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Plant-Soil Microbiome Interactions for Sustainable Agriculture

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Abstract
Soil microbiome is a basic biological part of agricultural ecosystems and consists of various microorganisms, like bacteria, fungi, archaea, protists, viruses and other microbial groups. The interactions between these communities and the root, soil minerals, organic matter and other communities are dynamic, with the rhizosphere having the most intricate interactions. The rhizosphere is formed by the plants, which can shape it by their root exudates and other properties of their roots, and by the microorganisms, which can influence acquisition of nutrients, root development, plant defence, soil structure and plant tolerance to environmental stresses. The plant-microbe interactions are significant for sustainable agriculture, as they help in nutrient cycling, biological nitrogen fixation, mobilization of P, disease suppression and stress resilience.

Arbuscular mycorrhizal fungi extend the ability of plant roots to explore the soil, and improve nutrient and water uptake, while plant-growth-promoting microorganisms promote plant growth by mobilizing nutrients, regulating plant hormones and suppressing pathogens. In reality the effectiveness of microbial inoculants in the field can be variable and subject to the impact of soil properties, crop genotype, environment, native soil microbial community, and interactions among the existing soil microbial community.

To manage the microbiome sustainably, therefore, it is necessary to take a holistic approach that transcends the use of individual microbial strains. Maintaining diverse and active microbial communities can be achieved through crop diversification, managing organic matter, minimizing soil disturbance, balanced fertilization, and using microbial inoculants and microbiome-informed practices. Technological developments in multi-omics, synthetic microbial communities, precision microbiome management, microbiome-informed breeding, and microbial engineering are opening up new avenues for targeted manipulation of the plant-soil microbial interaction. Incorporating plants, soil and microbes can play a role in productive, resource-efficient, climate-resilient and sustainable agriculture systems.

Keywords: Plant microbiome, soil microbiome, Rhizosphere, plant-microbe interactions, soil health, sustainable agriculture, climate resilience

1. Introduction

There has been a tremendous growth in food production in modern agriculture, which is frequently associated with intensive fertilizer, pesticide, irrigation and soil-management practices. The use of these inputs can be inefficient, leading to nutrient loss, soil degradation, environmental pollution, loss of biodiversity and emissions of greenhouse gases. Hence, sustainable agriculture must be based on strategies that will ensure productivity and enhance the efficiency of the use of resources. Soil is more than just a substrate for plants. A living system with a variety of microorganisms contributing to the decomposition process, nutrient conversion, turnover of organic matter, mineral weathering, disease suppression and other soil fertility related activities. Soil microbiomes are also tightly linked to biogeochemical processes that are sensitive to climate (Jansson & Hofmockel, 2020) [10]. Soil and the associated microorganisms are dynamic biological systems. Microbial communities affect both nutrient uptake and growth, resistance to stress, and resistance to pathogens, while plants affect microbial communities through root exudates, root architecture, immune responses, and resource availability (Trivedi *et al.*, 2020) [30]. This reciprocal relationship is very significant in the context of sustainable crop production (Singh *et al.* 2020) [28].

2. Aim and Objectives

Aim: To learn about plant-soil microbiome interactions and their importance for nutrient cycling, plant growth and development, soil health, disease suppression, stress tolerance, and sustainable agriculture.

Objectives:

1. To explore plant - microbe interactions and functioning of rhizosphere.
2. To review microbial roles in nutrient cycling and plant growth promotion.
3. To discuss microbiome-mediated disease and stress tolerance.
4. To evaluate soil microbiomes response to agricultural practices.
5. To highlight microbial inoculants, consortia, multi-omics, and microbiome engineering for sustainable agriculture.

3. Methodology

This article is a narrative review of the published scientific literature in the field of plant-soil microbiome interactions and sustainable agriculture. Research articles, review articles and recent studies relevant were reviewed. Literature was gathered thematically including rhizosphere interactions, nutrient cycling, plant growth promotion, mycorrhizae, disease suppression, abiotic stress tolerance, soil structure, agricultural practices, microbial inoculants, consortia, and new microbiome technologies. Results were critically synthesized to highlight the key mechanisms, benefits, limitations and potential applications in sustainable agriculture.

