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MICROBIAL SOLUTIONS: A SUSTAINABLE APPROACH TO MITIGATE PLANT STRESS IN CHALLENGING ENVIRONMENTS

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Abstract

This study examines how beneficial microorganisms, specifically endophytic microbes, arbuscular mycorrhizal fungi, and plant growth-promoting rhizobacteria (PGPR), increase plant's resistance to abiotic conditions such heat, salinity, drought, and heavy metal toxicity. Beneficial microorganisms, such as arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR), play a pivotal role in promoting plant health by enhancing defence mechanisms against abiotic stresses, including heat, drought, salinity, and heavy metals. These microbes utilize distinct metabolic pathways to boost plant stress tolerance. For example, AMF colonizes plant root zones, improving nutrient uptake, soil health, and protection against environmental stressors. Additionally, AMF and PGPR trigger metabolic changes that regulate stress hormones, enhancing plant performance under challenging conditions. PGPRs contribute to plant growth by synthesizing essential growth regulators like auxins, cytokinins, and gibberellins, supporting plant development under stress. These microbial strategies promote plant health and offer significant potential for sustainable agriculture. By fostering beneficial plant-microbe interactions, farmers can reduce reliance on chemical fertilizers and pesticides, embracing eco-friendly farming practices. Ultimately, microbial adaptation mechanisms can contribute to a healthier ecosystem, more efficient crop yields, and increased food security, offering a promising solution for mitigating the impacts of climate change and environmental stressors on agriculture. For better production systems, incorporating these microbial tactics offers tremendous promise for developing resilient cropping systems, sustaining food security, and keeping ecosystems robust amid increasing environmental challenges.

Key words: Microorganisms; Arbuscular mycorrhizal fungi; Plant growth-promoting rhizobacteria; Environmental stressors; Abiotic stresses; Sustainable agriculture; Plant-microbe interactions

Introduction

Environmental degradation, including abiotic stresses such as drought, salinity, temperature extremes, and heavy metal toxicity, has significantly decreased global agricultural productivity and ecosystem stability. These stressors disrupt physiological processes in plants, leading to decreased growth and yields and, in severe cases, crop failures (Fahad *et al*., 2017; Hossain *et al*., 2021). Climate change and unsustainable agriculture demand sustainable strategies to enhance plant resilience and global food security (Hossain *et al*., 2020; Afzal *et al*., 2023). Traditional genetic, chemical, and selective breeding methods are limited, expensive, and environmentally harmful. These microbial interactions mitigate immediate stress responses and contribute to resilience to subsequent plant stress events (Gu *et al*., 2024).

Recent advances in molecular biology and biotechnology have been applied and achieved successfully, indicating a better understanding of plant-microbe interactions under abiotic stress. Mainly, microbial inoculants had good results as ecological alternatives to classical chemical treatments in agriculture (Mishra *et al*., 2023). Recent advances in technologies such as multi-omics technologies offer comprehensive insights into the genetic and metabolic mechanisms of microbial stress resilience, facilitating the engineering of stress-resistant, genetically modified microbes (Trivedi *et al*., 2020). However, at scale, bioengineered microbial solutions are expected to rapidly cycle nutrients and improve overall plant health, particularly in antagonistic environments (Bender *et al*., 2016).

The synergistic roles of plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and endophytic microbes in boosting plant tolerance and adaptability are the main focus of this work, which examines different microbiological strategies for reducing abiotic stress in plants (Egamberdieva *et al*., 2017; Javeed *et al*., 2023). By balancing recent discoveries with an established mechanistic understanding of microbial influence, this work seeks to elucidate how microbiological interventions may potentially be harnessed for the benefit of sustainable agricultural systems. It provides an overview of potential microbial solutions for more sustainable and climate-resilient agriculture, bridging traditional knowledge with state-of-the-art research (Glick, 2014; Pandey *et al*., 2023).

Microorganisms like bacteria, fungi, and archaea are highly significant mediators of plant responses to abiotic stressors via diverse mechanisms. Such products include osmolytes, antioxidants, phytohormones, increased nutrient acquisition, and improved soil health (Vurukonda *et al*., 2016; Parveen *et al*., 2023). PGPR is known to enhance drought and salinity tolerance of plants through the biosynthesis of exopolysaccharides, which stabilize soil structure and conserve water (Rafique *et al*., 2024). Similarly, AMF forms symbiotic associations with plant roots, facilitating increased water and nutrient capture and mitigating heavy metal-induced oxidative stress (Begum *et al*., 2019).

