MICROBIAL SYNERGY: LEVERAGING PLANT MICROBIOMES FOR SUSTAINABLE AND SMART AGRICULTURE

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Microorganisms function as interactive communities rather than isolated entities, and their cooperative actions are fundamental to ecosystem processes. Microbial synergy describes interactions among distinct microbial taxa that result in enhanced functional outcomes beyond individual capabilities. In the rhizosphere, the synergistic associations among bacteria and fungi regulate nutrient mobilization, phytohormone production, and pathogen suppression through metabolic complementation and signalling. Microbial consortia often outperform single inoculants by providing functional diversity and thus, maintain ecological stability, particularly under environmental stress conditions. In recent times, beneficial microbes are increasingly being used to enhance crop production, healthy plant growth, soil fertility, and pest and disease management.

The plant microbiome offers new possibilities for utilizing beneficial microbes for controlling pathogens through advanced biotechnological approaches. The complex interactions within the plant microbiome are crucial in maintaining the balance of agroecosystem (Figure 1). However, various mechanisms governing the microbial compatibility, and persistence are poorly understood. This highlights the need of targeted research to make use of microbial formulations for sustainable agriculture.

PLANT MICROBIOME: A HIDDEN ECOSYSTEM

Plant microbiome or phytomicrobiome encompasses a diverse and dynamic community of microorganisms, such as bacteria, fungi, archaea, viruses, and other microbes, that reside on the surfaces and within the tissues of plants. These microbes benefit crop plants and perform different ecological balancing functions (Singh *et al.,* 2020). Various plant associations, like the bulk soil or rhizospheric soil, anthosphere, caulosphere, spermosphere, phyllosphere, and endosphere, serve as habitats for the establishment of the plant microbiome (Figure 2). The rhizosphere-associated microbiome is a key component of agroecosystem sustainability due to its role in supporting various soil biological processes, nutrient cycling through organic matter decomposition, enhancement of soil quality and plant growth, carbon sequestration, pathogen suppression through secreted metabolites, activation of plant immune responses, and building a resilient agroecosystem.