4. The Plant-Soil Microbiome as an Ecological System

Plant associated microorganisms exist in interdependent habitats such as the bulk soil, rhizosphere, rhizoplane, endosphere of roots, phyllosphere, seeds and crop residues. The rhizosphere is among these and is of special significance due to the direct action of plant roots on the rhizosphere. The rhizosphere is not the same as bulk soil, as the roots exude carbon-based molecules like sugars, amino acids, organic acids, phenolics, flavonoids, enzymes and metabolites. These compounds serve as nutrients and chemical signals that can affect microbial recruitment and activities (Ma *et al*., 2022) [17]. Plants are important filters of the environment. Microbial communities associated with the roots are not random groups of soil microorganisms but are influenced by plant genotype, root traits, soil properties and environment (Trivedi, *et al*., 2020) [30]. Soils are extremely diverse with metagenomics uncovering a vast assemblage of previously unknown microbial species. Soil microbial communities are highly genetically diverse, as has been shown in large-scale genomic studies (Ma *et al*., 2023) [16]. But the diversity of microbes should not be measured just by the number of different groups of microbes. Similar communities may vary in functional genes, activity, microbial interactions, C use efficiency, and nutrient cycling. Therefore, sustainable agriculture should aim at maintaining the diversity of the microbial communities that can ensure nutrient cycling, plant growth, disease suppression, stress tolerance and soil health.

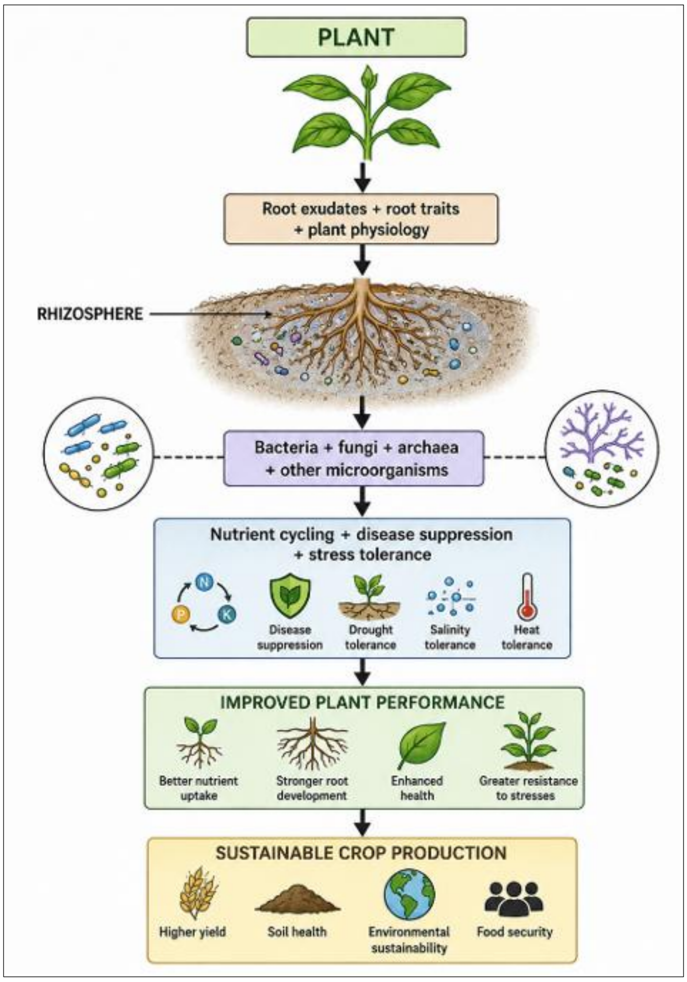

Fig 1: Conceptual model of plant-soil microbiome interactions

5. Root Exudates and Plant-Microbe Communication

Root exudates play a key role as important below ground players affecting soil chemistry, microbial activity, nutrient mobilization and plant-microbial communication. These are made up of different plant species, developmental stage, environment, and microbial interaction, depending on the plant species (Ma *et al*., 2022) [17].

Root exudates have three major functions:

1. Resource supply - providing carbon and nutrients to microorganisms.
2. Chemical modification - altering soil pH, nutrient availability, and soil chemistry.
3. Information exchange - influencing microbial recruitment and plant-microbe interactions.

Plants emit metabolites which influence the attraction, colonization, metabolism and community assembly of microbes. Metabolites and signals are synthesized by microorganisms which can affect the development, nutrition, defense and stress responses of plants (Trivedi *et al*., 2020) [30]. Thus, plant-microbe communication is bidirectional, allowing plants and microorganisms to influence each other's development and activity.

This bidirectional interaction plays a role in creating a microbial community that can help plants perform and adapt to environmental change.

