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OPTIMIZING THE MICROBIOME TO IMPROVE PLANT STRESS RESILIENCE

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Abstract

Plant-associated microbial consortia represent an indispensable component of the phytobiome, regulating plant growth, yield, and ecological resilience to both abiotic and biotic stresses through complex interactions among roots, soil, and associated microbes. Beneficial microorganisms, particularly plant growth-promoting rhizobacteria PGPR, arbuscular mycorrhizal fungi (AMF), and endophytes, enhance plant resistance to drought, salinity, heat, and pathogen attacks by regulating phytohormones, enhancing nutrient and water acquisition, and activating antioxidant and defense pathways. Strategies for microbiome optimization include microbial inoculants and synthetic microbial consortia, manipulation of root exudates, microbiome-aware breeding, and sustainable soil management practices that enhance microbial diversity and stability. Despite considerable progress, challenges remain in achieving consistent field-level performance due to issues of microbial specificity, persistence, and environmental variability. Emerging technologies such as integrated omics, systems biology, predictive modeling, and microbiome engineering offer new avenues for designing resilient and sustainable agroecosystems. This review synthesizes current knowledge on plant–microbiome interactions, highlights recent advances in microbiome optimization, and discusses future strategies for leveraging beneficial microbes to improve plant stress tolerance and promote climate-smart farming.

Key words: Plant microbiomes; Abiotic stress; Climate change; Stress resilience; Sustainable agriculture

Introduction

Climate change and intensive agriculture are improving the frequency of both abiotic stresses such as heat (EL Sabagh *et al*., 2021, 2022; Habib-ur-Rahman *et al*., 2022), salinity (Yasir *et al*., 2021; Sagar *et al*., 2023), drought (Ahmad *et al*., 2021; Chowdhury *et al*., 2021; El Sabagh *et al*., 2020, 2022; Islam *et al*., 2025) and heavy metal stress (Awad *et al*., 2021; Naz *et al*., 2021), and biotic challenges like pathogen outbreaks (Din *et al*., 2021; Ristaino *et al*., 2021; Lahlali *et al*., 2024). Climate-induced pressures restrict crop productivity and make agricultural systems more vulnerable. Traditional remedies, such as chemical fertilizers, pesticides, and irrigation, frequently give short-term respite. Moreover, their overuse contributes to soil degradation, environmental pollution, and declining effectiveness under severe stress conditions. contributing to environmental deterioration and failing under great stress.

The plant microbiome has emerged as a viable option, including services such as better nutrition uptake, hormone regulation, osmotic balance, and systemic priming of host defenses (Singh *et al*., 2023). Recent research suggests that plants under abiotic stress actively change their associated microbial communities, enriching taxa with stress-reducing characteristics (Li *et al*., 2025). Harnessing and optimizing these beneficial microbiomes is an effective technique for sustainable agriculture (Hanif *et al*., 2024). These microbes are essential to maintaining the health of plants and live in many plant areas, including the rhizosphere, phyllosphere, and endosphere. Through root exudates, plants in the rhizosphere supply microbes with carbon sources, including sugars and amino acids, which promote microbial development (Ullah *et al*., 2025).

However, field-level implementation remains challenging due to environmental variability and the inherent complexity of microbial communities. This paper explores the functions and mechanisms of PGPR, AMF, and endophytes in relieving stress and highlights their potential as a sustainable strategy for strengthening plant tolerance under changing climatic environments.

Role of beneficial microbes in plant stress resilience: Microbial symbionts such as endophytes, mycorrhizal fungi, and plant growth-promoting rhizobacteria (PGPR) serve as integral components in enhancing plant resilience against environmental adversities by boosting nutrient uptake, adjusting phytohormonal balance, and activating intrinsic defense cascades (Ahmed *et al*., 2025). Their cooperative interactions with the host plant not only alleviate the negative influences of biotic and abiotic stressors but also foster sustainable crop productivity. Moreover, the frequency and stability of these mutualistic associations with microorganisms substantially strengthen a plant`s adaptive capacity to withstand stress (Sarraf *et al*., 2023). Furthermore, plant-associated microbiomes serve as organic stress response mediators, allowing plants to bounce back from environmental shocks. Microbiomes support the restoration of ecological processes like carbon sequestration and nutrient cycling by promoting plant health and reducing the impact of climate change on ecosystems (Favela *et al*., 2021).