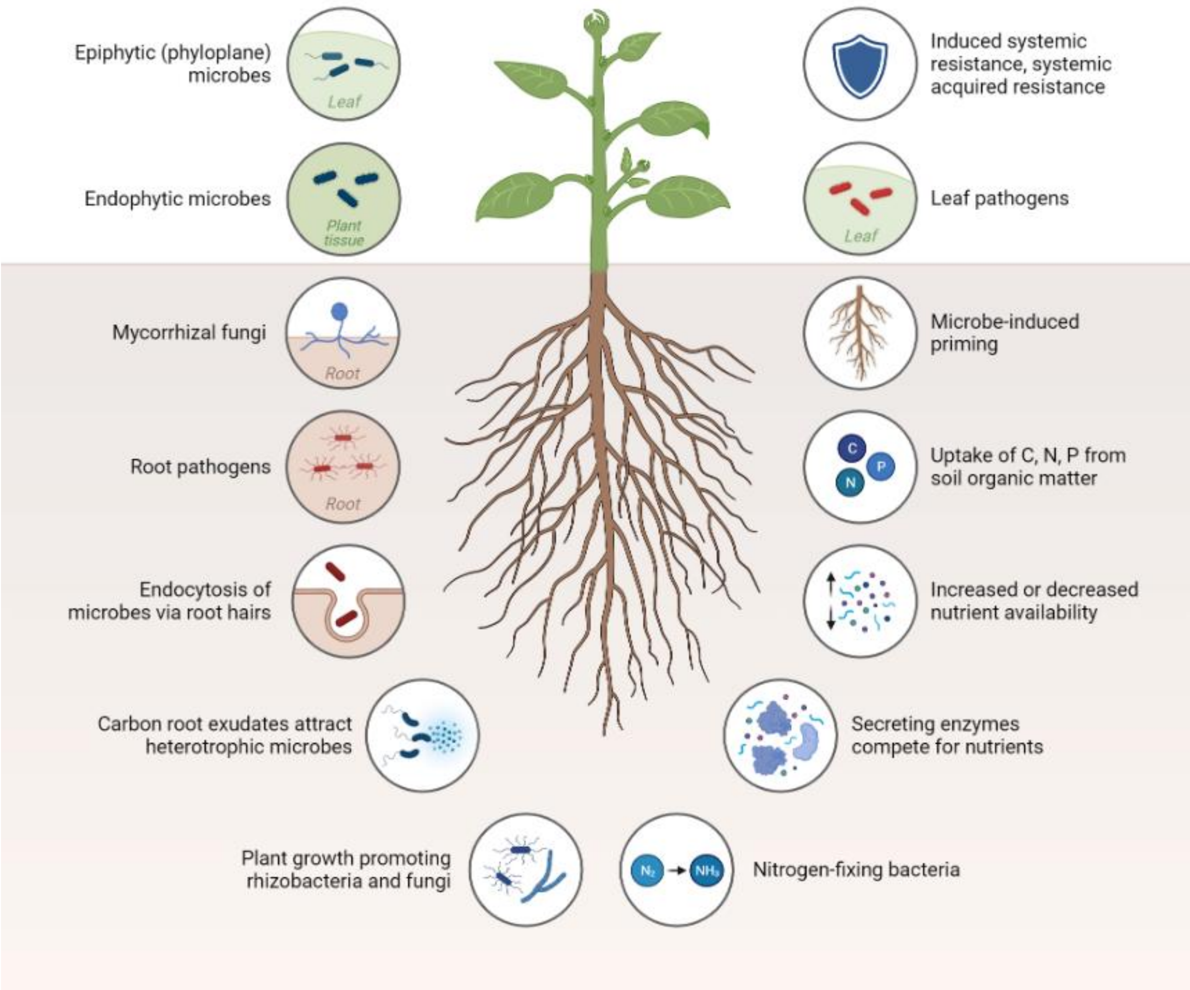

Figure 1. Plant-Microbe Interactions (Source: https://www.biorender.com/template/plant-microbe-interactions)

The phyllosphere microbiome, derived from environmental resources such as soil, water, seeds, and air, adapts to survive on plant surfaces and is shaped by various factors including microbial immigration, and leaf physicochemical properties, collectively influencing the crop health and productivity. Endophytic microbes, which colonize in the internal plant tissues without causing disease symptoms, form symbiotic associations support healthy plant growth by inducing disease resistance, and alleviating various biotic and abiotic stresses through producing antimicrobial and signalling compounds (Rai et al., 2023).

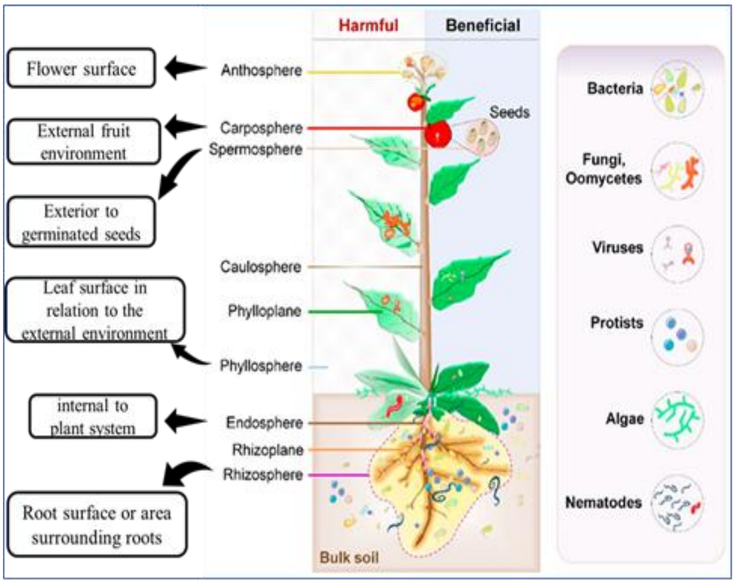

Figure 2. Plant microbiome and its colonization of diverse ecological niches (Source adapted and modified from: Shelake et al., 2019)

HARNESSING THE PLANT MICROBIOME FOR SUSTAINABLE AGRICULTURE

Microbes linked with the plant microbiome influence plant health either neutrally or beneficially, supporting nutrient availability and uptake, suppressing diseases, enhancing tolerance to abiotic stresses, inducing systemic resistance, facilitating adaptation to climatic changes, and promoting root colonization (Fallah *et al.* 2023). Some major functions of rhizospheric and endophytic microbial communities are explained below:

Plant Growth Promotion

Microbial diversity within plant microbiome influences the growth and development of plants through direct and indirect mechanisms. Rhizosphere-associated Plant Growth-Promoting Rhizobacteria (PGPR) promotes plant growth directly by producing phytohormones, enhancing nutrient acquisition, and solubilizing minerals. Indirectly, they activate plant immune responses and suppress plant pathogens through competition and inhibition. Studies have confirmed that colonization of diverse bacterial communities linked with plants, exhibiting growth-promoting properties. Plant growth-promoting microbes include *Arthrobacter* sp., *Rhizobium* sp.*, species of* Actinobacteria*, Bacillus* sp., *Burkholderia* sp., *Pseudomonas* sp., and *Azotobacter* sp. Mycorrhizal fungi are major groups of microbiome-associated microbes that contribute to plant growth and support multiple mechanisms (El Malahi *et al.,* 2025).

Nutrient Mobilization

Microorganisms associated with plant microbiomes also aid in solubilizing essential nutrients like phosphorus and potassium, which are often available in limited quantities in their organic forms for growing crop plants. Phosphate-solubilizing microbes (PSMs) solubilize insoluble phosphate into organic available forms through producing organic acids. Similarly, potassium-solubilizing microbes (KSMs) enhance K availability by secreting organic acids, producing exopolysaccharides, and releasing metal-complexing ligands, which play a critical role in plant water regulation and enzyme activation. For example, *Burkholderia* sp., *Bacillus megaterium, Paraburkholderia* sp., *Collimonas* sp., *Agrobacterium* sp., and *Pseudomonas fluorescens* have demonstrated diverse solubilization activities and ability to produce various organic acids, thereby improving plant growth in nutrient-deficient soils (Zhang *et al.,* 2024, Shirale et al., 2019).

Disease Management

The plant microbiome serves multiple functions role in defending plants from pathogen attacks through diverse mechanisms, such as parasitism, activating immune responses, competition for space/nutrients, and induced systemic resistance (ISR) by initiating a response to biotic stresses. The root microbiota plays a crucial role in conferring resistance to above-ground plant diseases through ISR, which is a key mechanism in plant growth-promoting bacteria that contribute to disease resistance. Nysanth et al. (2023) reported that the phyllosphere microbiota in tomato plants enhance resistance against bacterial wilt caused by *Ralstonia solanacearum*. Some beneficial microbes like *Bacillus*, *Paenibacillus, Pseudomonas, Burkholderia*, *Enterobacter*, *Pantoea*, *Streptomyces, Trichoderma harzianum,* and *Penicillium* sp. play important role in microbiome-mediated disease resistance activation (Ali et al., 2023).

Stress Tolerance

A plenitude of abiotic stresses affects plants, including water scarcity, extreme temperatures, soil salinity, acidity, nutrient deprivation, and waterlogging, all of which are expected to intensify due to climate change. A diverse group of bacteria from plant roots' endophytic and rhizospheric microbiome promote plant growth by producing phytohormones like IAA, ACC deaminase, and cytokinin (Hussain *et al.,* 2018).

Plants often respond to stress conditions by altering or reprogramming their metabolic mechanisms, while microorganisms, with their inherent metabolic and genetic capabilities, are well-suited to withstand abiotic stress and can induce systemic responses in plants (Santos and Olivares, 2021). To further understand stress response and adaptation mechanisms, such as stress signalling, metabolism, and gene expression, microbiome engineering has gained interest as a strategy to enhance crop characteristics like tolerance to biotic and abiotic stresses, thereby supporting sustainable agricultural production.

MICROBIAL INOCULATION: SINGLE MICROBE TO MICROBIAL CONSORTIA

Microbial inoculation is a fundamental strategy in agricultural microbiology for enhancing crop productivity. The process begins with the selection of strains exhibiting plant growth–promoting traits such as nitrogen fixation, phosphate solubilization, indole-3-acetic acid production, and phytohormone regulation under controlled conditions. Promising strains are subsequently evaluated through greenhouse trials and field testing. Although single-strain inoculants, including *Rhizobium, Azospirillum, Bacillus, Pseudomonas*, and related genera, have demonstrated productivity gains under controlled environments, their field performance often remains inconsistent due to environmental variability. Consequently, microbial consortia are increasingly favoured over single-strain inoculants, as they provide synergistic effects that enhance plant growth, suppress diseases, and improve stress resilience at optimal concentrations (Figure 3).