6. Microbial Contributions to Nutrient Cycling

Microorganisms are essential for the cycling and transformation of nitrogen, phosphorus, carbon, sulfur, iron, and other nutrients. Their activity determines not only the total nutrient pool but also the chemical forms that are available to plants.

6.1 Nitrogen cycling

Soil N cycle is dominated by the activity of microorganisms and includes biological nitrogen fixation, mineralization/ immobilization, nitrification and denitrification. These microbial transformations determine soil N availability and the N species present and have a significant impact on N nutrition of plants and N losses from agriculture (Kuypers *et al*., 2018) [12].

Biological nitrogen fixation is important especially in legume systems, because the rhizobial bacteria take up residence in the plant's root and create a specialized root nodule that contains bacteria that fix nitrogen. In this symbiosis, the plant provides carbon compounds, other nutrients, etc to the bacteria and in return the rhizobia enzymatically convert the atmospheric N_2 into ammonia, which can be used by the plant in a biologically useful form of N compounds (Lindström & Mousavi, 2020) [14].

In suitable legume-based production systems, therefore, biological nitrogen fixation could help to increase the supply of biologically fixed N and decrease the use of external N input. Biological N fixation is not a panacea for synthetic N fertilizers and varies with plant genotype, rhizobial strain, soil conditions and environmental factors (Lindström & Mousavi, 2020; Palmero *et al*. 2022) [14, 20].

6.2 Phosphorus cycling

Phosphorus plays a vital role in energy metabolism, nucleic acid synthesis and membrane formation. The macronutrient phosphorus (P) is a necessary component of energy transfer and metabolism, nucleic acid synthesis, membrane formation and other basic cellular functions. Soils may also contain significant amounts of total P, but much of it is in poorly soluble or strongly bound to soil minerals or organic matter, and unavailable to plants (Peñuelas *et al*., 2026; Santoyo *et al*., 2026) [21, 23].

Microorganisms play an important role in P mobilization and cycling by transforming inorganic and organic P into forms that are more accessible to plants. Important microbial mechanisms include the following:

- Organic acid production, which can acidify the rhizosphere and promote the dissolution of poorly soluble phosphate minerals;
- Phosphatase activity, which catalyzes the hydrolysis of organic P compounds.
- Mineral dissolution and proton release, which can mobilize inorganic P associated with minerals.
- chelation of metal ions, which can facilitate the release of mineral-bound P; and
- decomposition and mineralization of organic phosphorus, increasing the pool of inorganic P available for plant uptake (Peñuelas *et al*., 2026; Santoyo *et al*. 2026) [21, 23].

Therefore, the production of P-solubilizing and P-mobilizing microorganisms can enhance P availability and potentially boost P acquisition by plants as well as phosphorus-use efficiency, depending on the soil properties, microbial strain or community, crop species, and environmental conditions (Santoyo *et al*., 2026; Sun *et al*., 2026) [23, 29].

6.3 Micronutrients

Micronutrients, including iron (Fe), zinc (Zn), manganese (Mn) and copper (Cu), are needed in very small amounts but are necessary for plant growth and metabolism. The availability and cycling of these elements is influenced by soil microorganisms through mineral dissolution, chelation, redox transformations and the production of metal-binding compounds (de Andrade *et al*., 2023) [6].

Iron is especially significant because it is commonly found in most soils, but a significant proportion of this can exist in poorly soluble forms where it is unavailable to plants. The siderophore-producing microorganisms are able to bind Fe^{3+} with high affinity, which changes the solubility and availability of Fe in the rhizosphere and enhances plant growth. Microbial siderophores can help plants to better acquire iron under certain soil and plant conditions (Ahmed & Holmström, 2014; de Andrade *et al*., 2023) [1, 6].

Microbial interactions can be especially relevant in soils where micronutrients limit plant growth; however, they will depend on the soil properties, microbial species and genera, plant genotype, and environment (de Andrade *et al*., 2023) [6].

Table 1: Major microbial functions relevant to soil fertility

Microbial function	Main process	Agricultural significance
Nitrogen fixation	Conversion of atmospheric N_2 into biologically available N (Kuypers *et al.*, 2018; Lindström & Mousavi, 2020) [12, 14]	Biological N supply
N mineralization	Microbial decomposition of organic N compounds (Kuypers *et al.*, 2018) [12]	Release of plant-available N
P mobilization	Organic-acid production, mineral dissolution, and phosphatase activity (Santoyo *et al.*, 2026; Sun *et al.*, 2026) [23, 29]	Improved P availability
Siderophore production	Chelation and mobilization of Fe (Ahmed & Holmström, 2014) [1]	Improved Fe acquisition
Decomposition	Microbial breakdown of organic matter (Compant *et al.*, 2025) [5]	Nutrient recycling
Mineral weathering	Microbial-mediated dissolution and transformation of minerals (Hartmann & Six, 2023) [8]	Release of mineral nutrients
Soil aggregation	Microbial polymers and fungal hyphal networks contribute to aggregate formation and stabilization (Rillig *et al.*, 2002; Hartmann & Six, 2023) [22, 8]	Improved soil structure and stability

