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Plant microbe interactions in the age of climate change: Challenges and opportunities.

Zeng Yu*

Department of Biotechnology, Zhejiang University, China

***Corresponding to:** Zeng Yu, Department of Biotechnology, Zhejiang University, China, E-mail: yuzeng@zju.edu.cn

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Introduction

Climate change is reshaping ecosystems across the globe, altering temperature regimes, precipitation patterns, and soil health. These shifts pose significant threats to agricultural productivity and food security. Yet, within the soil and on plant surfaces lies a powerful ally microbes. The intricate relationships between plants and microbes are critical for nutrient acquisition, stress tolerance, and disease resistance. As climate change intensifies, understanding and harnessing plant microbe interactions offers both challenges and transformative opportunities for sustainable agriculture [1, 2].

Plants coexist with a diverse community of microorganisms, including bacteria, fungi, archaea, and viruses. These microbes inhabit the rhizosphere (soil surrounding roots), phyllosphere (leaf surfaces), and endosphere (internal tissues). These interactions are dynamic and context-dependent, influenced by plant genotype, soil conditions, and environmental factors. Rising temperatures can alter microbial community composition, reduce microbial diversity, and affect enzyme activity. Heat stress may impair symbiotic relationships, such as nitrogen fixation by rhizobia [3, 4].

Drought conditions reduce microbial mobility and nutrient diffusion in soil. However, certain microbes help plants cope by producing osmoprotectants and ACC deaminase, which modulate ethylene levels and improve root growth. Higher atmospheric CO_2 can enhance root exudation, potentially stimulating microbial activity. Yet, the long-term effects on microbial diversity and function remain uncertain [5, 6].

Climate-induced erosion, salinization, and nutrient depletion disrupt microbial habitats, weakening beneficial interactions and increasing susceptibility to pathogens. Harnessing microbes offers promising strategies to mitigate climate impacts: PGPR such as *Bacillus*, *Pseudomonas*, and *Azospirillum* enhance drought tolerance by improving water uptake, producing exopolysaccharides, and modulating stress-responsive genes. Halotolerant microbes can alleviate salt stress by maintaining ion balance and producing antioxidants. For example, *Halomonas* and *Salinibacter* species have shown potential in saline soils [7, 8].

Soil microbes play a vital role in carbon cycling. Promoting microbial biomass and activity can enhance soil organic carbon storage, contributing to climate mitigation. Beneficial microbes suppress pathogens through competition, antibiosis, and immune priming. This reduces reliance on chemical pesticides, which can exacerbate environmental degradation. Integrating plant–microbe interactions into agricultural practices can enhance resilience and sustainability: Microbial performance can vary across soil types, climates, and crop systems. Field efficacy often falls short of laboratory results [9, 10].

Conclusion

In the age of climate change, plant–microbe interactions are more than ecological curiosities—they are strategic assets for sustainable agriculture. By understanding and harnessing these relationships, we can build resilient cropping systems, restore degraded soils, and reduce environmental footprints. The challenges are real, but the opportunities are vast. With science, innovation, and collaboration, synthetic and natural microbial allies can help secure the future of food and ecosystems.

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