



Plant-Microbe Interactions and Rhizosphere Dynamics for Sustainable Agriculture: A Review

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ABSTRACT

The rhizosphere, a narrow zone of interaction between plant roots and soil, represents a critical interface regulating plant growth, nutrient cycling and soil health. This study reviews the ecological and functional significance of plant-microbe interactions within the rhizosphere and their implications for sustainable agriculture. Root exudates, microbial diversity and soil physicochemical properties collectively shape the composition and activity of microbial communities. Beneficial organisms, including plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, facilitate nutrient mobilization, enhance stress tolerance and suppress soil-borne pathogens. Conversely, pathogenic microbes such as *Fusarium* and *Ralstonia* negatively impact crop productivity and threaten agricultural sustainability. Emerging biotechnological approaches harness these beneficial interactions to improve soil fertility and reduce dependence on chemical fertilizers and pesticides. Techniques such as microbial inoculants, rhizosphere microbiome engineering and biocontrol agents show promise for enhancing crop performance under sustainable farming systems. However, their efficiency is often limited by variable microbial colonization, inconsistent field responses and environmental heterogeneity. Recent advancements in molecular tools, including metagenomics and the development of synthetic microbial communities, provide new insights into rhizosphere complexity and functionality. Understanding and managing these interactions can drive the development of ecologically sound strategies to enhance crop productivity, promote soil resilience and address global challenges of food security and climate change.

Key words: Microbial inoculants, PGPR, Plant-microbe interactions, Rhizosphere dynamics, Sustainable agriculture.

A limited area of soil known as the rhizosphere is directly impacted by plant roots through the emission of different organic chemicals, root exudates and sloughed-off root cells. With a varied and vibrant microbial community, this biologically dynamic zone acts as a vital contact between plants and the soil environment. By promoting nutrient uptake, strengthening defenses against soilborne infections and raising soil fertility and structure, the rhizosphere is essential to plant growth (Alzubaidy *et al.*, 2016). Plant health, soil quality and the stability of the ecosystem as a whole are all greatly impacted by interactions within this zone.

Sustainable agriculture helps in the production of agricultural and horticultural crops in a safe and viable manner. Sustainable agriculture helps in the reduction of chemical fertilizers and pesticides, which can cause long term environmental hazards. Instead, it seeks to utilize natural biological processes to maintain soil fertility and protect biodiversity (Afridi *et al.*, 2022). Within this context, rhizosphere interactions are of paramount importance. The process of nutrient cycling, decomposition of various organic matters and maintaining the structure along with fertility of the soil are all done by the vast plant growth promoting rhizobacteria and mycorrhizal fungi. They assist in solubilization of vital nutrients improve biotic and abiotic stress tolerance and suppress harmful pathogens through natural mechanisms (Butler *et al.*, 2003). Understanding and harnessing these interactions offer promising avenues

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to enhance soil health, increase crop productivity and promote a sustainable and resilient agricultural system without relying heavily on chemical interventions.

Rhizosphere biology directly contributes to global sustainability goals, particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action). By enhancing nutrient cycling, improving soil fertility and promoting plant resilience, rhizosphere microorganisms play a vital role in increasing agricultural productivity while reducing reliance on chemical fertilizers and pesticides, supporting sustainable food systems central to the goal of zero hunger (Mahendran *et al.*, 2025). Additionally, managing the rhizosphere microbiome can enhance soil carbon sequestration and reduce greenhouse gas emissions, aligning with SDG 13 by

mitigating climate change impacts. Integrating rhizosphere-based biotechnologies into farming practices therefore offers a dual pathway to secure food supply and foster climate-resilient agriculture

The rhizosphere dynamics

The rhizosphere is the narrow region of soil directly influenced by plant roots and their secretions. It is a dynamic environment where roots interact with a wide variety of microorganisms, including bacteria, fungi and protozoa (Hartmann *et al.*, 2008). These interactions often enhance nutrient availability for the plant, making the rhizosphere critical for plant health and growth. The composition of the rhizosphere soil is different from the bulk soil, mainly due to the biological activity stimulated by the presence of roots.

Plants release a variety of organic compounds into the rhizosphere, such as sugars, amino acids and enzymes. These root exudates serve as energy sources for microorganisms, leading to higher microbial activity compared to non-rooted soil areas. In return, many of these microorganisms assist plants by fixing nitrogen solubilizing phosphorus, or producing growth-promoting substances (Atkinson and Watson, 2000). The continuous exchange of nutrients and signals between roots and microbes creates a highly active zone that is essential for soil fertility and plant productivity.

Environmental factors like soil type, moisture, temperature and the plant species itself influence the structure and function of the rhizosphere. Some plants are known to cultivate specific microbial communities to support their growth or protect themselves from pathogens (Durán *et al.*, 2018). Understanding the processes in the rhizosphere is crucial for developing sustainable agricultural practices, as it offers ways to naturally improve soil health, enhance crop yields and reduce dependency on chemical fertilizers (Hartmann *et al.*, 2008).