7. Plant-Growth-Promoting Microorganisms and Root Development

Plant-growth-promoting microorganisms (PGPMs) are made up of different types of bacteria and fungi including *Bacillus*, *Pseudomonas*, *Azospirillum*, *Azotobacter*, *Rhizobium*, *Streptomyces*, *Trichoderma* and arbuscular mycorrhizal fungi. They stimulate the growth of plants in a variety of ways, such as nitrogen fixation, solubilization of phosphorus, acquisition of iron, production of phytohormones and modifications in root development. They also exhibit anti-pathogenic, competitive foraging of nutrients and ecological niches, secretion of antimicrobial metabolites, induction of plant defense, and environmental stress tolerance (Chandran *et al*., 2021) [4].

Microorganisms may also influence plant hormonal regulation and signalling pathways and thus fine-tune the architecture of the root system. Many of the pathways in which plant growth promoting rhizobacteria (PGPR) act involve auxin, cytokinin, ethylene, gibberellins and abscisic acid, including primary root growth, lateral root formation, root branching and root hair development (Vacheron *et al*., 2013) [31]. These changes may benefit soil exploration for water and nutrients. In a broader sense, plant-associated microbiomes can interact with the host physiological and signalling processes to affect plant growth, nutrient uptake, stress response and health (Trivedi *et al*., 2020) [30].

In this way, PGPMs support plant development, nutrient use efficiency, root growth and stress resistance; however, the effectiveness of PGPMs is dependent on soil characteristics, environmental conditions, crop genotype and interactions between the native microbiome (Chandran *et al*., 2021) [4].

8. Arbuscular Mycorrhizal Fungi

Arbuscular mycorrhizal fungi (AMF) are fungi that grow in symbiotic associations with the roots of most terrestrial plant species. They have extraradical hyphae that grow beyond the immediate root zone and search for larger soil volumes, thus reaching nutrients and water that are not readily available to the roots. Here, plants supply carbon to the fungi, and AMF help fungi absorb nutrients, especially phosphorus, nitrogen, water and other mineral elements. These associations can enhance plant nutrition, improve drought and abiotic stress resistance, and provide resistance to some pathogens and pests (Schaefer *et al*., 2021) [24].

Additionally, AMF can affect soil physical properties through the development of hyphal networks that play a role in the aggregation and stabilization of soil. Fungal hyphae physically bind soil particles and mycorrhizal compounds may contribute to aggregate stability. Therefore, AMF help to link soil nutrient acquisition to soil structural processes and to sustain the functioning and sustainability of agroecosystems (Rillig *et al*. 2002; Schaefer *et al*. 2021) [22, 24].