Rhizobacteria that promote plant growth: Plant growth-promoting rhizobacteria (PGPR) are rhizosphere-dwelling bacteria that have several direct and indirect ways of

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increasing plant development (Majid *et al.,* 2020; Hartman and Tringe, 2019). PGPRs are recognized as functionally significant soil-dwelling microorganisms capable of forming mutualistic associations with plants to enhance soil quality, stimulate growth, and strengthen innate immunity. However, the direct applications of PGPR under field conditions encounter practical challenges, primarily due to their limited survival under variable climatic and edaphic aspects such as soil PH and temperature. These environmental constraints substantially limit the long-term persistence and functional stability of introduced microbial inoculants, posing a major limitation to the broader utilization of biofertilizers and sustained realization of their growth-enhancing potential (Feng *et al*., 2025). PGPR stimulates plant development in several ways, either directly or indirectly. Increased nutritional availability, the generation of phytohormones, the development of shoots and roots, defense against various phytopathogens, and a decrease in illnesses are some advantages that these bacteria can offer (De Andrade *et al*., 2023). PGPR are free-living or root-associated microbes that play a vital function in improving plant growth and stress resilience. Their beneficial effects can be categorized into the following mechanisms:

PGPR produces phytohormones such as auxins, cytokinins, and gibberellins to maintain root and shoot growth under stress (Bouremani *et al*., 2023). Furthermore, these rhizobacteria sustain plant growth by mitigating stress induced ethylene production through 1-aminocyclopropane-1-carboxylate (ACC) deaminase. PGPR strains possessing ACC deaminase capability significantly enhance crop growth and development in various abiotic conditions like salt stress, water scarcity, waterlogging, temperature excesses, and the existence of pesticides, heavy metals, and other organic pollutants (Shahid *et al*., 2023). Recently, knowledge of transcription factor families and hormonal networks was expanded, exposing the complex interactions that shape plant development and resilience. Furthermore, these molecules' production, transport, and signaling, as well as how they interact with stress-responsive pathways, have become important research topics (Thilakarathne *et al*., 2025).

By fixing atmospheric nitrogen, solubilizing phosphorus, and mobilizing potassium, these bacteria enhance nutrient availability. These processes guarantee a consistent flow of nutrients to plants, especially in harsh environments like drought and salinity. Al-Turki *et al*., (2023) found that through nutrient solubilization, phytohormone synthesis, and systemic resistance induction, PGPR has a positive influence on plant growth and stress tolerance. The development of technology to boost crop productivity will be made possible by an advanced understanding of the interaction between root exudates and microbiome modification in response to plant nutritional status, as well as the underlying mechanisms thereof (Pantigoso *et al*., 2022).

PGPR alleviate oxidative stress damage by stimulating antioxidant defense enzymes and stimulating the accumulation of osmoprotectants, including proline and glycine betaine. This biochemical support enhances plant tolerance to adverse environments. Well-studied examples, like *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Azospirillum brasilense* have been consistently reported to enhance plant performance under drought and salinity stress (Fanai *et al*., 2024; Ullah *et al*., 2025). A potential remedy for reducing these stresses and boosting plant resistance is Plant Growth-Promoting Rhizobacteria (PGPR). The function of PGPR in reducing abiotic stress is examined in this review, with an emphasis on drought (Chattaraj *et al*., 2025).