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Modulation of abiotic stress by microbes is diverse and intricate. Under stressful conditions, beneficial microbes produce osmoprotectants (e.g., proline and glycine betaine) to stabilize cellular structures (Kaushal & Wani, 2016). They also induce the antioxidant defence systems that scavenge the reactive oxygen species released by the stress exposure, establishing systemic plant tolerance (Pandey *et al*., 2023). These microbial interactions suppress immediate stress responses and give plants resilience to future stress events (Gu *et al*., 2024).

Recent advances in molecular biology and biotechnology have improved our understanding of plant-microbe interactions under abiotic stress. Such advancements in technologies, like multi-omics, have been used to get a more holistic interphase of the genetic metabolic basis for low-stress mitigation; they are grouped for microbes-based stress classification (Trivedi *et al*., 2020) and have the prospect of genetically modified microbes as a medium in withstanding stress-specific conditions. Microorganisms have been identified as potentially beneficial in faster nutrient cycling bioengineered solutions predicted (Bender *et al*., 2016) in challenging environments, increasing overall plant health.

This work reviews several microbiological approaches to mitigate abiotic stress in plants, emphasizing how PGPR, AMF, and endophytic microbes alleviate abiotic stress in plants and enhance their tolerance. Framing novel findings with tested mechanisms of microbial action, this work aims to discuss how these microbiological interventions have been harnessed to further sustainable agricultural systems. It provides a comprehensive overview of the potential of microbial solutions for more sustainable and climate-resilient agriculture by combining traditional knowledge with up-to-date research.

Microorganisms function in reducing abiotic stress: Microorganisms (bacteria, fungi, archaea) mediate plant response to abiotic stressors. They include stimulating the synthesis of stress-mitigating compounds like osmolytes, antioxidants, and phytohormones, improvement of nutrient uptake and soil performance (Vurukonda *et al*., 2016). One of the mechanisms PGPR employs involves the production of exopolysaccharides, which stabilize soil structure and minimize water loss rates, thus making them helpful in improving plant drought and salinity tolerance (Rafique *et al*., 2024). AMF are critical mycorrhizal fungi that form symbiotic associations with roots to enhance root water and nutrient uptake and alleviate heavy metal stress-induced oxidative stress (Birhane *et al*., 2012; Begum *et al*., 2019). Additionally, soil microorganisms actively influence soil pH, thereby increasing the bioavailability of essential nutrients (Moraes *et al*., 2020). Recent research highlights the significance of volatile organic compounds (VOCs) in improving plant stress tolerance, demonstrating their potential role in plant-microbe interactions (Fincheira & Quiroz, 2018; Thomas *et al*., 2020). Further, enhanced synergistic effects with some microbial consortia benefited the whole plant response in the presence of stress conditions (Bhattacharyya & Jha, 2012).

Salinity, drought, heavy metal contamination, and extraordinarily high or low temperatures are the foremost abiotic stresses that jeopardize crop yield globally. Understanding how plants sense biotic/abiotic stresses and how these stresses affect associated microbes is crucial for developing sustainable agricultural strategies to mitigate the impacts of environmental change (Mittler, 2006). Soil microorganisms (SMs) are essential in maintaining soil fertility, promoting plant growth, and sustaining an environmentally friendly ecosystem in natural communities. Soil is a complete ecosystem that includes bacteria, actinomycetes, cyanobacteria, fungi, and other microorganisms, collectively forming a diverse microbial population (El Sebai & Abdallah, 2022). These microorganisms play a crucial role in nutrient cycling, organic matter decomposition, and enhancing soil structure, ultimately improving plant productivity. Their antioxidant systems are activated in response to environmental stressors, producing free radical scavengers that detoxify reactive oxygen species (Hasanuzzaman *et al*., 2021). By mitigating oxidative stress, these microbial communities contribute to plant resilience against abiotic stressors and support sustainable soil health, making them vital components of agroecosystems (Hasanuzzaman *et al*., 2021).