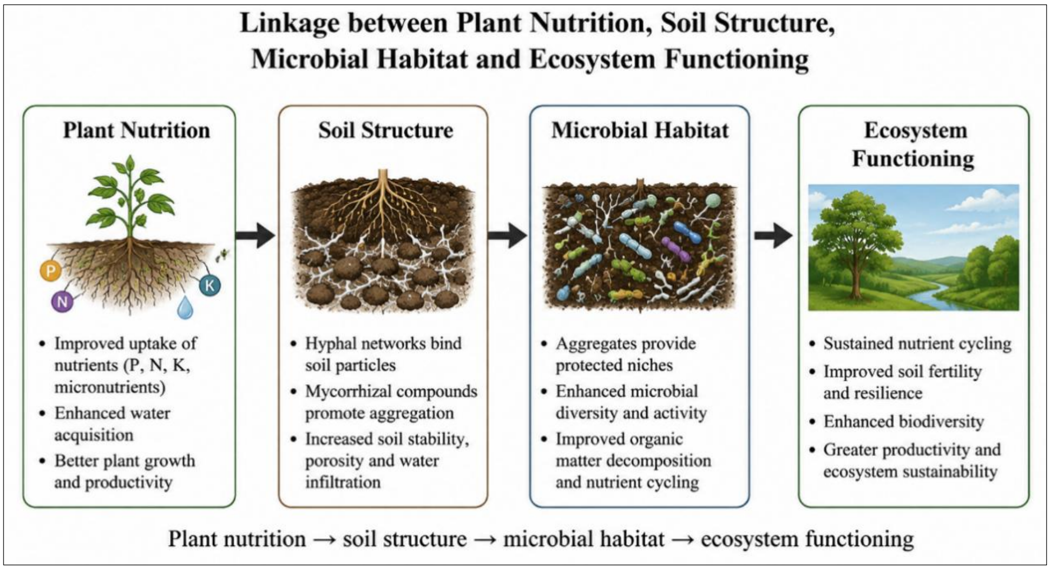

Fig 2: Linkage between Plant Nutrition, Soil Structure, Microbial Habitat, and Ecosystem Functioning

9. Plant Microbiome and Disease Suppression

Soil microorganisms reduce plant pathogens in both direct and indirect ways. They can competitively exclude pathogens for carbon, nutrition, iron, space and root colonization sites. Various microbes also generate antimicrobial compounds, lytic enzymes, siderophores and volatile metabolites.

Another important mechanism is the stimulation of plant defenses. Some beneficial microorganisms induce systemic resistance, which helps plant resist pathogenic attacks.

Thus, disease suppression is not necessarily a characteristic of a single microbial strain. Indigenous microbial communities can, through their combined activities, create disease-suppressive soils (Schlatter *et al*., 2017) [25].

Such an ecological approach also indicates that it might be possible to maintain and manage disease suppressive indigenous microbial communities as a supplemental management strategy to the use of introduced biocontrol agents.

10. Microbiome-Mediated Abiotic Stress Tolerance Under Climate Change

There are more droughts, salinity, heat, flooding, and other environmental stresses due to climate change. Changes in soil microbiomes can alter the soil fauna and flora, soil microbiomes have the capacity to change soil carbon and nutrient cycles and greenhouse gas processes (Jansson & Hofmockel, 2020) [10].

Plant associated microorganisms have the potential to promote abiotic stress resistance through a range of mechanisms including root development, water and nutrient uptake, osmotic adjustment, antioxidant activity, hormonal regulation and others involved in stress responses (Omae & Tsuda, 2022) [19].

Drought impacts the rhizosphere microbial communities by altering the way photosynthesis, carbon allocation, root growth, hormone metabolism, and root exudation occur. Microorganisms such as *Streptomyces coeruleorubidus* and *Leifsonia shinshuensis* that are enhanced by drought conditions in wheat change the metabolites associated with the rhizosphere. The following findings illustrate how the introduction of these microorganisms helped plants resist drought: Drought-associated microbiome changes were functionally correlated with drought resistance (Li *et al*., 2025) [13].

Heat induces osmotic and ionic stress, and affects photosynthesis, membrane stability, enzyme activity, water relations, reproduction, while salinity affects osmotic and ionic stress. Beneficial microorganisms can mitigate these impacts by helping to improve root establishment, nutrient and water uptake, anti-oxidative ability, osmolyte accumulation, ion homeostasis, and plant growth regulation (Omae & Tsuda, 2022) [19]. Under saline and other abiotic stresses, mycorrhizal associations can also help plants to get better water and nutrient uptake and plant performance.

More work is needed to understand the combined effects of stress, such as drought, heat, salinity and flooding, as these are often experienced concurrently in field crops. The overall relationship is two-way; on one hand, climate and environmental stressors influence the characteristics of microbial communities, and on the other, microbial communities have the potential to alter plant physiological responses and impact stress resilience (Jansson & Hofmockel, 2020; Omae & Tsuda, 2022) [10, 19].

11. Soil Structure and Microbiome Functioning

The soil structure regulates water movement, oxygen diffusion, nutrient transport, root penetration, and microbial habitats. Microorganisms also contribute to soil structure through fungal hyphae, extracellular polymers, decomposition products and aggregate formation.

Hartmann and Six (2023) [8] emphasized the strong relationship between soil structure and microbiome function. Soil structure controls resource flow, whereas microbial communities contribute to aggregation and fertility.

This creates positive feedback:

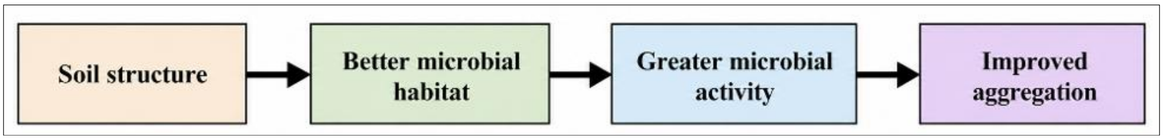

Fig 3: Relationship between soil structure and microbiome functioning.