Mycorrhizal arbuscular fungi (AMF): Arbuscular mycorrhizal symbiosis (AM) represents the cornerstone of sustainable agriculture, conferring improved resilience to biotic and abiotic stresses. By forming intimate associations with plant roots, AM fungi optimize water and nutrient acquisition, balance hormonal signalling, and activate antioxidant defense networks, collectively sustaining plant growth and yield under challenging environmental conditions (Thind *et al*., 2022; Ahmed *et al*., 2025). The goal of synthetic microbial consortia is to create synergistic biofertilizers that resemble natural soil ecosystems by combining PGPR with nitrogen-fixers or mycorrhizal fungi. developments in synthetic biology, including PGPR strains modified by CRISPR to exhibit improved stress tolerance or chemotaxis specific to root exudate (Song *et al*., 2025). AMF form symbiotic associations with plant roots, creating an efficient interface for nutrient and water exchange that enhances plant growth and resilience to stress. Their functions can be summarized as follows:

AMF hyphae extend beyond the rhizosphere, increasing the acquisition of necessary nutrients, especially phosphorus and micronutrients, and decreasing metal toxicity in the host plant (Bhantana *et al*., 2021). AMF increases a plant's ability to withstand and recover from abiotic stressors such as drought, salt, and heavy metal toxicity. These advantages result from the arbuscular mycorrhizal interface, which makes it easier for fungus and plant partners to exchange nutrients, signaling molecules, and protective compounds. AMF colonization also modulates osmotic adjustment, hormone control, and antioxidant defense systems of plants (Wahab *et al*., 2023). By lowering ion toxicity, improving nutrient uptake, and adjusting phytohormone levels, rhizobacteria can lessen the detrimental effects of saline soil (Guo *et al*., 2023).

By improving hydraulic conductivity and enhancing water-use efficiency, AMF help host plants maintain better water status during drought episodes. By enhancing plant growth performance under drought stress, leaf water potential, and relative water content, AMF improve plant water status (He *et al*., 2019). AMF encourages plant growth by improving nutrient, water, and mineral uptake (Wahab *et al*., 2023). Arbuscular mycorrhizal fungi (AMF) influence soil structure and modify plant water relations. However, little is known about how AMF affects hydraulic conductivity and soil water retention (the relationship between soil water potential and soil water content) in various soil types (Pauwels *et al*., 2023).

AMF induce systemic resistance against pathogens and activate antioxidant defense mechanisms in host plants, thereby reducing oxidative stress. Notably, AMF associations have been revealed to significantly increase the drought and salinity tolerance of crops, highlighting their importance in sustainable stress management strategies (Khaliq *et al*., 2022). AMF colonization modulates osmotic adjustment, hormone regulation, and antioxidant defense mechanisms, which are all influenced by AMF invasion. Under abiotic stress, these responses enhance biomass output, photosynthetic efficiency, and overall performance of the plant (Wahab *et al*., 2023).

Endophytes: Strong evidence for the influence of endophytes on host plant disease resistance, stress reduction, and plant growth promotion is supported by the findings of several research teams (Xia *et al*., 2022). Endophytes produce extracellular enzymes that facilitate host colonization and synthesize secondary active substances that protect plants from pathogens. By generating phytohormones and detoxifying harmful compounds, they enhance plant growth in thriving in unfavourable soil circumstances (Ameen *et al*., 2024). These non-pathogenic microorganisms reside within plant tissues and contribute significantly to overall plant health and stress resilience. Their primary functions include:

Endophytic bacteria and fungi produce metabolites that either directly suppress pathogens or trigger systemic acquired resistance (SAR), improving the plant's defense capacity. Velmurugan *et al*., (2023) claimed that endophytic *Bacillus* spp. produce antifungal antibiotics and induce systemic resistance against rice blast disease, making them a valuable addition to blast disease management strategies. The key mechanisms of disease suppression, involving siderophores production, lytic enzymes, antibiosis, and induced systemic resistance (ISR), have been extensively documented (Jacob *et al*.,2020). Endophytes strengthen the host's antioxidant system, decreasing reactive oxygen species (ROS) accumulation during heat, drought, and other abiotic stresses. Endophytic fungi boost plant stress resilience by secreting higher antioxidants and scavenging ROS, promoting climate-resilient, sustainable agriculture (Verma *et al*., 2022). Both enzymatic and non-enzymatic antioxidants prevent the accumulation of ROS in plant cells. By efficiently scavenging ROS, they mitigate cellular damage under stressful environments (Nie *et al*., 2024).