Evidence indicates that some microbes, like *Rhizobium* and *Azospirillum* species, ameliorate drought effects through root architecture, greater moisture uptake, and the secretion of hormones like abscisic acid (Agunbiade & Babalola, 2023). Thus, different saline soils have shown the possibility of isolating microbial inoculants that can also increase the survival and productivity of crops under saline conditions. In addition, PGPR increases plant productivity through nitrogen fixation, mineral solubilization, and the generation of phytohormones. They also enhance resistance to environmental stressors via mechanisms like nutrient recycling and antibiotic synthesis (Rafique *et al*., 2024). Numerous microbial species, including *Pseudomonas* and *Arthrobacter* spp., are recognized for their soil detoxification abilities, either by transforming heavy metals into insoluble forms or by promoting their sequestration into non-edible plant tissues. This process effectively mitigates the toxic impact of heavy metals on crops (Singh & Gupta, 2018).

Recent advances in molecular biology and biotechnology have significantly increased our knowledge on plant-microbe responses to abiotic stress. Microbial inoculants have emerged as a prospective green biopesticide in ameliorating soil health and nutrient availability, thus increasing crop yield to overcome the shortage of food production. New technologies, such as multi-omics technologies, enhance our understanding of the genetic and metabolic basis of microbial stress management, enabling the development of genetically modified microbes tailored to specific stressors(Trivedi *et al*., 2020). Understanding these Microbial-based solutions, bioengineered microbial solutions can help enhance nutrient cycling and promote plant health in challenging environments (Bender *et al*., 2016).

Rhizobacteria that promote plant growth-reduction of abiotic stress: Recent developments in microbial genetics and ecological methods have greatly advanced our knowledge of the role rhizobacteria play in promoting plant growth and reducing stress. Through a variety of processes, such as phytohormone synthesis, nutrient solubilization, and antioxidant enzyme activation, PGPR increase plants' resistance to abiotic stresses such drought, salinity, and temperature extremes (Mishra *et al*., 2023). These intricate relationships have been further elucidated by developments in genomics and molecular biology, which have made it possible to rationally design efficient microbial biostimulants (Backer *et al*., 2018).

Synthesis of phytohormones like auxins by PGPR promotes the enlargement of the root system (to facilitate nutrient uptake), which is a crucial function in stressful conditions (Ali *et al*., 2024; Chowdhury *et al*., 2024). They are also responsible for the solubilization of key nutrients like phosphate, which have a high capacity of availability for plants in nutrient-limited conditions (Chowdhury *et al*., 2024). Additionally, PGPR enhances plant resilience to abiotic stressors by stimulating antioxidant enzymes, thereby mitigating oxidative stress and Under both ideal and stressful conditions, it is essential for controlling a number of physiological and biochemical processes that control plant growth and productivity (El Sabagh *et al*., 2022a,b; Ali *et al*., 2024). Advancements in genomic techniques, such as metagenomics and transcriptomics, have deepened our understanding of plant-microbe interactions, identifying key genes and pathways that contribute to stress tolerance (Ali *et al*., 2024). Notably, molecular characterization has identified strains like *Bacillus paralicheniformis* and *B. licheniformis* as possessing significant plant growth-promoting traits, including abiotic stress resistance (Ajdig *et al*., 2024). Numerous PGPR strains have been isolated and characterized for their tolerance to various abiotic stresses, demonstrating potential applications across diverse agroecosystems (Chowdhury *et al*., 2024). However, the application of PGPR enzymes faces challenges, such as inconsistent field performance and regulatory constraints, underscoring the need for further studies and detailed characterizations (Ali *et al*., 2024). So, the potential of PGPR to mitigate abiotic stress is clear; however, field conditions are very variable, and point-specific products are required for different crops in different locations. These beneficial bacteria are called PGPR, which are attached to the roots of the plants and facilitate growth, particularly under stress conditions. PGPR improves the resistance properties of economic plants to abiotic stresses like drought, salinity, heavy metals, and compound temperature by inducing biochemical and physiological responses that enhance plant resistance to abiotic stresses (Glick, 2014). For instance, they can produce phytohormones–hormones that help roots to take up nutrients, and fight off pathogens, auxins, cytokinins, and gibberellins (Egamberdieva *et al*., 2017). Certain PGPR synthesized abscisic acid in unfavourable water conditions, increase water use efficiency to a greater extent (Agunbiade *et al*., 2024). In addition, PGPR usually activates antioxidant enzymes, such as superoxide dismutase (SOD) and catalase (CAT), which shield the cells from oxidative stress after being exposed to different stressors, including heavy metals and dryness (Ghosh *et al*., 2018). The interaction between the crop plants and the microbial population creating this phenomenon is highly attributed to the adaptation of field crops for thriving in abiotic environments, often referred to as Induced Systemic Tolerance (IST) (De Souza *et al*., 2020). PT+, a biostimulant used in crop production, contains PGPR with biochemicals that enhance plant antioxidant activity and reduce oxidative stress, as confirmed by Akkurak *et al*., (2024). PGPR has been shown to increase drought resistance by advancing roots to search for more water and producing stress-related hormones (such as abscisic acid) (Agunbiade & Babalola, 2023). Also, the use of PGPR would lead to sustainable agriculture as a result of reducing the application of chemical-based pesticides and chemical fertilizers (Hosseini-Moghaddam *et al*., 2024) whilst improving soil structure, the one that contributes to the retention of moisture and nutrients.

