

PLANT MICROBIOMES AND CLIMATE RESILIENCE

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ABSTRACT



Plant microbiomes, comprising diverse communities of bacteria, fungi, and archaea, play a vital role in enhancing plant resilience under changing climatic conditions. These microorganisms, particularly in the rhizosphere, form mutualistic associations with plants and contribute to nutrient acquisition, hormonal regulation, and stress mitigation. Climate change, characterized by rising temperatures, altered precipitation patterns, and increased frequency of extreme events, significantly influences plant–microbe interactions. Understanding these dynamic relationships is essential for developing climate-resilient agricultural systems. Advances in microbiome research, including microbial consortia design and metagenomics, offer promising strategies for sustainable crop production under environmental stress.

KEYWORDS: Abiotic stress, Climate resilience, Plant microbiome, Rhizosphere, Sustainable agriculture

INTRODUCTION

Plants do not exist in isolation but interact continuously with complex microbial communities that inhabit their immediate environment. These communities, collectively referred to as the plant microbiome, include bacteria, fungi, and archaea that colonize plant surfaces and the rhizosphere. Among these, rhizosphere microorganisms are particularly significant due to their close association with plant roots and their direct influence on plant growth and health.

In recent years, plant microbiomes have gained considerable attention for their role in enhancing plant tolerance to abiotic stresses such as drought, salinity, and temperature extremes. As climate change intensifies these stresses, understanding plant–microbe interactions has become increasingly important for ensuring food security and sustainable agricultural production. These microbial communities function as an extension of the plant system, contributing to nutrient cycling, stress tolerance, and overall plant resilience.

ROLE OF PLANT MICROBIOMES IN ENHANCING STRESS TOLERANCE

Plant-associated microorganisms contribute significantly to plant adaptation under adverse environmental conditions. In the rhizosphere, plants release root exudates comprising sugars, amino acids, and organic acids—that serve as energy sources for microbial communities. In return, these microorganisms establish mutualistic relationships that benefit plant growth and survival.

One of the primary mechanisms through which microbiomes enhance plant resilience is improved nutrient acquisition. Under stress conditions, nutrient availability often becomes limited due to reduced soil moisture or altered soil chemistry. Beneficial microbes facilitate nutrient solubilization and mobilization, thereby improving plant access to essential nutrients.

Microbial communities also regulate plant hormonal pathways, which are crucial for stress adaptation. For instance, abscisic acid (ABA), a key stress hormone, plays an essential role in regulating stomatal closure during drought conditions. Certain microbes can influence ABA synthesis and signalling, thereby enhancing plant water-use efficiency. Additionally, microorganisms produce secondary metabolites such as osmoprotectants and antioxidants that help plants cope with stress-induced damage.

Another important contribution of microbiomes is the induction of systemic tolerance. Rather than confining their effects to localized regions, beneficial microbes can trigger whole-plant responses that improve resilience across different tissues. Furthermore, rhizosphere microorganisms enhance root architecture by promoting the formation of lateral roots and root hairs, which increases the plant's ability to absorb water and nutrients under stress conditions.

Beyond direct plant interactions, microbial activity also improves soil health by enhancing soil structure, organic matter content, and nutrient cycling. These indirect effects further contribute to plant growth and resilience in challenging environments (Trivedi et al., 2022).

CLIMATE CHANGE AND ITS IMPACT ON PLANT–MICROBE INTERACTIONS

Climate change is significantly altering the dynamics of plant–microbe interactions. Rising temperatures, shifting precipitation patterns, and increased frequency of extreme weather events are influencing both plant physiology and microbial community structure. As a result, the stability and functionality of plant-associated microbiomes are being affected (Muhammad et al., 2025).

Temperature is a major factor influencing microbial diversity and activity. Warmer conditions tend to

favor heat-tolerant microbial species while suppressing those sensitive to temperature fluctuations. This shift can disrupt microbial diversity and reduce the availability of essential ecosystem services such as nutrient cycling and disease suppression.

Changes in rainfall patterns also play a crucial role in shaping microbial communities. Extended dry periods can reduce microbial activity, whereas excessive rainfall may lead to oxygen depletion in soils, negatively affecting aerobic microorganisms. Such fluctuations influence microbial growth rates, metabolic activity, and the production of secondary metabolites. Consequently, the balance between beneficial and harmful microorganisms in the rhizosphere may shift, potentially affecting plant health (Ullah et al., 2025).

