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Review Article

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Harnessing Beneficial Microbes for Abiotic Stress Tolerance and Nutrient Uptake in Horticultural Crops: Mechanisms, Applications and Future Prospects

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Abstract

Abiotic stresses, including drought, salinity, and nutrient limitations, pose significant threats to horticultural productivity and soil integrity. Beneficial microorganisms-such as arbuscular mycorrhizal fungi , plant growth-promoting rhizobacteria , and endophytes-provide sustainable solutions by enhancing plant stress tolerance, nutrient acquisition, and soil health. This review critically examines the mechanisms by which these microbes alleviate stress, highlighting their roles in hormonal regulation, antioxidant defense, osmotic balance, and modulation of gene expression. Particular attention is given to microbial consortia, which often outperform single-strain inoculants under complex, multi-stress environments. Grapevine is employed as a representative model to illustrate species-specific microbial interactions. Additionally, recent innovations in microbial delivery including drip fertigation and portable bioreactors are evaluated for their potential to translate laboratory insights into field-level applications. By synthesizing advances across microbial taxa and delivery technologies, this review emphasizes the transformative potential of microbiome-based strategies for sustainable and climate-resilient horticultural systems.

Keywords: Abiotic Stress, Mycorrhizae, Nutrient Uptake, Soil Health, Sustainable Agriculture.

Introduction:

Climate-induced hydric and edaphic stresses, declining soil fertility, and lower crop productivity are increasingly challenging modern horticulture worldwide (Das et al. 2022; Caicedo-Lopez et al., 2021). Excessive reliance on synthetic agrochemicals exacerbates environmental degradation, undermining long-term soil health and resilience (Meena et al., 2017). Beneficial soil microorganisms, such as arbuscular mycorrhizal fungi and plant growth-promoting rhizobacteria, provide an eco-friendly approach to alleviating abiotic stresses and improving nutrient acquisition. These microbes enhance soil structure, water-holding capacity, nutrient bioavailability, and plant stress tolerance (Khaliq et al., 2022). With salinity affecting 1 billion hectares globally and projections suggesting that half of all arable land could face salinization by 2050, sustainable interventions are urgently needed (Rahman, Biswas, and Meena 2024; Basak et al., 2022). Conventional remediation techniques remain costly and environmentally unsustainable (Wang et al., 2023). In contrast, plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi naturally enhance resilience by improving nutrient uptake, soil fertility, and reducing dependency on chemical inputs (Brokate, Papenbrock & Turcios 2024). Increasing drought incidence has made water scarcity a major limitation for horticultural productivity and food security (Zhang et al., 2020). Hydrological disruptions alter plant-soil water interactions, causing significant yield losses. Root exudates in the rhizosphere shape microbial communities that modulate drought responses (Aslam et al., 2022). Rhizosphere microbes, notably PGPR such as Azospirillum and Pseudomonas, enhance photosynthetic efficiency, mitigate oxidative stress, and improve drought tolerance (Chieb & Gachomo 2023). Chronic stresses, including drought, salinity, heavy metals, and extreme temperatures, can reduce yields by up to 70% (Ashokan et al., 2024). AM fungi provide sustainable mitigation by boosting nutrient uptake and stress tolerance while lowering dependence on chemical fertilizers (Corratgé-Faillie et al., 2022). AM symbiosis activates genes and hormone pathways that sustain plant growth under stress, though agrochemical interactions and field performance remain challenges needing further exploration (Ahmed et al., 2024).