Mycorrhizal fungi and their role in stress management: Mycorrhizae are essential fungi that form symbiotic relationships with plant roots, enhancing plant resilience and nutrient absorption, thereby improving tolerance to abiotic stresses like salinity, drought, and waterlogging (Thind *et al*., 2022; Wahid *et al*., 2022) and the transmission of nutrients and the survival of both partners are the main functions of symbiotic relationships between fungi and plants. Recent advances in microbiological methods and microbial genomics have clarified the complicated molecular commensalism between these fungi and their plant hosts, revealing specific pathways that enhance stress tolerance. Mycorrhizal fungi improve water and nutrient uptake (especially phosphorus and nitrogen) (Chaudhary *et al*., 2024). They help plants with drought and salt (Chaudhary *et al*., 2024) tolerance by achieving osmotic balance and inducing the synthesis of antioxidants that minimize oxidative stress in an adverse environment (Ali *et al*., 2024). Genomic and transcriptomic approaches in recent mismatch-based studies have elucidated the molecular signalling pathways underpinning plant-microbe interactions that remain at the base of plant resilience towards stress. Studies also found that mycorrhizal fungi can upregulate genes involved in phytohormone signalling and oxidant scavenging, supporting plant health under stress (Ali *et al*., 2024;However, intensive agricultural practices can threaten the beneficial effects of these fungi, which can sever these networks, highlighting the need to practice sustainable agriculture to protect these and other vital relationships for long-term agricultural productivity. Beyond the benefits direct from the mycorrhizal associations, the larger microbial community in the rhizosphere contributes to increased plant health and productivity. Mycorrhizal fungi and plant roots establish beneficial symbiotic relationships, which remarkably enhance the plant's tolerance against different abiotic factors by increasing the nutrient and water uptake, allowing the plants to grow in extreme conditions like saline, drought, or nutrient-deficient soils (Wahab *et al*., 2023). Additionally, AMF regulates complex signalling events with the host plants, which explains the ability of plants to exhibit elevated photosynthetic rates and enhanced gas exchange properties that promote rapid plant growth in stressful environments (Birhane *et al*., 2012).

Besides fungal interactions, plant-associated microorganisms alleviate abiotic stresses by producing various chemicals, including phytohormones. For example, auxins promote elongation and root branching, enhancing water and nutrient uptake, while cytokinins improve plant vigor and delay leaf senescence, particularly during drought (El-Sabagh *et al*., 2022). Moreover, many specific microorganisms generate exopolysaccharides (EPS), appearing as a matrix surrounding plant roots, which in turn retain moisture and prevent the infiltration of salt in saline soils, enhancing root penetration and salt tolerance through achieving better soil aggregation (Sandhya *et al*., 2009). Promising results have been obtained in field conditions to control abiotic stress using microbial inoculants. These microorganisms help retain soil water and stimulate root development, allowing the host plants to better access soil moisture during dry periods (Vurukonda *et al*., 2016).