Protecting this relationship may be more important than maximizing microbial abundance.

12. Agricultural Practices and the Soil Microbiome

Soil microbial communities are significantly affected by agricultural practices, as they affect plant diversity, inputs of organic C, soil structure, nutrient availability and microbial habitats. Crop diversification, intercropping, cover cropping, organic amendments, reduced tillage, residue retention, agroforestry and balanced fertilization are important practices (Hartmann & Six, 2023; Compant *et al*., 2025) [8, 5].

12.1 Crop Diversification

Crop diversification has the effects of changing root exudates, rooting patterns, nutrient demand, and soil microhabitats. Diversified cropping can enhance prokaryotic richness, diversity and generate more complex microbial community networks under conventional nitrogen fertilisation, revealed by field evidence (Liu *et al*., 2023) [15].

12.2 Organic Matter and Soil Disturbance

Organic residues and amendments help to feed microorganisms and to maintain microbial activity and nutrient cycling. Minimized soil disturbance associated with reduced tillage can aid in maintaining soil aggregates, soil pore spaces, and microbial ecosystems (Hartmann & Six, 2023) [8]. Therefore, management of the microbiome is not only possible with microbial inoculants, but also with changes in the plant community, carbon input and soil variables.

Table 2: Agricultural practices and their potential microbiome effects

Agricultural practice	Major microbiome effect	Potential benefit
Crop diversification	Alters microbial diversity and network structure (Liu *et al.*, 2023) [15]	Improved functional diversity
Intercropping	Increases root and exudate diversity (Compant *et al.*, 2025) [5]	Enhanced microbial interactions
Cover crops	Extends living-root and carbon inputs (Compant *et al.*, 2025) [5]	Nutrient retention and microbial activity
Organic amendments	Provides microbial substrates (Hartmann & Six, 2023) [8]	Increased microbial activity and nutrient cycling
Reduced tillage	Preserves soil structure and microbial habitats (Hartmann & Six, 2023) [8]	Improved soil-microbiome functioning
Residue retention	Increases organic-carbon inputs (Hartmann & Six, 2023) [8]	Enhanced nutrient recycling
Agroforestry	Increases habitat heterogeneity (Compant *et al.*, 2025) [5]	Greater biological complexity
Excessive fertilization	Alters soil chemistry and microbial communities (Hartmann & Six, 2023) [8]	May disrupt beneficial interactions

Overall, sustainable agricultural management should aim to maintain soil structural integrity, diverse plant inputs, and microbial biodiversity, rather than relying on a single management practice (Hartmann & Six, 2023; Liu *et al.*, 2023) [8, 15].

13. Biofertilizers, Microbial Inoculants and Their Limitations

Biofertilizers are microbial formulations which can enhance the growth of plants, nutrient availability and nutrient-use efficiency. The important groups are nitrogen-fixing bacteria (*Rhizobium*, *Bradyrhizobium*, *Azospirillum*, and *Azotobacter*) and phosphate-solubilizing bacteria (*Bacillus* and *Pseudomonas*) and arbuscular mycorrhizal fungi. Other beneficial microbial inoculants can also stimulate plant growth by enhancing nutrient uptake, water uptake and biological disease suppression (Aloo *et al.*, 2022; Schütz *et al.*, 2018) [2, 26].

These microorganisms improve the availability of nutrients in plants by providing nitrogen fixation and nutrient solubilization (including phosphate solubilization) and some strains provide suppression of plant diseases. Biofertilizers containing plant growth-promoting rhizobacteria (PGPR) can be used to enhance plant growth and soil fertility in crops (Aloo *et al.*, 2022) [2].

The inconsistency of microbial inoculants in the field is caused by environmental changes, native microorganisms, host specificity, soil characteristics and the complex interactions among the microorganisms (Compant *et al.*, 2025; Haskett *et al.*, 2021) [5, 9]. Practical challenges of formulation, storage and difficult measurement of microbial function remain.

Compatibility between the microbial technology, the host plant, native microbiome, soil and environment are essential for success. They work best when combined with proper soil management, fertilization and cropping practices, rather than as a panacea for fertilizers and pesticides (Compant *et al.*, 2025) [5].