To support plant survival under adverse conditions, endophytes synthesize antimicrobials, osmoprotectants, and phytohormones. Notable examples include endophytic Enterobacter strains and Piriformospora indica, which have been shown to increase heat and drought tolerance in vegetables and cereals (De Souza *et al*., 2020). Endophytes contribute directly to plant defense by synthesizing and releasing metabolites with antimicrobial properties, including directly contributing to the synthesis and release of siderophores, antibiotics, and hydrolytic enzymes. Indirectly, they inhibit pathogens by competing for nutrients and colonization sites (Santoyo *et al*., 2015).

Integrated action of microbial consortia: Plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungus (AMF) can work together to enhance plant growth (Zhang *et al*., 2024). The combined activity of PGPR, AMF, and endophytes often produces synergistic effects that enhance plant resilience more effectively than individual microbial applications. Integrating these microbial groups leverages their complementary functions to improve plant growth and stress tolerance. The beneficial impacts that each organism can have on the plant can be increased or amplified by the interaction between PGPB and AMF (Santoyo *et al*., 2021).

AMF enhances nutrient uptake, which can stimulate endophyte activity, while PGPR increase root exudates, facilitating AMF colonization. These interactions collectively improve plant water and nutrient status, activate defense mechanisms, and modulate stress-responsive pathways, creating a coordinated system of stress alleviation. Munir *et al*., (2022) reported that beneficial microbes, involving PGPRs, AMFs, and endophytes, are fundamental for mitigating abiotic stresses and optimal plant development. Compared to single-strain inoculants, multi-microbial consortia (PGPR + AMF + endophytes) have demonstrated greater efficacy in increasing tolerance to abiotic stresses like drought, salinity, and heat, in addition to biotic stresses from pathogens. Such consortia act as an "extended genome" for the plant, enhancing metabolism, systemic defense, and overall resilience (Singh *et al*., 2023; Hanif *et al*., 2024; Liu *et al*., 2025). These integrated microbial interactions form the basis for understanding the stress-tolerance mechanisms mediated by the plant microbiome, which are discussed in the next section.

Stress-tolerance mechanisms mediated by the microbiome: PGPRs reduce metal toxicity, stimulate plant development, and improve mineral uptake via catalytic activities and metal binding capacity (Kumar *et al*., 2019). These microorganisms actively contribute to bioremediation processes by influencing metal availability via a range of mechanisms, such as the secretion of chelators, pH shifts, and phytohormones. By facilitating resource acquisition and serving as biocontrol agents to counteract pathogens' inhibitory effects, PGPRs enhance plant development. (Glick 2012; Hnini *et al*., 2024). Beneficial microbes, for example, PGPR, AMF, and endophytes, enhance plant resilience to abiotic and biotic stresses through multiple complementary mechanisms, including hormonal regulation, nutrient acquisition, osmotic adjustment, antioxidant defense, and microbial community reorganization.

Phytohormone regulation: Plant hormones, such as auxins, cytokinins, gibberellins, and ethylene, are influenced by microbial partners. ACC deaminase-producing PGPR decrease stress-induced ethylene accumulation, preventing growth inhibition during drought or salinity stress (Fanai *et al*., 2024; Hanif *et al*., 2024). This hormonal modulation promotes root and shoot development, enhancing overall plant vigor. Many phytohormones are naturally produced by plants but plants' associated microorganisms can also secrete these phytohormones, influencing plant responses. By modulating the metabolism of key phytohormones, these microbes alter signalling pathways and regulatory networks within the host plants (Dhar *et al*., 2022).