Microbes are vital for abiotic stress tolerance due to their diversity, rapid and sustainable colonization, and production of diverse secondary metabolites, including antimicrobial compounds and VOCs. Microbial methods have emerged as green alternatives to chemical treatments by reducing chemical runoff and soil destruction (Singh *et al*., 2018) and lessening the need for synthetic pesticides and fertilizers. Moreover, the microbial biocontrol agents can control the pest in an organic manner, which lowers the risk of resistance, while microbial volatiles improve the crop's productivity by reducing synthetic inputs (Thomas *et al*., 2020). These integrated microbial strategies promote profitable and sustainable agricultural practices based on mycorrhizal fungi and other plant-associated microbes' role in effective stress responses in Microbial Genomics for stress resistance. Abiotic stresses like drought, salinity, elevated temperature and heavy metal toxicity pose serious challenges to global agricultural productivity and ecosystem stability. These stressors interfere with the physiological processes of plants, causing reduced growth, yield losses, and, in extreme cases, crop failure. Moreover, climate change and unsustainable global agriculture aggravate these challenges, increasing the need for sustainable approaches to improve plant resilience and support worldwide food security. In this connection, microbiological approaches have been proposed that promise to mitigate abiotic stresses by taking advantage of beneficial plant-microbe interactions (Glick, 2014). Microorganisms provide a valuable alternative to chemical inputs, leveraging their natural ability to withstand extreme environments, diversity, and potential crop–plan interactions (El Sebai & Abdallah, 2022).

Microbial mechanisms for abiotic stress tolerance: Most well-known contributors regulating plant responses to abiotic stressors are microorganisms, which can be bacteria, fungi, and archaea (Table 1). They produce stress-relieving substances, including osmolytes, antioxidants, and phytohormones; they enhance nutrient uptake and soil health (Vurukonda *et al*., 2016; Yasin *et al*., 2021). As one of the mechanisms involved, PGPR promotes drought and salinity tolerance in plants via the production of exopolysaccharides that stabilize soil microstructure and reduce the rate of water loss (Rafique *et al*., 2024). Conversely, the AMF forms symbiotic root relationships that enhance water and nutrient uptake, thus mitigating heavy metal toxicity-induced oxidative stress (Birhane *et al*., 2012; Begum *et al*., 2019). In addition, certain microorganisms can change soil pH to increase the bioavailability of specific nutrients (Moraes *et al*., 2020). Recent studies also show that VOCs are responsible for improving plant tolerance to stress (Fincheira and Quiroz, 2018; Thomas *et al*., 2020). Furthermore, studies reveal the synergistic effects of specific microbial consortia in enhancing plant resilience to various stress conditions. Notably, microbial genera such as Bacillus and Trichoderma have significantly improved plant stress tolerance (Thakral *et al*., 2024).

PGPR in abiotic stress reduction: PGPR are beneficial bacteria on plant roots that enhance growth and play a role in plant development in adverse environments. PGPR induces biochemical and physiological responses that improve plant resistance against abiotic stressors such as high temperature, salinity, droughts and heavy metals (Glick, 2014). Some PGPRs produce a wide range of phytohormones such as auxins, cytokinins, and gibberellins, which lead to increased root growth as well as absorption of nutrients and enhance plant body resistance (Egamberdieva *et al*., 2017). Drought stress also induces some PGP-RI to act as abscisic acid (ABA) synthesizers that increase water use efficiency (Agunbiade *et al*., 2024). Moreover, these bacteria stimulate antioxidant enzymes in plants like SOD and CAT, which protect cells from oxidative damage by heavy metals, dehydration, and other stressors (Ghosh *et al*., 2018). This adaptation of plants in response to disabled abiotic conditions is predominantly through interactions with microbes and is collectively known as IST (De Souza *et al*., 2020). Moreover, an increase in the antioxidant activity in the plants has been recorded, thereby aiding in mitigating oxidative stress, with a resultant increase in the plant's drought tolerance through the induction of root architectures with a concomitant increase in water absorption (Agunbiade *et al*., 2024; Akkurak *et al*., 2024). Moreover, using PGPRs in agriculture not only reduces reliance on chemical fertilizers and pesticides but also enhances nutrient uptake and improves soil structure, which in turn optimizes water and nutrient retention for plant growth (Hosseini-Moghaddam *et al*., 2024; Rafique *et al*., 2024).