14. Microbial Consortia

The complexity of soil ecosystems has increased interest in microbial consortia that combine microorganisms with complementary functions. Such consortia may provide broader functional benefits than those of individual strains. However, microbial members may compete or respond differently to soil and environmental conditions, affecting their establishment and performance in the rhizosphere. Therefore, effective consortium design requires consideration of microbial compatibility, ecological interactions, host plants, and soil conditions, rather than simply mixing beneficial strains (Shayanthan *et al.*, 2022; Nunes *et al.*, 2024) [27, 18].

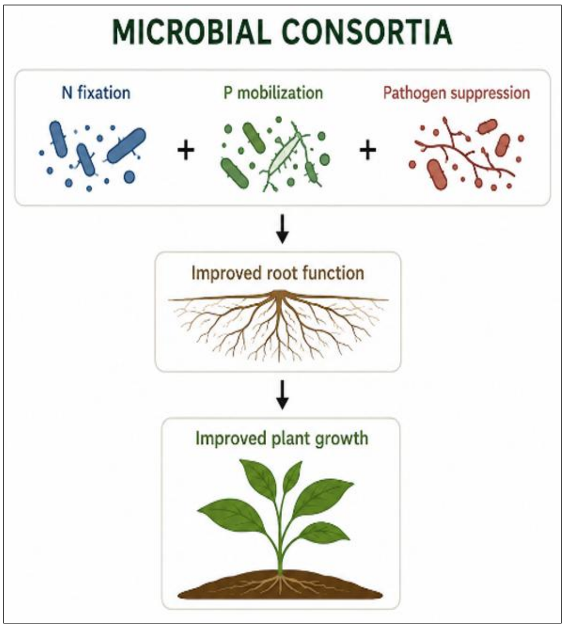

Fig 4: Microbial Consortia and Their Effects on Plant Growth

15. Microbiome Engineering

Microbiome engineering seeks to deliberately modify microbial communities and their functions. Ke *et al.* (2021) [11] described microbiome engineering as an emerging synthetic biology approach for improving plant-associated microbial functions.

Two broad approaches can be distinguished.

- **Bottom-up:** selection, characterization, engineering, and introduction of individual microorganisms.
- **Top-down:** manipulation of microbial communities as an ecological system.

Synthetic microbial communities can be designed to investigate combinations of nutrient acquisition, disease suppression, root development, and stress tolerances.

However, engineered microorganisms require careful assessment of environmental persistence, non-target effects, ecological displacement, horizontal gene transfer and biosafety.

16. Multi-Omics Approaches

Modern microbiome research integrates metagenomics, metatranscriptomics, metaproteomics, metabolomics, soil chemistry, and plant phenotyping to obtain a comprehensive understanding of microbial functions and plant responses. Such integration is important because microbial community composition and gene abundance alone may not accurately reflect gene expression, protein activity or metabolic function (Arıkan & Muth, 2023) [3].

17. Precision Microbiome Management

Precision microbiome management aims to select microbial communities and management practices according to specific soil, crop, and climatic conditions, rather than relying on universal microbial formulations. Important factors include soil properties, crop genotype, microbial composition, moisture, weather, disease history, and agricultural practices (French *et al.* 2021) [7].

18. Future Prospects

Sustainable microbiome-based agriculture: shifting from a single to ecosystem management. Major prospects are microbiome-informed crop breeding, synthetic microbial communities, stress-adapted microbiomes, precision inoculation, microbiome-compatible farming and AI-assisted microbiome design (Wei *et al.*, 2026) [32].

Microbiome-informed breeding may help in choosing crops that effectively recruit beneficial microbes. Synthetic communities can be built with microbes with specific functions, and stress-adapted microbiomes can enhance resilience to drought and salinity. Precision inoculation can be used to tailor microbial products to specific crops and soils, and diversified cropping, organic matter management and reduced disturbance can promote native beneficial microbial communities. Artificial intelligence can further help in finding the right combinations of microbes (Wei *et al.*, 2026) [32].

19. Integrated Systems Perspective and Framework for Agricultural Application

The major strength of plant-soil microbiome interactions is the interconnection of microbial functions. Improved microbial activity can enhance nutrient cycling and availability, thereby promoting plant growth, root biomass, and carbon inputs. Increased carbon availability can further stimulate microbial activity and contribute to soil aggregation, whereas improved soil structure enhances water infiltration and retention. Together, these processes create a positive feedback loop among the soil, microorganisms, and plants.