Another important aspect is the alteration of root exudation patterns under climate stress. Plants often modify the composition and quantity of root exudates in response to environmental changes. These exudates act as chemical signals that influence microbial recruitment and community composition. As a result, climate-induced changes in plant physiology can indirectly reshape the rhizosphere microbiome.

These interactions highlight the complex and dynamic nature of plant–microbe relationships under climate change, emphasizing the need for a deeper understanding of their ecological and functional implications (Afkhami et al., 2026).

MICROBIOME-MEDIATED MECHANISMS OF CLIMATE RESILIENCE

The ability of plant microbiomes to enhance climate resilience is based on multiple interconnected mechanisms. One of the most critical functions is the improvement of nutrient uptake efficiency. Under stress conditions, root function is often compromised, limiting nutrient absorption. Microbial symbionts compensate for this limitation by facilitating nutrient acquisition and transport.

Microorganisms also play a key role in regulating plant stress hormones. By modulating hormonal pathways, particularly those involving ABA, they help plants maintain water balance and adapt to drought conditions. Additionally, microbes produce osmoprotectants such as trehalose and proline-like compounds, which protect plant cells from dehydration and osmotic stress.

Another important mechanism is the enhancement of antioxidant defense systems. Under abiotic stress, plants generate reactive oxygen species (ROS), which can cause cellular damage. Beneficial microbes stimulate the production of antioxidant enzymes that neutralize ROS, thereby protecting plant tissues.

Furthermore, microbial communities contribute to improved root development, enabling plants to explore a larger soil volume for water and nutrients. This is particularly advantageous in arid and semi-arid

regions where resource availability is limited. Collectively, these mechanisms demonstrate the crucial role of microbiomes in supporting plant adaptation to climate stress.

RISKS AND CHALLENGES UNDER CHANGING CLIMATE

While plant microbiomes offer significant benefits, climate change also introduces risks that can disrupt these interactions. Extreme weather conditions, such as prolonged droughts or excessive rainfall, can alter microbial community composition and reduce the abundance of beneficial microorganisms.

In some cases, these changes may favor opportunistic pathogens, leading to increased disease incidence and reduced crop productivity. The delicate balance between beneficial and harmful microbes is therefore at risk under changing environmental conditions.

Another challenge lies in the variability of field conditions. Microbial inoculants that perform well under controlled conditions may not always function effectively in diverse agricultural environments. Factors such as soil type, climate, and crop species influence microbial survival and activity, making it difficult to ensure consistent results.

Addressing these challenges requires a comprehensive understanding of microbial ecology and the development of robust strategies for microbiome management.

FUTURE PERSPECTIVES AND EMERGING APPROACHES

Recent advances in microbiome research are opening new avenues for enhancing climate resilience in agriculture. One promising approach is the development of synthetic microbial communities (SynComs), which are carefully designed consortia of beneficial microorganisms with complementary functions.

Metagenomic and genomic tools are being used to identify stress-resilient microbial strains and understand their functional roles in plant systems. These insights enable the selection and optimization of microbial inoculants for specific environmental conditions.

In addition, emerging technologies such as gene editing and precision microbiome engineering are being explored to enhance beneficial traits in microorganisms. These approaches aim to create stable and efficient microbiome solutions that can perform reliably under field conditions.

The integration of microbiome-based strategies with other climate-smart agricultural practices has the potential to reduce dependence on chemical inputs while improving crop productivity and sustainability (Fadji et al., 2025).

CONCLUSION

Plant microbiomes represent a critical component of climate-resilient agriculture. Through their roles in nutrient acquisition, hormonal regulation, and stress mitigation, these microbial communities enhance plant adaptability to adverse environmental conditions. However, climate change poses significant challenges by altering microbial diversity and disrupting plant–microbe interactions. Future research should focus on understanding these complex interactions and developing innovative strategies for microbiome management. By harnessing the potential of beneficial microorganisms, it is possible to build sustainable agricultural systems capable of withstanding the impacts of climate change while ensuring food security.

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