Nutrient acquisition and root development: PGPR and AMF enhance nutrient availability and root proliferation, expanding surface area for water and nutrient uptake, thereby developing plant tolerance in saline or nutrient-deficient soils (Li *et al*., 2025; Liu *et al*., 2025). To improve soil fertility and nutrient cycling and promote plant development, soil microorganisms play a crucial role. The two primary microorganisms found in the rhizosphere are AMF and PGPR (Fasusi *et al*., 2023). These interactions include pathogen/pest modulation through biocontrol processes, plant growth encouragement through phytostimulation, and nutrient supplementation through biofertilization (Song *et al*., 2021).

Osmotic adjustment and antioxidant define: Microbes endorse the build-up of soluble sugars, proline, glycine betaine, and other osmoprotectants, helping plants maintain cell turgor and osmotic balance under drought, salinity, and heat stress. For instance, plant-associated microbes improve plant drought acclimatization by osmoprotectant biosynthesis, maintaining cellular osmotic equilibrium (Chen *et al*., 2025). PGPR, AMF, and endophytes enhance antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX) activity, which mitigate reactive oxygen species (ROS) injury caused by abiotic and biotic stresses (Parasar *et al*., 2024; Ullah *et al*., 2025). Colonizing the root surface, plant growth-promoting rhizobacteria (PGPR) supply vital minerals including phosphate, potassium, and nitrogen while decreasing the harmful influences of salt stress (Neshat *et al*., 2022).

Beneficial microbes produce VOCs and secondary metabolites that activate systemic stress tolerance mechanisms. For example, Bacillus-derived VOCs have been reported to induce heat shock protein expression in stressed plants, enhancing thermotolerance (Li *et al*., 2025). The ecological interactions between microorganisms and plants depend heavily on microbial volatile organic compounds (mVOCs), which are essential for plant defense, communication, and growth promotion (Ali *et al*., 2025). Endophytes and rhizobacteria synthesize antimicrobial compounds, phytohormones, and osmoprotectants that contribute to pathogen suppression, growth promotion, and stress adaptation (De Souza *et al*., 2020). It was recently demonstrated that Mesorhizobium loti produces infection threads that could direct non-rhizobial endophytic bacteria onto nodule primordia in a selective manner. Together with rhizobia, these endophytes can then move and colonize the root nodule, taking advantage of the nodule's higher carbon contents (Zgadzaj *et al*., 2015).

Stress-induced microbiota reassembly: Abiotic stresses often alter root exudate profiles, which in turn reshape the rhizosphere microbial group. This selective enrichment favors beneficial microbes that can alleviate stress effects and provide plant growth. Chen and Liu (2024) revealed that root exudates influence colonization ability and facilitate root colonization by beneficial bacteria, and they play significant roles in rhizobacterial colonization and plant-microbe interactions. Plants under stress may actively recruit specific microbial taxa as an adaptive response, enhancing resilience through the enrichment of stress-alleviating microbes (Ge & Wang, 2025).

Improved water relations and osmotic balance: AMF hyphal networks and PGPR-mediated osmolyte production increase water uptake and maintain cell turgor, supporting photosynthesis and growth during drought and heat stress (Ge & Wang, 2025). Land plants form a mutualistic relationship with arbuscular mycorrhizal fungus (AMF), which profoundly influences plant growth, water uptake, inorganic nutrition, and tolerance to abiotic stresses. Plants function as highly adaptive and dynamic systems under fluctuating drought environments (Bahadur *et al*., 2019).

Defense activation and antioxidant priming: PGPR and endophytes activate plant antioxidant enzymes and prime signaling pathways (salicylic acid and jasmonic acid), enhancing systemic resistance against pathogens and reducing oxidative stress caused by abiotic factors (Ullah *et al*., 2025). When PGPRs interact with the host plant they are known to activate plant defences. Unlike the innate immune system, the plants' broad-spectrum, nonspecific immune system defends them in contrast to a wide range of phytopathogens (Seth *et al*., 2023).