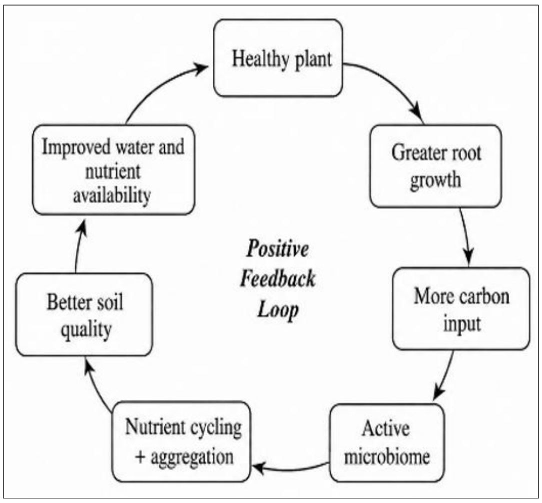

Fig 5: A Systems Perspective of Plant-soil microbiome interactions

This systems perspective highlights the need to manage plants, soil, and the microbiome as an integrated system for sustainable agriculture. Therefore, microbial interventions should be selected according to the ecological conditions in which they will operate, considering soil properties, plant traits, native microbial communities, and environmental conditions.

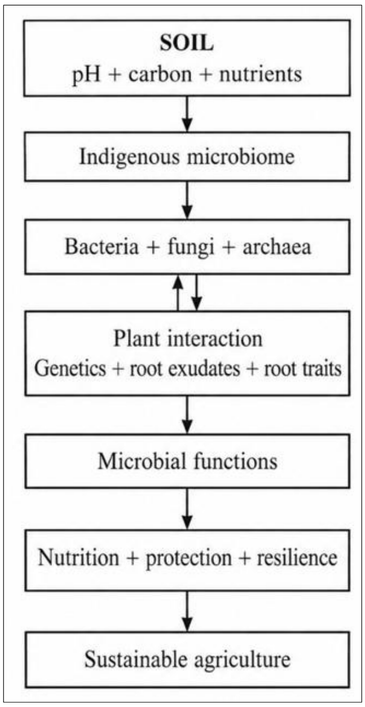

Fig 6: Integrated Plant-Soil Microbiome Management for Sustainable Agriculture

This framework emphasizes that microbial interventions should be selected based on the ecological conditions in which they will operate.

20. Conclusion

Plant-soil microbiome interactions are at the core of agriculture. Soil microorganisms around plant roots contribute to cycles of nutrients, decompose organic matter, help soil to aggregate, promote plant growth, inhibit disease, and facilitate plant adaption to changing environments.

The rhizosphere, the area around plant roots is where plant biology meets soil ecology. The types and activities of microbes available are influenced by substances secreted by the plant roots (exudates). At the time these microbes help with plant nutrition, influence root development and strengthen plant defenses and responses to stress (Ma *et al.*, 2022; Trivedi *et al.* 2020) [17, 30].

Various beneficial bacteria such as *Rhizobium, Bacillus, Pseudomonas, Azospirillum* and *Streptomyces* and fungi such as arbuscular mycorrhizal fungi and *Trichoderma* play different and interconnected roles in enhancing crop sustainability. Under the right circumstances, some bacteria are able to fix nitrogen, which decreases the need for synthetic nitrogen fertilizers. Plant-available phosphorus is released by phosphorus-mobilizing microbes. This extra root system allows plants to access soil volume to obtain water and nutrients from it (Schaefer *et al.*, 2021) [24].

They also regulate pathogens and increase drought, high salt, heat and other stress tolerance in plants. The wheat drought experiment by Li *et al.* (2025) [13] has shown that stress alters the surrounding community of plants, and that alteration of the community can impact plant survival.

Do not use microbiome based tools as a substitute for fertiliser and/or pesticides. They are effective in soils, crops, climate and in the presence of other microbes, as well as their ability to inhabit their surroundings (Haskett *et al.* 2021; Compant *et al.* 2025) [9, 5].

So it's not simply a matter of adding microbes. Controlling all the microbiomes. The ultimate goal is integrated plant-soil ecosystem management. This is possible through the use of crop diversity, improved use of organic matter, reduced tillage, appropriate nutrient management, smart inoculation, crop species compatible to the microbes, -omics science and precision agriculture. These practices can create a resilient and biologically robust farming system when combined together and implemented.

Soil should not be considered a medium. It is an alive organism. However, microbial communities are not just present, they are players, in nutrition cycles, plant health, soil formation, environmental resilience and overall ecosystem functioning. Making the most of these processes while keeping the ecosystem stable could be one of the most important ways to create agricultural systems that are productive, efficient and sustainable.

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