Grapevine (*Vitis vinifera* L.) is one of the most widely cultivated fruit crops, grown in many parts of the world under varying climatic conditions for both fresh and processed products. Abiotic stresses such as drought, salinity, and nutrient deficiency, exacerbated by climate change, threaten both productivity and fruit quality (Mickelbart, Hasegawa, & Bailey-Serres 2015). These stresses impair grape physiology by disrupting photosynthesis, water balance, and metabolic homeostasis, often inducing oxidative damage and reducing yield and quality (Carvalho, Vidigal, & Amâncio, 2015). Stress responses vary among cultivars and rootstocks-for instance, 'Grenache Noir' shows heat tolerance, whereas 'Chardonnay' is sensitive to salinity-highlighting the need for targeted adaptation strategies (Zhou-Tsang et al. 2021). Rootstocks modulate physiological traits and shape rhizosphere microbial communities, which support stress tolerance, nutrient cycling, and plant-microbe interactions (Santesteban et al., 2023). PGPR, endophytes, and arbuscular mycorrhizal fungi (AMF) contribute to sustainable viticulture by enhancing nutrient absorption, ROS detoxification, and hormonal regulation (Basile et al., 2020). They can also reprogram gene expression and metabolic pathways, enabling plants to better withstand abiotic stresses (Pacifico et al., 2019). Notably, microbial consortia, combining multiple beneficial strains, outperform single-strain inoculants, particularly under multifactorial stress conditions (Habib, Kausar & Saud 2016).

To address climate-driven stresses and promote sustainable horticulture, this review focuses on PGPR, AMF, endophytes, and microbial consortia, examining their collective roles in stress mitigation, nutrient acquisition, and gene regulation. By synthesizing recent findings and identifying research gaps, it highlights microbiome-based innovations that advance climate-resilient, low-input horticulture (Ansabayeva et al., 2025).

Literature survey:

Extensive research has demonstrated the vital role of beneficial microbes-including PGPR, AMF, endophytes, and microbial consortia-in enhancing crop resilience to abiotic and biotic stresses. These microbes improve nutrient uptake, regulate hormones, and activate stress defense pathways across diverse horticultural and field crops. The combined application of multiple microbial groups often yields superior results compared to single strains. The following table summarizes key studies highlighting microbial mechanisms and their impacts on crop productivity and stress tolerance.

Mechanisms of stress tolerance induced by beneficial microbes

Beneficial microorganisms, including AMF, PGPR, and endophytes, enhance horticultural crop tolerance to drought, salinity, and heat stress by improving nutrient acquisition, hormonal regulation, antioxidant defenses, and stress-responsive gene expression. Mycorrhizal fungi such as *Rhizophagus irregularis* and *Funneliformis mosseae* increase water uptake and antioxidant activity by modulating genes like *VvNCED1* (ABA) and *VvP5CS* (proline) (Dagher et al., 2025). They also enhance chlorophyll content and volatile compound accumulation under stress (Velasquez et al., 2020), while *R. irregularis* regulates miRNAs and the phenylpropanoid pathway (Campos et al., 2020). PGPR strains, including *Bacillus subtilis* and *Pseudomonas fluorescens*, stimulate phytohormone production, reduce ethylene via ACC deaminase activity, and elevate chlorophyll and antioxidant levels (Navarro-Torre et al., 2023). *Bacillus amyloliquefaciens* (QST 713) promotes growth under drought by modulating hormonal pathways (Papantzikos et al., 2024). PGPR consortia, such as *Pantoea agglomerans* and *Micrococcus luteus*, further enhance stress tolerance by increasing proline accumulation, photosynthetic efficiency, and enzymatic activity (Navarro-Torre et al., 2023). Endophytes like *P. fluorescens* RG11 and *Serendipita indica* activate melatonin and antioxidant pathways, improving oxidative protection and ion homeostasis (Ma et al., 2017, Alimam et al., 2024). Overall, microbial consortia consistently outperform single strains due to their synergistic effects on stress mitigation.