Table 1. Summary of microbial mechanisms alleviating abiotic stress in plants.

Microbial group	Primary function	Mechanism of action	Stress type	References
PGPR (Plant Growth-Promoting Rhizobacteria)	Increase root development, nutrition uptake, and stress tolerance	Synthesis of exopolysaccharides (EPS), ACC deaminase, antioxidant enzymes, and phytohormones (auxins, cytokinins, and gibberellins)	Drought, salinity, heavy metals	Glick, 2014; Rafique *et al*., 2024
AMF (Arbuscular Mycorrhizal Fungi)	enhanced water and nutrient uptake via symbiotic colonization of roots	Osmotic modulation, antioxidant induction, phosphate mobilization, and gene upregulation	Drought, salinity, heavy metals	Begum *et al*., 2019; Wahab *et al*., 2023
Endophytic Microbes	Promote internal stress tolerance and metabolite synthesis	Regulation of stress hormones and the production of osmoprotectants (glycine betaine, proline)	Heat, drought, toxins	De Souza *et al*., 2020; Pandey *et al*., 2023
Soil Microbes (Archaea, Bacteria, Fungi)	Maintain soil fertility and environmental stability	Organic material breakdown, pH control, and nutrient cycling	Drought, salinity, temperature extremes	El Sebai & Abdallah, 2022
Microbial VOCs (Volatile Organic Compounds)	Promote growth and cultivate systemic tolerance	Signaling molecules that activate stress-protective genes	Multiple abiotic stresses	Fincheira *et al*., 2021

Mycorrhizal fungi and stress management: Mycorrhizal fungi form beneficial symbiotic relationships with the roots of plants, enhancing their tolerance to multiple abiotic stress factors. These fungi enable plants to absorb more nutrients and water, improving their performance in extreme conditions like saline, drought-affected, and nutrient-deficient soils (Wahab *et al*., 2023). Mycorrhizal fungi are a natural stress management technique because they transfer nutrients and water to the plants and vice versa in challenging conditions. AMF enhances photosynthetic rates and gas exchange characteristics through a complex cross-talk between the plant and the fungus, and assists the host plants to grow much faster under stressful environments. Mycorrhizal fungi-AMF- also enhance plant phosphorus uptake-one of the nutrients more limiting to plants in many stressed soils (Smith & Read, 2008) and also soil aggregation, not only improving water infiltration but aeration as well (Rillig & Mummey, 2006). In addition, plant tolerance against symptoms of heavy metals has been enhanced by many species of AMF (Khan *et al*., 2000). These discoveries underscored the promise of modulating the rhizosphere microbiome's composition in various ways to bolster plant health and productivity (Kandasamy *et al*., 2021). Recent work investigating plant-microbe interplay and microbial metabolism further adds to this area's knowledge pool.

Compounds from microbes to relieve stress: Various chemicals produced by plant-associated microorganisms alleviate abiotic stress on plants. Among these, the phytohormones most relevant to stress management are auxins and cytokinins. Auxins increase the elongation and branching of plant roots, promoting the uptake of nutrients and water, a beneficial effect in drought conditions, while cytokinins also enhance vigour and delay the senescence of leaves, resulting in further growth even under suboptimal conditions (Kurepa & Smalle, 2022). The biofilm formed by different microorganisms' EPS coats the plant roots, which helps retain moisture and prevents salt deposits in saline agricultural soils. The EPS also enhances soil aggregation and root penetration, aiding in stress resistance. Moreover, a few strains of bacteria produce antioxidant enzymes (like catalase and superoxide dismutase), which enhance the ability of plants to combat oxidative damage in adverse conditions (Sandhya *et al*., 2009). Osmoprotectants, such as trehalose, are organisms (such as Tazmania) that help maintain cellular turgor under arid conditions (Argüelles, 2000). Compatible solutes like proline and glycine betaine, synthesized by microorganisms, also protect plant cells against osmotic stress (Ashraf and Foolad, 2007). Various empirical studies (Vurukonda *et al*., 2016) deciphered that microbial inoculants significantly enhance plant water retention, development of roots, and moisture uptake from the soil by a plant after a prolonged drought.

