ID: 780

Current Approaches to Plant Microbiota: A Trend Study

Yaira Ulugbekovna Rakhmetova[1,2*], Zeliha Selamoglu[3,4]

[1]*Research and Production Center for Microbiology and Virology LLC, Almaty, Kazakhstan*
[2]*Al - Farabi Kazakh National University, Almaty, Kazakhstan*
[2]*Department of Medical Biology, Medicine Faculty, Nigde Omer Halisdemir University, Nigde, Türkiye*
[3]*Department of Biology, Faculty of Sciences, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan*

Abstract

Plant microbiota has emerged as a central topic in modern plant sciences, driven by its critical role in plant health, productivity, and ecosystem sustainability. Advances in high-throughput sequencing, multi-omics technologies, and computational biology have transformed our understanding of plant-associated microbial communities. This study provides a comprehensive overview of current approaches used in plant microbiota research, highlighting emerging trends, methodological advancements, and future directions. Particular emphasis is placed on microbiome engineering, synthetic communities, and sustainable agriculture applications.

Keywords: *Culturomics, Microbial community, Microbiota, Plant, Plant Microbiota*

Introduction

Plants do not exist as isolated organisms but rather as complex meta-organisms, often referred to as "holobionts," which include the host plant and its associated microbial communities. These microbiota inhabit various plant compartments, including the rhizosphere (soil-root interface), endosphere (internal tissues), and phyllosphere (above-ground surfaces). Over the past two decades, the study of plant microbiota has shifted from culture-dependent methods to advanced molecular and computational approaches, enabling a deeper understanding of microbial diversity, structure, and function. The importance of plant microbiota extends beyond basic ecological interactions; it plays a crucial role in nutrient acquisition, stress tolerance, disease resistance, and plant growth promotion. Consequently, there has been a growing interest in leveraging microbiota for sustainable agricultural practices. This has led to the development of innovative approaches aimed at manipulating microbial communities to improve crop productivity and resilience (Singh et al., 2020; Ebadi et al., 2025a).

Conceptual Framework of Plant Microbiota

The plant microbiota is shaped by a dynamic interplay of biotic and abiotic factors, including plant genotype, soil composition, climate, and agricultural practices. Host plants actively recruit and select specific microbial taxa through root exudates and immune signaling pathways. This selective process results in the formation of highly structured microbial communities that differ significantly between plant species and environments. Recent conceptual advances emphasize the role of microbial networks and interactions rather than individual taxa. Microbial consortia exhibit cooperative and competitive interactions that influence community stability and functionality. These interactions are increasingly studied using ecological and systems biology frameworks, highlighting the complexity of plant-microbe relationships (Compant et al., 2019).

Current Methodological Approaches

High-Throughput Sequencing Technologies

One of the most transformative developments in plant microbiota research is the widespread use of next-generation sequencing (NGS). Techniques such as 16S rRNA gene sequencing and internal transcribed spacer (ITS) sequencing allow for taxonomic profiling of bacterial and fungal communities, respectively. Metagenomics further enables the characterization of the entire genetic content of microbial communities, providing insights into functional potential. Shotgun metagenomic sequencing has become particularly valuable, as it allows researchers to move beyond taxonomic identification and explore metabolic pathways, resistance genes, and ecological functions. This approach has revealed the immense functional diversity within plant-associated microbiomes (Berendsen et al., 2012).

Multi-Omics Approaches

To fully understand plant microbiota, researchers increasingly employ multi-omics strategies, including metatranscriptomics, metaproteomics, and metabolomics. These approaches provide a comprehensive view of microbial activity and interactions at different biological levels. Metatranscriptomics focuses on gene expression, revealing which microbial genes are actively transcribed under specific conditions. Metaproteomics identifies proteins produced by microbial communities, while metabolomics analyzes small molecules involved in plant-microbe interactions. Together, these techniques offer a holistic understanding of microbiome functionality (Mendes et al., 2013).

Culture-Dependent and Culturomics Approaches

Despite the dominance of molecular techniques, culture-based methods remain essential for isolating and characterizing individual microbial strains. Recent innovations in culturomics—high-throughput microbial culturing—have significantly increased the number of cultivable microorganisms. This is particularly important for developing microbial inoculants and biofertilizers (Berg et al., 2020).

Synthetic Microbial Communities (SynComs)

A major trend in plant microbiota research is the development of synthetic microbial communities. SynComs consist of defined sets of microbial species assembled under controlled conditions to study their interactions and effects on plant hosts. These systems allow researchers to test hypotheses about microbial functions and community dynamics in a reproducible manner. SynComs are increasingly used to identify beneficial microbial consortia that can enhance plant growth, improve nutrient uptake, and provide resistance against pathogens (Trivedi et al., 2020).

Microbiome Engineering

Microbiome engineering represents a cutting-edge approach aimed at manipulating plant-associated microbial communities to achieve desired outcomes. Strategies include the application of beneficial microbes, genetic modification of microbial strains, and the use of soil amendments to influence microbial composition. Microbiome engineering is a ground-breaking field with profound implications for human health, agriculture, and industrial biotechnology. By leveraging probiotics and synthetic biology, scientists are able to manage microbial communities to achieve optimal disease prevention, industrial process optimization, and environmental sustainability.This approach holds significant promise for sustainable agriculture, as it reduces reliance on chemical fertilizers and pesticides while promoting environmentally friendly practices (Busby et al., 2017; ; Ebadi et al., 2025a).