Table 1: Summary of Reviewed Literature on Beneficial Microbes in Horticulture

Key Findings	Microbial Group	Crop/Context	Stress Targeted	Mechanisms/Effects	Reference
Boost growth, cut chemicals, ensure resilient farming.	PGPMs (PGPR, PSRB, BCAs -Bacteria & Fungi)	Wheat, Maize, Tomato, Chili	Salinity, Pathogens	Nutrient mobilization, growth promotion, and pathogen control.	Ansabayeva et al., 2025
AMF boosts stress genes, hormones, soil fertility, and crop resilience.	Arbuscular Mycorrhizal Fungi (AMF)	Soybean, Maize, Rice, Wheat, Citrus	Drought, Salinity, Heavy Metals	Nutrient uptake, hormone modulation, and stress defense.	Ahmed et al., 2025
PGPR enhances drought tolerance and yield by reshaping the rhizosphere.	PGPR (*Azospirillum, Bacillus, Pseudomonas*)	Wheat, Maize, Rice, Soybean, Sorghum	Drought	Stress relief via N fixation, ROS control, and hormone balance.	Liu et al., 2025
Algal-microbial bio stimulants boost resilience and promote a circular economy.	PGPR, AMF, Microalgae, Cyanobacteria	Horticulture crops	Drought, Salinity	Growth aid via hormones, nutrients, and ROS control.	Brito-Lopez et al., 2025
Multi-species consortia excel, backed by gene-level evidence for field use.	AMF, PGPR, Endophytes, Microbial Consortia	Grapevine (*Vitis vinifera*)	Drought, Salinity, Heat	Gene control, melatonin, antioxidants,	Dagher et al., 2025
Oil microbes ease drought stress and boost nutrients.	Bacteria, Fungi, Archaea, PGPR	General crops	Hydric & Edaphic	Nutrient cycling, biofilms, soil health, detox, and defense.	Das et al., 2025
PGPR and AMF boost yield and stress tolerance.	PGPR, AMF, *Trichoderma, Bacillus spp.*	General crops (wheat, maize, rice, tomato)	Drought, Nutrient Deficiency	Hormones, root growth, nutrient uptake, and defense.	Chen et al., 2024
Enhance soil, nutrients, roots; growing mycorrhizae and rhizobia use.	Bacteria, Fungi, Actinomycetes	General crops	Pathogens, nutrient loss	EPS, hormones, stress relief, and defense.	Wei et al., 2024
Inoculants boost yield and resilience through PGPR, AMF, and rhizobia synergy.	PGPR, AMF, Rhizobia, Endophytes	Maize	Drought, Salinity, Heat, Biotic	ROS detox, osmoregulation, gene and hormone control, stress proteins.	Burlakoti et al., 2024
Bacillus Mix and Bio Veria significantly increased the lettuce yield	Bacillus Mix and Bio Veria	Batavia lettuce (*Lactuca sativa*)	Fertilization regime	Yield and nutritional content.	UCAR et al., 2025
Microbes boost olive stress tolerance and sustainability.	PGPR, PGPF (including AMF, *Trichoderma*)	Olive trees	Drought, Salinity, Heat	Nutrient uptake and photosynthesis.	Dias et al., 2024
Better growth, yield, stress resistance, and soil health.	Arbuscular Mycorrhizal Fungi (AMF)	Various (e.g., maize, tomato, soybean, etc	salinity, heavy metals, pathogens	Improved nutrient uptake, antioxidants, osmoregulation, and hormones.	Wahab et al., 2023
Boosts soil fertility, nutrient cycling, crop stress tolerance.	PGPR & AMF	Various (e.g., legumes, cereals)	Biotic and abiotic	N fixation, siderophores, P solubilization, hormone production.	Fasusi et al., 2023
PGPR-AMF synergy boosts yield, quality, and stress tolerance.	PGPR & AMF	Horticultural crops (e.g., lettuce, tomato, onion, citrus)	Nutrient deficiency, cold, pathogens	N fixation, nutrient solubilization, hormones, and defense.	Shahrajabian et al., 2023

Table 2. Mechanisms of Abiotic Stress Tolerance Induced by Beneficial Microbes in Grapevines