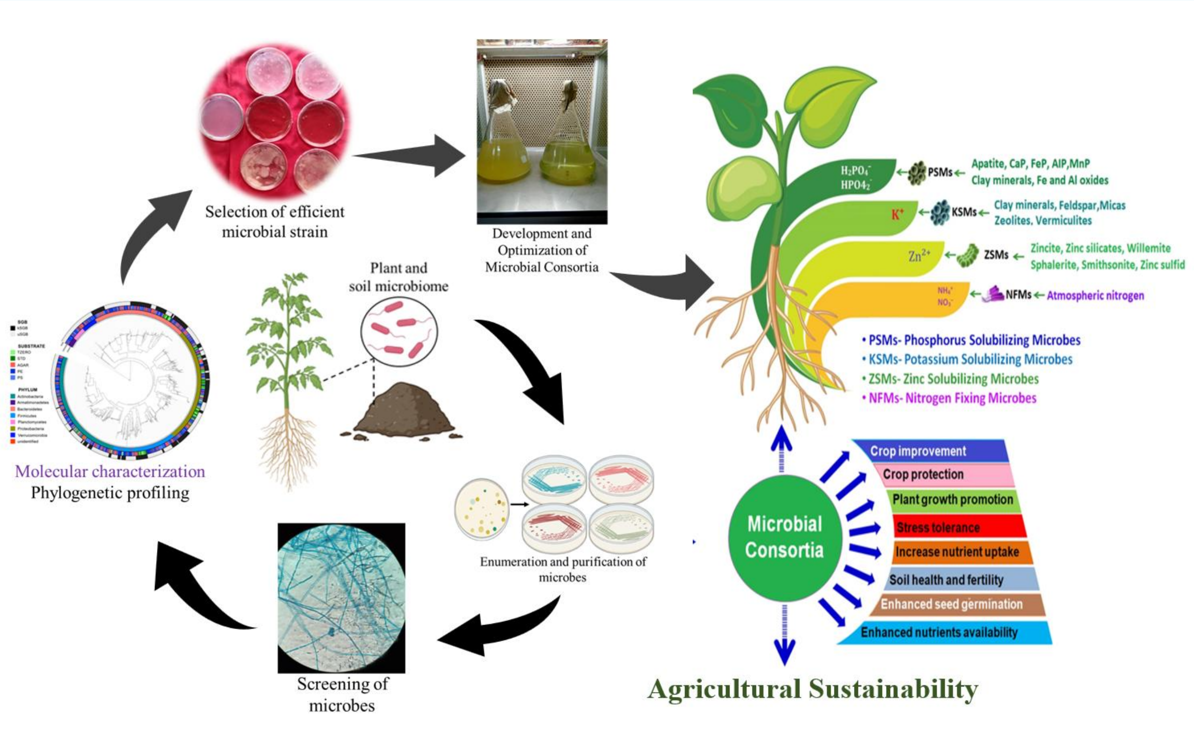

Figure 3. Functional Mechanisms of Microbial Consortia Driving Crop Productivity and Agricultural Sustainability (Source: adapted and modified from Negi et al., 2024)

MICROBIOME ENGINEERING: EMERGING MODELS FOR SMART AND SUSTAINABLE AGRICULTURE

The development of novel microbial systems represents a frontier in microbiome engineering for sustainable agriculture. Notably, the Intraspecies Cross Environmental (ICE) and Combinatorial CRISPR Array-Guided Engineering (CRAGE) systems enable the design of high-performance microbial communities (Hanif et al., 2024). ICE facilitates the construction of synthetic consortia by combining environmentally adaptable, beneficial strains that enhance plant growth and stress tolerance, while CRAGE employs CRISPR-based genome engineering to improve microbial traits related to nutrient acquisition, stress resilience, and disease suppression. Together, these approaches optimize microbial functionality and advance our understanding of plant–microbe interactions.

The advancement of Synthetic Microbial Communities (SynComs) and Culture-based Methods (Culturomics) is transforming microbiome research by enabling more effective and reliable field applications. Figure 4 depicts the key traits of an Ideal Synthetic Microbial Community (SynCom), emphasizing core microbiome strains, robust plant colonization, enhanced microbial features (host recognition, quorum sensing, biofilm formation, and phytohormone production), efficient nitrogen fixation, persistence in soil alongside native microbes, and the role of in silico modeling in designing and predicting SynCom performance for sustainable agriculture. One of the most promising developments is the integration of SynComs into smart farming systems, where unmanned aerial vehicles equipped with sensors and mobile DNA sequencers facilitate automated monitoring of plant responses and microbial community dynamics. By integrating microbiome–phenome–environment datasets, we can enhance the prediction of microbial dynamics, enabling the scalable application of SynComs in precision agriculture. Additionally, tailoring microbial consortia to specific crops and environmental conditions presents a promising strategy for addressing current agricultural challenges.