Protection against pathogens: In addition to producing antimicrobial chemicals, endophytes and rhizobacteria compete with pathogens for resources and niches, providing broad-spectrum protection against foliar and soil-borne diseases (De Souza *et al*., 2020). Endophytes are intracellular organisms, mostly fungi and bacteria, that frequently colonize the internal tissue of plants. They include microorganisms that live within plants and can be readily isolated using standard microbial or plant growth media (Sawarkar *et al*., 2024).

Methods for enhancing the plant microbiome: Recognizing the intricate connection between the rhizosphere microbiota and root exudates brings up new possibilities for modifying microbial communities to improve agricultural yield (Kuroyanagi *et al*., 2022). Enhancing the plant microbiome is an auspicious plan to improve crop resilience against abiotic and biotic stresses. Various approaches, from microbial inoculants to host-directed breeding and advanced synthetic biology, can be used to optimize beneficial microbial communities.

Traditional microbial inoculants include well-characterized strains of *Bacillus, Trichoderma, Azospirillum*, and AMF. These inoculants promote growth and stress tolerance by enhancing nutrient uptake, hormone regulation, and defense activation. However, their field efficacy can be inconsistent due to competition with native soil microbiota and environmental variability (De Souza *et al*., 2020). The two most significant elements of the plant microbiome that are now being researched are arbuscular mycorrhizal fungi (AMF) and Trichoderma species; their interactions enhance plant health (Santoyo *et al*., 2021). Co-inoculation with complementary microbial strains improves ecological stability and functional redundancy. For example, consortia of Bacillus, Pseudomonas, and AMF have been exposed to improve tolerance to salinity and drought, providing synergistic benefits beyond single-strain applications (Ullah *et al*., 2025).

SynComs are small, well-defined microbial assemblies designed based on specific functional traits. These consortia facilitate mechanistic studies, reproducible results, and can be scaled for field applications. The development of SynComs is supported by gnotobiotic systems and iterative design pipelines (Liu *et al*., 2025). By using defined microbial communities, SynComs offer enhanced reproducibility, controlled interactions, and predictable functional outcomes compared to natural or single-strain inoculants. For example, SynCom inoculation promotes maize growth under low-fertility conditions, increasing root-shoot ratio by 78-121% (Jiang *et al*., 2023).

A novel artificial selection method called "microbiome breeding" aims to alter the genetic makeup of microbiomes for the benefit of plant or animal hosts (Mueller & Linksvayer, 2022). Plant genotypes differ in their capacity to recruit valuable microbes. Holobiont breeding targets plant traits, such as resistant responses and root architecture, that favor the assembly of advantageous microbiomes (Fanai *et al*., 2024). Modifying root exudation profiles can selectively enrich beneficial microbial taxa, enhancing stress tolerance and nutrient acquisition. Breeding or engineering plants with optimized exudates is a promising approach to guide microbial community composition (Fanai *et al*., 2024).

Field management techniques, including organic amendments, cover crops, and conservation tillage, and reduced chemical inputs, can enhance beneficial microbial populations, improve inoculant persistence, and stabilize the native microbiome (Etesami, 2024). Despite growing interest in leveraging microbial functions to improve crop productivity, resource efficiency, and stress resistance, research has struggled to harness the advantageous traits of agricultural microbiomes (French *et al*., 2021).

Genetic engineering and CRISPR-based tools can enhance microbial traits, such as osmolyte production or nutrient mobilization, to improve plant stress resilience. Riaz *et al*., (2025) reported that CRISPR-Cas9 technology can enhance rice productivity and resilience under environmental stress conditions, promoting food security and agricultural sustainability. Synthetic biology enables the creation of “smart microbes” capable of sensing environmental stressors and responding with protective mechanisms. However, regulatory and biosafety considerations remain key challenges for field applications (Hanif *et al*., 2024) Table 1.