Microbial Group	Species/Inoculant	Type of Stress	Mechanism of Action	Reference
AMF	*Glomus mosseae*	Drought	Enhanced water and nutrient uptake	Kamayestani et al., 2019
	Funneliformis mosseae	Heat, Drought	VOC production, antioxidant activation	Nogales et al., 2021
	Rhizophagus irregularis	Salinity	Improved root growth and P uptake	Sensoy, 2022
PGPR	*Bacillus subtilis, Pseudomonas fluorescens*	Drought, Salinity	Phytohormone modulation, ACC deaminase	Karaca & Sabir, 2018
	Pantoea agglomerans, Micrococcus luteus	Salinity, Arsenic	Increased auxins, antioxidant enzyme activity	Karaca & Sabir, 2018
Endophytes	*Serendipita indica*	Drought	Cytokinin and proline accumulation	Ma et al., 2017
	Pseudomonas fluorescens RG11	Salinity	Melatonin biosynthesis and ROS scavenging	Karimi & Noori, 2022
Consortia	AMF + PGPR (*Glomus mosseae + Streptomyces*)	Salinity	Hormonal balance and chlorophyll stability	Alimam & Al-A'Areji, 2024

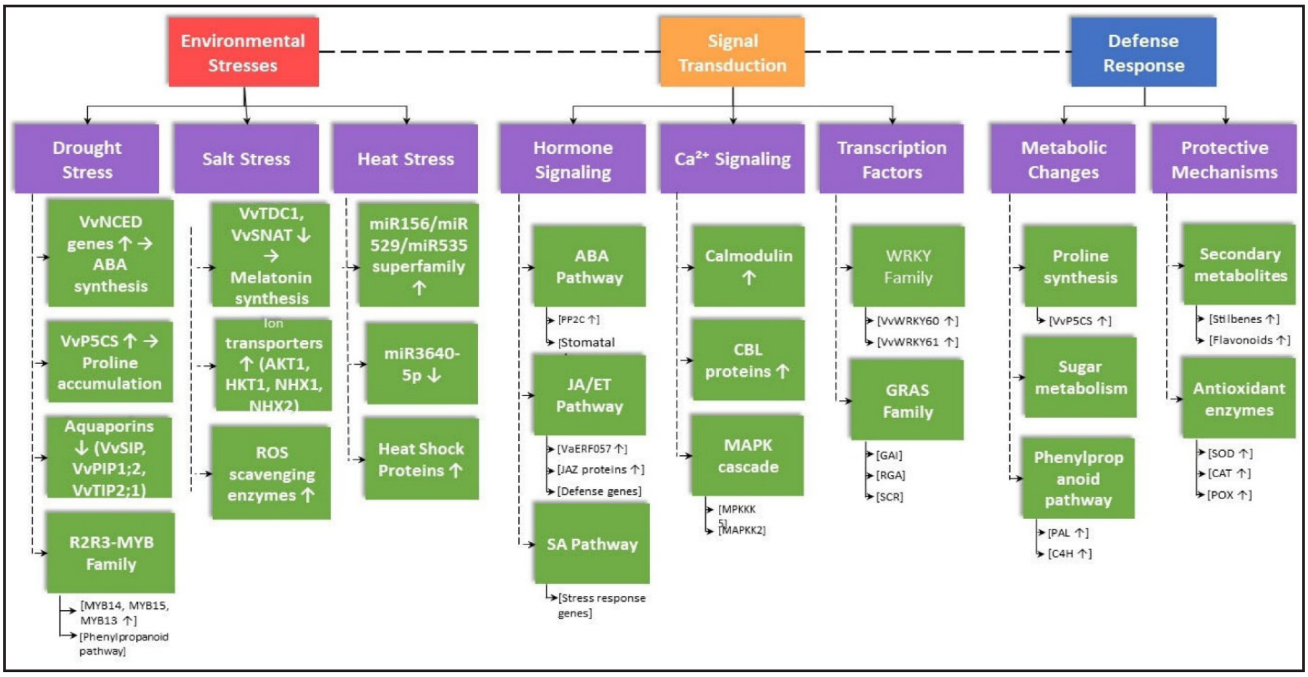

Figure 1: Schematic representation of plant responses to abiotic stresses (Dagher et al, 2025)