Emerging Trends in Plant Microbiota Research

Integration of Artificial Intelligence and Big Data

The increasing complexity of microbiome data has necessitated the use of advanced computational tools. Machine learning and artificial intelligence are now widely used to analyze large datasets, identify patterns, and predict microbial interactions. These technologies enable the development of predictive models for microbiome behavior under different environmental conditions (Toju et al., 2018).

Climate Change and Microbiome Resilience

Climate change is a growing concern in plant microbiota research. Studies are increasingly focused on understanding how environmental stressors such as drought, temperature fluctuations, and soil degradation affect microbial communities. There is a particular interest in identifying microbiomes that enhance plant resilience to climate stress.

Sustainable Agriculture and Biofertilizers

The application of plant microbiota in agriculture is one of the most promising areas of research. Biofertilizers and biopesticides derived from beneficial microbes are gaining popularity as sustainable alternatives to chemical inputs. These products not only improve crop yield but also enhance soil health and biodiversity (Ebadi et al., 2025b).

Holobiont and Systems Biology Perspective

The concept of the plant holobiont is becoming increasingly central to plant science. This perspective considers the plant and its microbiota as an integrated system. Systems biology approaches are used to model these complex interactions and understand their implications for plant health and productivity. The integration of bioactive plant compounds into drug design has allowed significant therapeutic breakthroughs to occur, showing efficacy in the control of chronic disease, the enhancement of standard therapy, and new directions for drug discovery. However, problems of standardization, safety, and regulatory harmonization must be addressed to fully realize their potential. Emerging technologies such as nanotechnology, biotechnology, and artificial intelligence present new solutions for improving the efficacy, bioavailability, and scientific evidence of herbal therapeutics (Ebadi and Selamoglu, 2025).

TURSTEP
Turkish Science and Technology Publishing (TURSTEP)
www.turstep.com.tr

Conclusion

Despite significant advancements, several challenges remain in plant microbiota research. One major limitation is the difficulty in establishing causal relationships between microbial communities and plant traits. Additionally, environmental variability and experimental reproducibility pose significant challenges. Another issue is the gap between laboratory findings and field applications. Microbial inoculants that perform well under controlled conditions often show inconsistent results in natural environments. This highlights the need for more field-based studies and long-term experiments. The future of plant microbiota research lies in the integration of interdisciplinary approaches, combining molecular biology, ecology, computational science, and agronomy. Advances in gene editing technologies, such as CRISPR, may enable precise manipulation of microbial genomes, opening new possibilities for microbiome engineering. Furthermore, personalized agriculture—tailoring microbial solutions to specific crops and environments—represents a promising direction. As our understanding of plant-microbe interactions deepens, it is expected that microbiota-based strategies will become a cornerstone of sustainable food production systems. Plant microbiota research has undergone a rapid transformation, driven by technological advancements and increasing awareness of its importance in agriculture and ecosystem health. Current approaches, including high-throughput sequencing, multi-omics, synthetic communities, and microbiome engineering, provide powerful tools for exploring and manipulating plant-associated microbial communities. Emerging trends such as artificial intelligence integration, climate resilience studies, and sustainable agricultural applications highlight the dynamic nature of this field. Despite existing challenges, continued research and innovation are expected to unlock the full potential of plant microbiota, contributing to global food security and environmental sustainability.

References

Berendsen, R. L., Pieterse, C. M. J., & Bakker, P. A. H. M. (2012). The rhizosphere microbiome and plant health. *Trends in Plant Science*, 17(8), 478–486.

Berg, G., Rybakova, D., Fischer, D., et al. (2020). Microbiome definition re-visited: old concepts and new challenges. *Microbiome*, 8(1), 103.

Busby, P. E., Soman, C., Wagner, M. R., et al. (2017). Research priorities for harnessing plant microbiomes in sustainable agriculture. *PLoS Biology*, 15(3), e2001793.

Compant, S., Samad, A., Faist, H., & Sessitsch, A. (2019). A review on the plant microbiome: ecology, functions, and emerging trends. *Microbiological Research*, 206, 29–37.

Ebadi, A. G., Rakhmetova, Y., Issa, H. Y., Naeem, M. Y., & Selamoglu, Z. (2025a). Microbiome Engineering: Exploring Probiotic and Synthetic Biology Approaches for Health and Industry. *Eurasian Journal of Medical and Biological Sciences*, *5*(2).

Ebadi, A. G., Naeem, M. Y., & Selamoglu, Z. (2025b). Biohybrid Systems for Waste Valorization: Synergizing Synthetic Biology and Green Engineering to Enable Circular Resource Recovery. *International Journal of Environmental Science and Green Technology*, *1*(2), 25-37.

Ebadi, A. G., & Selamoglu, Z. (2025). Exploring the role of herbal medicines in modern pharmacology and drug development. *Lat. Am. J. Pharm*, *44*(4), 401-406.

Mendes, R., Garbeva, P., & Raaijmakers, J. M. (2013). The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. *FEMS Microbiology Reviews*, 37(5), 634–663.

Singh, B. K., Trivedi, P., Egidi, E., et al. (2020). Crop microbiome and sustainable agriculture. *Nature Reviews Microbiology*, 18, 601–602.

Trivedi, P., Leach, J. E., Tringe, S. G., et al. (2020). Plant–microbiome interactions: from community assembly to plant health. *Nature Reviews Microbiology*, 18, 607–621.

Toju, H., Peay, K. G., Yamamichi, M., et al. (2018). Core microbiomes for sustainable agroecosystems. *Nature Plants*, 4, 247–257.

Turkish Science and Technology Publishing (TURSTEP)
www.turstep.com.tr