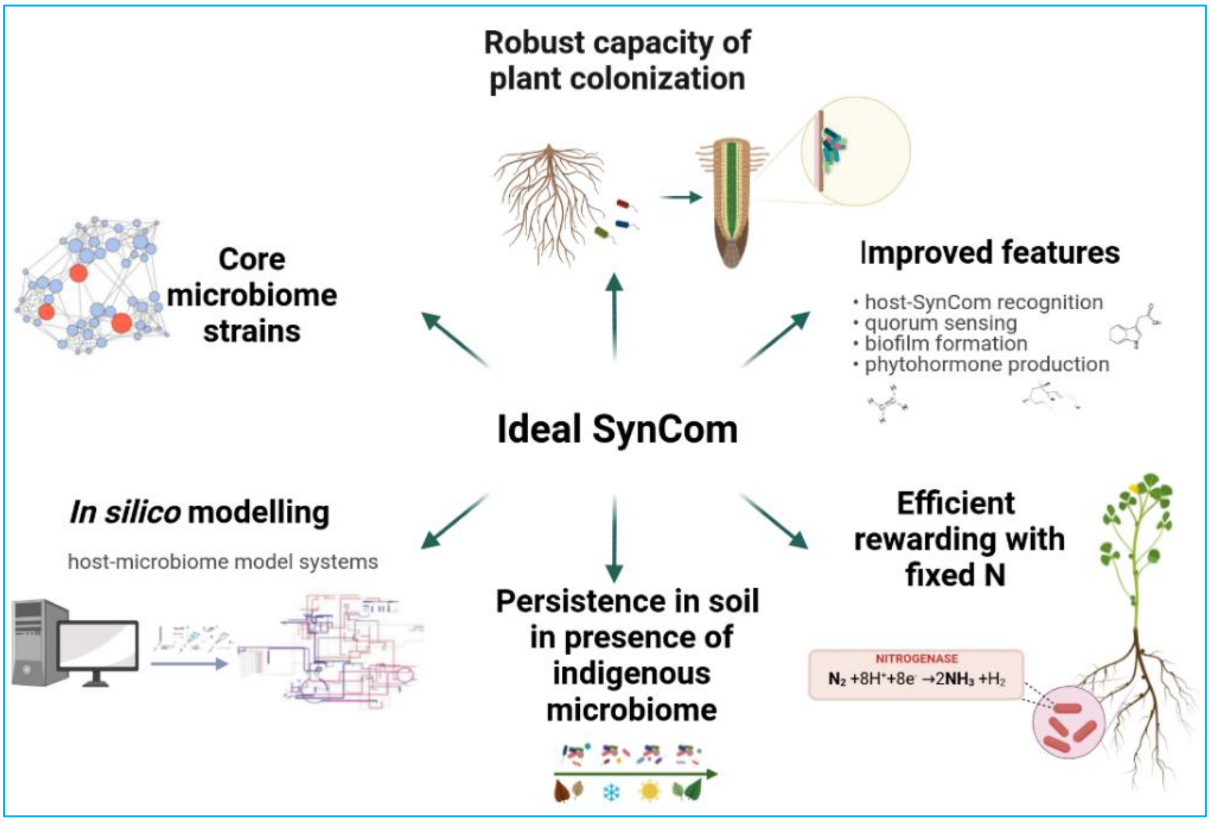

Figure 4: Schematic Representation of an Ideal SynCom for Plant Growth and Soil Health (Source: https://im.biol.uw.edu.pl/en/ synthetic-communities/)

CONCLUSION

Plant microbiomes offer a sustainable solution to the challenges of climate change, soil degradation, and ecosystem imbalance affecting agriculture. Advanced biochemical, molecular, imaging, and "omics" approaches have unravelled the complexity of microbial interactions, including signal exchange, root exudation, colonization, and disease suppression. Integrating sustainable practices like organic farming and intercropping enhances these beneficial interactions, boosting plant health and productivity. Also, next-generation plant breeding strategies to strengthen the plant-microbe relationships pave the way for resilient, sustainable crop production and long-term food security.

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