Under diverse abiotic stresses such as drought, salinity, and heat, plants activate an intricate network of molecular signaling pathways that coordinate physiological and biochemical defense mechanisms. Environmental stress perception triggers hormonal (ABA, JA/ET, and SA) and calcium-mediated signaling cascades, which subsequently modulate the activity of key transcription factors including WRKY, MYB, and GRAS families. These transcriptional regulators govern the expression of genes involved in proline accumulation, sugar metabolism, phenylpropanoid biosynthesis, and antioxidant enzyme activation (SOD, CAT, and POX). Such coordinated regulation leads to the synthesis of compatible solutes, enhancement of secondary metabolites, and maintenance of redox balance, thereby improving stress resilience and cellular homeostasis. This integrative model, as summarized in Figure 1 (Dagher et al., 2025), highlights the interconnectedness of stress perception, signal transduction, and defense responses in plants.

Role of soil microorganisms in nutrient dynamics and crop productivity:

Soil microorganisms are fundamental to soil fertility and sustainable agricultural practices, particularly within the rhizosphere, the interface between roots and soil where essential nutrient and growth processes occur. Nitrogen-fixing bacteria such as *Rhizobium*

Table 3. Microbial Roles in Soil Fertility

Microorganism Type	Organic Acids Released	Enzymes Produced	Degraded Substrate	Fertility Enhancement Role	Reference
Bacteria	Acetic acid, Citric acid	Cellulases, Proteases	Cellulose, Proteins	Enhances N, P, K availability	Xing et al., 2025
Fungi	Oxalic acid, Gluconic acid	Ligninases, Amylases	Lignin, Starch	Improves structure and nutrient cycling	Corbu et al., 2023b
Actinomycetes	Lactic acid, Propionic acid	Chitinases, Phosphatases	Chitin, Organic phosphates	Solubilizes phosphate and micronutrients	Kerchev & Van Breusegem, 2022
Archaea	Sulfuric acid	Ammonia Oxidases	Ammonia	Enhances nitrogen availability via nitrification	Lu et al., 2020
Protozoa	Acetic, Butyric acids	Hydrolytic Enzymes	Organic debris	Recycles nutrients through predation on microbes	Bhujbal et al., 2022
Yeasts	Malic acid, Succinic acid	Invertases, Lipases	Sugars, Lipids	Increases available carbon pool	Gong et al., 2024

and phosphate-solubilizing bacteria enhance nutrient availability by converting atmospheric nitrogen and releasing phosphorus from insoluble forms (Fahde et al., 2023; Zhang et al., 2025). Microbial enzymes decompose organic matter, increasing the accessibility of macronutrients (Corbu et al., 2023). By producing polysaccharides, these microbes improve soil structure, water-holding capacity, and root development (Philpott et al., 2024). They also synthesize phytohormones, including auxins and gibberellins, which stimulate root growth and enhance drought tolerance (DeLonge et al., 2016). Arbuscular mycorrhizal fungi (AMF) expand root networks, facilitating the uptake of less mobile nutrients such as phosphorus and zinc (Mitra et al., 2023). Additionally, many microbes, including *Pseudomonas* and *Trichoderma*, protect plants by suppressing pathogens and activating systemic resistance through defense-related genes and proteins (Mitra et al., 2023; Ravelo-Ortega et al., 2023; Xing et al., 2025). Collectively, these functions reduce dependence on chemical inputs and promote long-term crop health.

Microbial community structure and the influence of cropping practice

Soil microbial community composition is highly shaped by cropping practices. Monoculture systems often diminish microbial diversity and can favor opportunistic or pathogenic species (Gu et al., 2021). In contrast, crop diversification strategies, such as rotation and intercropping, produce varied root exudates that promote a more balanced and resilient microbial community (Zhou et al., 2021). Overapplication of chemical fertilizers, particularly nitrogen and phosphorus, can disrupt this equilibrium by stimulating fast-growing microbes while inhibiting beneficial species essential for nutrient cycling and disease suppression (Simansky et al., 2024). Likewise, frequent tillage adversely affects microbial habitats, whereas conservation tillage and the use of organic amendments help preserve microbial diversity and improve soil structure (Gupta et al., 2022). Integrating crop diversification, organic inputs, and reduced chemical reliance enhances beneficial microbial populations, thereby supporting soil health, nutrient use efficiency, and sustainable agricultural systems.