Key characteristics of rhizosphere soil

Nutrient enrichment

The rhizosphere typically exhibits higher levels of nutrients and enzyme activity compared to bulk soil. This is largely due to the presence of organic compounds derived from plant roots, which stimulate microbial activity and nutrient cycling. Research indicates that organic matter in the rhizosphere undergoes faster transformation, leading to increased concentrations of nitrogen, phosphorus and potassium in this zone (Das *et al.*, 2017).

Microbial diversity

The rhizosphere acts as a selective environment for microorganisms, often reducing microbial diversity compared to bulk soil. It serves as a “seed bank” for beneficial microbes that can aid in nutrient transformation processes, such as carbon and Nitrogen cycling. The abundance of specific microbial functions in the rhizosphere is influenced by the type of plants growing in the area, with different plant functional groups affecting

microbial community structure and activity (Ahmed *et al.*, 2017).

Soil structure and chemistry

The physical and chemical properties of the rhizosphere are altered by root activities. Roots can modify soil porosity and architecture, impacting water retention and aeration. Additionally, root exudates can lower soil pH by releasing organic acids, which further influences nutrient availability (Kandel *et al.*, 2017).

The rhizosphere effects

The soil surrounding a plant's roots is home to a diverse community of microorganisms that closely interact with the developing plant, especially during seed germination and seedling establishment (Dias *et al.*, 2017). As seeds germinate and roots grow, they release organic compounds into the soil. These exudates serve as a food source and chemical signal, encouraging the proliferation of microbial populations in a very narrow zone around the roots. This dynamic interaction between the roots and soil microbes is known as the rhizosphere effect (Morgan *et al.*, 2000).

The rhizosphere effect creates a highly active environment just a few milli meters thick that includes not only the root surface but also the immediate soil region influenced by root activities (Butler *et al.*, 2003). This area becomes a hotspot for microbial activity due to the continuous release of nutrients from the roots. The result is a specialized micro-ecosystem where plants and microorganisms communicate and influence each other's growth and health. This relationship is essential for nutrient cycling, plant health and soil fertility (Curá *et al.*, 2017).

The structure of the rhizosphere can be divided into three main parts: the root itself, the rhizoplane and the surrounding rhizosphere soil. The rhizoplane refers specifically to the root surface, including soil particles that are tightly bound to it. In contrast, the rhizosphere soil is the portion of soil directly impacted by root secretions and microbial activity (Ashraf *et al.*, 2025). Together, these zones form a crucial interface where plants and soil life interact intensively, affecting the biological and chemical properties of the soil (Ashraf *et al.*, 2025).

Root exudation and its role

Root exudation refers to the process by which living plant roots secrete a variety of organic molecules into the surrounding soil. This phenomenon occurs regularly and can happen through multiple pathways, with the rate of exudation varying greatly between plant species and environmental conditions (Kechid *et al.*, 2005). Root cells allow the movement of exudates across their membranes into the rhizosphere and root border cells also contribute by releasing plant compounds. Common components of root exudates include water-soluble sugars, amino acids, organic acids, hormones, vitamins, phenolic substances and sugar phosphate esters (Uren *et al.*, 2000).

The movement of these low molecular weight substances typically follows a concentration gradient, where they diffuse from the higher concentration within root cells to the much lower concentration in the surrounding soil. The permeability of root cell membranes plays a key role in this process, affecting how lipophilic (fat-loving) exudates pass through (Altuntas, 2018). Factors such as the physiological state of the root and the polarity of exuded compounds determine whether diffusion occurs directly through the plasma membrane or requires other mechanisms. Environmental stressors like nutrient deficiencies, extreme temperatures and physical damage to roots can significantly enhance the rate of exudation by impacting membrane integrity (Sagar *et al.*, 2018).

Several environmental conditions influence both the amount and type of compounds released during root exudation (Singh *et al.*, 2006). Elements like soil pH, oxygen availability, soil structure, light intensity, temperature and the presence of soil microbes all contribute to variations in exudate profiles, often more significantly than differences between plant species themselves. Additionally, the root is not an isolated system; certain beneficial endophytic bacteria can inhabit internal root tissues, further shaping the dynamic environment of the rhizosphere (Bowen *et al.*, 1999). This close interaction between roots and microbes fosters a thriving microecosystem critical for plant and soil health.

Factors affecting rhizosphere dynamics

Plant-related factors

Rhizosphere dynamics is affected by various plant related factors such as root exudates, plant development stage and host genotype. Plants release sugars, organic acids

and signaling molecules through root exudates, which directly shape microbial communities and nutrient availability (Ansari *et al.*, 2017) (Fig 1). Microbial communities shift as plants age, with nutrient demands and exudate profiles changing across growth phases. Plant genetics influence root architecture and exudate chemistry, determining which microbial taxa thrive in the rhizosphere (Ashraf *et al.*, 2021).

Soil properties

Soil properties like texture and structure, pH and nutrient availability and hydrolic conductivity plays an important role in microbiome development. Soil porosity and aggregation affect water retention, oxygen availability and microbial mobility. Acidic root exudates lower rhizosphere pH, altering nutrient solubility (Singh *et al.*, 2006). Nutrient-depleted zones around roots drive microbial competition for resources like nitrogen and phosphorus. Rhizosphere soil often retains water longer during drought but rewets slower after irrigation due to altered pore structure and mucilage secretion. This impacts root water uptake efficiency (Breitkreuz *et al.*, 2020).

