari *et al*., 2020
Microbial Consortia	Co-inoculation of PGPR + AMF + endophytes	Synergistic effects; stress resilience	Berendsen *et al*., 2012
Adaptive Laboratory Evolution	Long-term stress exposure to select adapted strains	Robust microbes for field use	Dragosits & Mattanovich, 2013

Conclusions

Diverse abiotic stressors such as drought, salinity, and extreme temperatures threaten the productivity of modern, high-input agricultural systems. Recent research highlights the potential of various microbial applications (e.g., PGPR, AMF, endophytic bacteria) to alleviate these stresses, enhance soil fertility, and improve nutrient cycling while reducing greenhouse gas emissions. Plant growth-promoting microorganisms stimulate growth via phytohormones, which assist in root development and nutrient uptake under stress, thereby minimizing the adverse effects of salinity and drought. Additionally, microbes can enhance nutrient availability and reduce reliance on fertilizers. Future research should focus on microbes' roles in osmotic balance, stress-response gene expression, and the development of genetically modified crops to increase tolerance to abiotic stresses. Furthermore, enhancing microbial efficacy through adaptive laboratory evolution is essential for widespread adoption of microbial stress mitigation practices.

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