Biofertilization and biocontrol potential:

The widespread dependence on chemical fertilizers poses significant environmental concerns, including soil degradation, water contamination, eutrophication, and increased greenhouse gas emissions associated with their energy-intensive production (McGuire et al., 2015). In contrast, microbial biofertilizers provide an eco-friendly alternative by facilitating sustainable nutrient cycling through natural biological processes (Mahanty et al., 2017). This encompasses nitrogen fixation by commonly used *Azotobacter chroococcum* and *Azotobacter vinelandii* (Mącik et al., 2020), as well as phosphate solubilization by strains such as *Bacillus megaterium*, *B. amyloliquefaciens* IT45, and *Pseudomonas fluorescens*. For potassium mobilization, *Frateuria aurantia* is applied commercially, while *Thiobacillus thiooxidans* and *Delfia acidovorans* enhance sulfur and zinc availability (Mącik et al., 2020). Many of these microbes also synthesize plant hormones, including Indole Acetic Acid (IAA), promoting root development and nutrient uptake, as observed in *Pseudomonas fluorescens* K-34, *P. fluorescens* 1773/K, and *Bacillus circulans* (Koolayan et al., 2012). By effectively colonizing the rhizosphere and roots, these microorganisms optimize plant growth without harming the environment (Bhardwaj et al., 2014). Their activities improve soil fertility, support long-term crop productivity, and contribute to environmental sustainability, making them promising alternatives to chemical fertilizers in modern agriculture.

Commercial applications and formulations :

Commercial AMF-based bioformulations are increasingly popular for boosting plant growth, nutrient uptake, and stress resilience. Products like Micosat F, Myke Pro, Dynamyco, and Plant Success combine AMF species (*Glomus intraradices, G. mosseae, Rhizophagus intraradices*) with beneficial microbes such as *Bacillus*, *Pseudomonas*, *Azospirillum*, and *Trichoderma* spp. (Ghorui et al., 2025). These inoculants are chosen for their adaptability to hosts, environmental compatibility, and genetic stability (Alladi et al., 2017). Formulations come in solid, liquid, encapsulated, and nanofiber types, each offering benefits in shelf life and delivery. Additives like trehalose, glycerol, and PVP, along with spray-drying and freeze-drying, extend shelf life up to 12 months (Zhou et al., 2017). Application varies from soil treatments to seed coatings, all optimized for rhizosphere colonization (Joshi et al., 2019). While innovations such as ROC systems producing up to 500,000 spores/L are promising, challenges remain, including field inconsistency, low farmer awareness, and regulatory hurdles. Nevertheless, with continued R&D and effective formulation strategies, microbial inoculants offer significant potential for sustainable agriculture.

Engineering innovations in microbial delivery and application systems:

Irrigation-integrated microbial delivery systems:

Drip and sprinkler irrigation systems are increasingly utilized not only for crop watering but also for the targeted delivery of microbial bioinoculants to the root zone. This strategy is particularly advantageous for horticultural crops requiring consistent and localized microbial colonization. These systems employ dosing pumps, inline Venturi injectors, and UV-sterilizable filters to deliver aqueous microbial formulations while minimizing clogging and contamination. The integration of such delivery mechanisms is critical for effective soil health interventions. Islam et al. (2020) reported that drip-applied PGPR enhanced root colonization in nutrient-deficient soils, improving nutrient uptake and drought tolerance. Additionally, these systems reduce manual labor and ensure precise dosing, especially when combined with fertigation routines. Studies by Rawal et al., (2024) and Kaul et al., 2021 demonstrate the high effectiveness of irrigation-mediated microbial applications in both open-field and greenhouse settings. Notably, this approach offers a more cost-efficient and environmentally sustainable alternative to conventional methods such as broadcasting or seed pelleting (Torky & Hasanein, 2020).