Genomics and omics to improve stress resistance: Plants can activate different stress-response pathways under different abiotic stressors, thus suggesting that those pathways interact synergistically or antagonistically (Phour & Sindhu, 2022). Most host plant genes are overexpressed under abiotic stress conditions (Mittler *et al*., 2006). Heritage and ADWL are likely to interact with signaling molecules and stress hormone networks (e.g., ethylene, jasmonic acid, and abscisic acid) and cascades (e.g., reactive oxygen species, transcription factors, and mitogen-activated protein kinases), which are crucial for activating effective defense responses(Manepalli *et al*., 2022). Advances in metagenomic analysis mean that the previously unmanageable diversity of rhizospheric microbial populations can be quickly assayed, while rhizosphere engineering is a practical means to enhance cellular stress tolerance (Babalola *et al*., 2021). Natural soil microorganisms play a crucial role in maintaining soil fertility as well as improving plant growth and environmental health. The advent of metagenomics and next-generation sequencing can, therefore, facilitate the identification of beneficial microbial strains and beneficial traits that bestow resistance to biotic and abiotic challenges. Genomics plays a crucial role in understanding the genetic basis of plant-microbe interactions and deepening our knowledge of soil microbial inoculants for specific environmental conditions (De Souza *et al*., 2020). This strategy has successfully improved stress tolerance and related gene expression profiles in crops like tomato, petunia, citrus, grape, potato, and apple (Parmar *et al*., 2017).

Our capacity to improve microbial interactions and increase plant resistance to abiotic stressors has been completely transformed by genomic and omics technology. While developments in microbial genomics have uncovered the molecular mechanisms behind microbial responses to stress, these tools have also made it easier to create precision microbial inoculants that are suited to particular crops and environments (Mishra *et al*., 2023).

Microbes ease abiotic stress via colonization, metabolites, and VOCs, benefiting understory plants in harsh conditions. Microbiome biocontrol also reduces pest resistance and acts naturally. In contrast, microbial inoculants might aid in keeping the plant defence mechanisms inside the crop and improve the general resilience as well. Microbial volatiles are promising candidates for integrated microbial strategies to enhance crop productivity and decrease dependence on artificial inputs (Singh *et al*., 2018; Thomas *et al*., 2020), as they provide economical and sustainable agricultural practices.

This review explores microbiological strategies for mitigating abiotic stress in plants, focusing on the roles of PGPR, AMF, and beneficial endophytes in enhancing plant adaptation to stressful environments. Advances in microbial technology show promise for beneficial microbes as a potential sustainable agriculture solution of the future. By creating a bridge between traditional knowledge and modern science, this work hopes to demonstrate the potential of microbiology in constructing resilient agricultural systems capable of combating the increasing threat of abiotic forces.

The scientific community and the agricultural sector are becoming more interested in more advanced techniques including phytoremediation, microbial engineering, bio-fertilizers, and biocontrol agents. One promising approach for improving the resilience of plants to abiotic stressors is the introduction of beneficial microorganisms into farming practice. Personal lead: Alongside increasing plant resilience, this technique can maximize crop output and promote sustainable land management. Encouraging beneficial interactions with plant-microbe associations by tuning crops to use (non-pathogenic) microbes more effectively, may also enhance overall stress tolerance. We need more data regarding their safety, efficacy, and regulation before understanding their real-world applications as potential genetically modified organisms in agricultural systems.

Conclusion

Utilizing modern microbiological procedures and microbial genomics represents an eco-friendly and practical approach to increase plant resistance against various abiotic stresses. By producing osmolytes, antioxidants, phytohormones, and exopolysaccharides that improve nutrient uptake, soil structure, and water retention, among other things, these microorganisms promote plant growth. The development of stress-tolerant microbial inoculants and bioengineered solutions suited to particular environmental problems has been made possible by advances in microbial genetics and biotechnology, which have expanded our understanding of plant–microbe interactions. In light of the increasing effects of climate change, microbial-based methods support sustainable, environmentally friendly agriculture and enhance global food security by lowering reliance on chemical pesticides and fertilizers.

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