Technologies that facilitate microbiome optimization: Recent technological advancements provide powerful tools to study, manipulate, and apply plant-associated microbiomes for improving stress resilience. Advances in technology have enabled new methods to study, modify, and use plant-associated microbiomes to increase stress resilience. These approaches provide mechanistic insights, supportive predictive management, and allow precise identification of advantageous microorganisms (Clouse & Wagner, 2021). These approaches allow precise identification of beneficial microbes, mechanistic insights, and predictive management strategies.

Metabolomics, metagenomics, and metatranscriptomics reveal stress-responsive microbial taxa and functional pathways. Integrated omics analyses have identified microbial fingerprints associated with drought tolerance in cereals, enabling targeted selection and application of beneficial microbes (Li *et al*., 2025). Advances in culturing techniques have expanded the diversity of cultivable microorganisms, facilitated the assembly of well-defined synthetic communities (SynComs), and improved reproducibility in experimental and field applications (Liu *et al*., 2025).

Controlled systems, such as rhizoboxes and root-on-a-chip platforms, allow detailed study of plant-microbe-stress interactions under reproducible conditions. These platforms help evaluate microbial functions, root architecture responses, and stress mitigation strategies (De Souza *et al*., 2020). Machine learning and predictive modeling integrate climate, soil, and microbiome data to estimate the performance of microbial inoculants under site-specific conditions. These approaches enable data-driven decision-making for precision microbiome management in the field (Ge & Wang, 2025).

Applications in agriculture: Harnessing plant-associated microbiota provides effective approaches for sustainable farming by improving stress resilience, improving nutrient acquisition, and reducing reliance on chemical inputs. The use of microbiological inoculants gives an excellent chance to improve agricultural landscapes (Yusuf *et al*., 2025). Agricultural productivity relies on the interplay between soil microbiota and plant cultivars. Cultivars with a stronger microbiome interaction trait (MIT) are expected to achieve superior performance with decreased dependence on chemical inputs.

Field applications of beneficial microbes, including PGPR, AMF, and endophytes, have established potential for improving crop growth and biotic and abiotic stress tolerance. Both single-strain inoculants and multi-strain consortia are being developed as bioformulations to deliver targeted benefits under diverse environmental conditions (Etesami, 2024). These microorganisms are essential to ecological processes like mineralization, organic matter breakdown, and nutrient recycling. As an eco-friendly substitute to chemical inputs, for chemical fertilizers and pesticides, plant growth-promoting rhizobacteria (PGPR) offer a promising tool for sustainable farming by facilitating green control, health, and growth of plants (Argentel-Martínez *et al*., 2025).

Microbiome-based strategies can be synergistically combined with plant breeding and agronomic practices to enhance crop performance. Breeding for traits that favor beneficial microbial recruitment, manipulating root exudates, and implementing soil management practices such as cover cropping, organic amendments, and decreased tillage can stabilize plant–microbiome interactions across varied agroecosystems (Etesami, 2024). Microbiota-based approaches thus contribute to environmentally friendly, climate-smart agriculture while maintaining or improving crop productivity (Etesami, 2024).

Prospects and challenges: There is great potential for increasing crop resilience to biotic and abiotic challenges by maximizing the plant microbiome. However, there are several limits on the use of microbial inoculants in agricultural fields that need to be overcome to generate reliable and extensive results. The performance of microbial inoculants is often inconsistent due to host specificity, competition with native microbiota, and environmental variability. These factors limit the effectiveness of single-strain or multi-strain inoculants under diverse field conditions, posing a major challenge for their large-scale adoption (Liu *et al*., 2025). Integrating microbial inoculants with sustainable soil management practices, for example, organic amendments, cover crops, and reduced tillage, can enhance microbial survival, enhance functional diversity, and support native microbiome resilience across varying agroecosystems (Etesami, 2024; Hanif *et al*., 2024).