Mobile bioreactor units for on-site inoculant production:

Microbial inoculant viability frequently decreases during transport and storage, particularly in warm climates. Mobile bioreactors address this challenge by enabling on-site production of fresh, high-quality PGPR and mycorrhizal cultures. These systems, equipped with stirrers, air pumps, sensors, and automated valves, maintain over 95% viability when applied within 24 hours (Rawal et al., 2024). This approach allows the formulation of tailored inoculants that suit specific soil characteristics and local environmental conditions, making them particularly suitable for nurseries, organic farms, and protected cultivation systems. Their modular and scalable design also allows seamless integration with existing irrigation or spraying infrastructure. As highlighted by Gavrilescu (2010) and Kaul et al. (2021), mobile bioreactors play a crucial role in enhancing accessibility and reducing costs in areas lacking centralized microbial production facilities.

Challenges and Future Perspective:

Despite the remarkable potential of beneficial microbes for enhancing abiotic stress tolerance and nutrient uptake in horticultural crops, several challenges limit their widespread adoption. Field application often faces inconsistencies due to environmental variability, soil heterogeneity, and competition with native microbial communities, which can reduce inoculant efficacy (Singh et al., 2024). Maintaining microbial viability during storage, transport, and field application remains a significant hurdle, especially for sensitive AMF and PGPR strains. Furthermore, limited farmer awareness, regulatory restrictions, and the high cost of high-quality inoculants constrain large-scale adoption.

Table 4. Engineering Innovations in Microbial Delivery and Application Systems

Technology	Microbial Target	Application Mode	Key Mechanical Component	Advantages	Reference
Drip Fertigation	PGPR, Mycorrhiza	Root Zone	Dosing pump, filters	Uniform distribution, low stress	Islam et al., 2020
Mobile Bioreactors	PGPR, Mycorrhiza	On-farm production	Fermenter tank, pH/ temperature control	Fresh culture, reduced cost	Rawal et al., 2024

Future research should focus on integrating microbial biotechnology with advanced delivery systems to overcome these limitations. Irrigation-integrated inoculation, AI-guided fertigation, and mobile bioreactors can improve site-specific inoculation, enhance microbial colonization, and ensure consistent performance across diverse agro-ecosystems (Rawal et al., 2024). Developing resilient microbial consortia capable of functioning under multifactorial stresses offers further potential to enhance plant stress tolerance. Additionally, combining microbial applications with precision agriculture, microbial encapsulation, and genome editing techniques like CRISPR could enable the creation of designer microbes tailored to specific crops, soils, and climates.

Overall, addressing these challenges and leveraging technological innovations will be key to translating laboratory advances into practical, sustainable, and climate-resilient horticultural practices. By bridging gaps between research, commercialization, and on-farm application, microbiome-based strategies hold promise for supporting global food security while reducing dependence on chemical inputs.

Conclusion:

Beneficial microorganisms, including Arbuscular Mycorrhizal Fungi (AMF), Plant Growth-Promoting Rhizobacteria (PGPR), and endophytes, play a pivotal role in alleviating abiotic stresses and enhancing nutrient uptake in horticultural crops. These microbes strengthen crop resilience, reduce reliance on chemical inputs, and promote long-term soil health. Recent developments in microbial inoculants, both single strains and consortia demonstrate substantial potential for climate-smart and precision agriculture. Microbial consortia, in particular, often outperform single strains under multiple stress conditions by modulating plant hormones, antioxidant systems, and stress-responsive gene networks. Beyond plant stress mitigation, microbial activity improves soil structure, fertility, and innate disease resistance, providing a holistic approach to sustainable horticulture. While smart delivery systems such as drip fertigation, and mobile bioreactors facilitate field-level application, the true transformative potential lies in harnessing the inherent power of these microorganisms to buffer crops against drought, salinity, heat, and nutrient deficiencies. Integrating microbial strategies with targeted precision tools promises resilient, high-yielding, and environmentally sustainable horticultural systems.

Declaration of conflict of interest and ethical approval:

The authors declare that there are no conflicts of interest regarding publication of this paper.

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