Recent technological advancements offer innovative solutions to overcome current limitations. High-resolution omics approaches (metagenomics, metatranscriptomics, and metabolomics) can identify keystone taxa and stress-responsive functional genes. Systems biology enables the modeling of complex plant–microbe–environment interactions, while synthetic biology and CRISPR-based editing facilitate the creation of “smart” microbial communities with enhanced stress-protective traits (Ge and Wang, 2025; De Souza *et al*., 2020). By integrating microbiome-aware breeding, rationally designed microbial consortia, and sustainable management practices, it is possible to develop resilient agroecosystems capable of withstanding climate-induced stresses. These methods can reduce the need for chemical pesticides and fertilizers, promote sustainable productivity, and contribute to climate-smart agricultural systems (Etesami, 2024; Hanif *et al*., 2024).

Table 1. Optimizing the microbiome to improve plant stress.

No	Section	Main topic	Key Points	Examples / References
1.	Introduction	The plant microbiome's function in stress tolerance	By controlling phytohormones, enhancing nutrition and water uptake, and triggering antioxidant defenses, beneficial microorganisms (PGPR, AMF, and endophytes) increase tolerance to drought, salinity, heat, and infections	Li *et al*., 2025; Hanif *et al*., 2024
2.	Types of beneficial microbes	PGPR, AMF, Endophytes	- PGPR: Systemic resistance, N fixation, and hormonal control.AMF: Water interactions, defense activation, and nutrient uptake. Endophytes: synthesis of metabolites, disease resistance, and antioxidant improvement.	Bouremani *et al*., 2023; Wahab *et al*., 2023; Velmurugan *et al*., 2023
3.	Stress-tolerance mechanisms	Mechanisms for enhancing stress resilience	-Hormonal regulation (ethylene is decreased by ACC deaminase activity). Osmoprotectant buildup (sugars, proline). Activation of antioxidant enzymes (SOD, CAT, APX). VOCs and the production of secondary metabolites	Fanai *et al*., 2024; Chen *et al*., 2025; Parasar *et al*., 2024
4.	Methods for Enhancing the Microbiome	Methods for optimizing the microbiome	- Inoculants with one or more strains. Synthetic communities of microorganisms (SynComs). Breeding holobionts and manipulating root exudate. Sustainable methods for managing soil	Ullah *et al*., 2025; Liu *et al*., 2025; Etesami , 2024
5.	Technologies Facilitating Optimization	Advanced analytical and engineering tools	The use of omics techniques (metabolomics, metagenomics). Phenotyping and microcosm systems. AI-based technologies and predictive modeling	Clouse & Wagner, 2021; Ge and Wang, 2025
6.	Agricultural Applications	Using advantageous microorganisms in agriculture	Bioformulations containing endophytes, PGPR, and AMF. Integration with soil management and plant breeding. Decreased reliance on chemical pesticides and fertilizers	Etesami, 2024; Yusuf *et al*., 2025
7.	7Future Prospects and Challenges	Stability in the field and extensive use	The challenges of environmental variability and microbial uniqueness. Integration with CRISPR-based microbiome engineering and systems biology	Liu *et al*., 2025; Hanif *et al*., 2024

Conclusion and Future Prospects

The plant microbiome represents a promising and sustainable avenue for enhancing crop resilience against the increasing frequency of abiotic and biotic stresses driven by climate change and intensive agriculture. Beneficial microbes, including plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and endophytes, contribute to stress mitigation through multiple mechanisms such as phytohormone regulation, improved nutrient and water acquisition, osmotic adjustment, antioxidant activation, and systemic resistance against pathogens. The synergistic action of microbial consortia often surpasses the benefits of single-strain inoculants, emphasizing the importance of integrated microbial strategies. The plant microbiome represents a promising and sustainable avenue for enhancing crop resilience against the increasing frequency of abiotic and biotic stresses driven by climate change and intensive agriculture. Beneficial microbes, including plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and endophytes, contribute to stress mitigation through multiple mechanisms such as phytohormone regulation, improved nutrient and water acquisition, osmotic adjustment, antioxidant activation, and systemic resistance against pathogens. The synergistic action of microbial consortia often surpasses the benefits of single-strain inoculants, emphasizing the importance of integrated microbial strategies.

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