Microbial interactions

One of the important factor determining rhizosphere dynamics is microbes. The microbial life style strategies, functional diversity and cross kingdom signalling are the important activities of microbiomes that influence rhizosphere dynamics. Fast-growing copiotrophs (bacteria like *Pseudomonas*) dominate in nutrient-rich rhizospheres, while slow-growing oligotrophs (e.g., fungi) prevail in bulk soil. Agricultural fertilization intensifies this dichotomy (Ahemad and Kibert, 2014). Microbes mediate nutrient

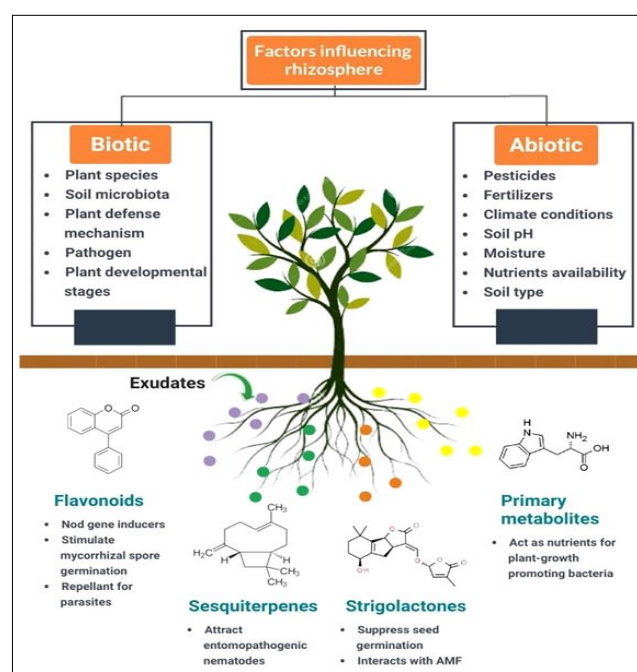


Fig 1: Factors influencing rhizosphere dynamics and the root exudates.

cycling (e.g., nitrogen fixation, phosphorus solubilization) and pathogen suppression. Plant exudates selectively attract beneficial taxa, creating species-specific microbiomes. Plants release strigolactones and flavonoids to recruit symbiotic microbes, while microbes produce phytohormones (e.g., auxins) to enhance root growth (Ávila *et al.*, 2020).

Environmental and management factors

High soil moisture induces hypoxia, altering microbial respiration and exudate profiles (e.g., ethanol accumulation). Drought stress amplifies competition for water, favoring drought-tolerant microbes. Agricultural Practices like crop rotation, tillage and irrigation modify rhizosphere microbial networks and soil organic matter turnover. For example, maize-sorghum rotations enhance bacterial diversity compared to monocultures (Thepbandit *et al.*, 2024). Climate Variability including light intensity and humidity regulate photosynthesis-driven carbon allocation to roots, indirectly affecting exudate production.

Plant-microbe interactions in the rhizosphere

Within the microenvironment of rhizosphere, intricate and vital interactions occur between plants, soil components and the diverse community of microorganisms. These interactions involve complex biochemical processes and the exchange of signaling molecules between plants and microbes (Thepbandit *et al.*, 2024). Microorganisms within the rhizosphere compete for essential resources like water, nutrients and space and often improve their survival chances through close associations with plant roots, which significantly influence the plant's growth and ecological success (Hartmann *et al.*, 2009, Kumar *et al.*, 2019).

A rich diversity of organisms inhabits the rhizosphere, forming a community known as the rhizobiome. These organisms work together dynamically to promote plant health and resilience (Kumar *et al.*, 2017) (Fig 2). One important form of interaction in this environment is allelopathy, where chemical compounds released by the roots of one plant can affect the roots of neighboring plants,

often influencing their growth either positively or negatively (Olanrewaju *et al.*, 2018). While allelopathic effects are driven by plants, other types of interactions are facilitated by the microorganisms themselves, highlighting the complex web of relationships that characterize the rhizosphere ecosystem.

The rhizosphere is home to a wide array of microorganisms, including viruses, fungi, bacteria and archaea (McNear, 2013). The interactions among these microbial groups help shape the structure and function of the rhizobiome. How these species coexist, compete and cooperate has a profound impact on the overall health of the soil and the plants growing within it (Kaushal and Wani, 2016). The balance of microbial relationships ultimately determines the quality of the rhizosphere and plays a crucial role in supporting sustainable plant growth.

Role of plant growth-promoting microorganisms (pgpm) in enhance plant health and alleviate stress

Plant growth-promoting bacteria (PGPB) enhance plant health and resilience by using various strategies. These beneficial microorganisms can directly assist plants by producing chemicals that stimulate growth or supply essential nutrients. Indirectly, they can suppress harmful pathogens through the production of protective metabolites (Ahemad and Kibert, 2014). Additionally, they play a significant role in helping plants cope with abiotic stresses such as drought, salinity and temperature extremes (Ghosh and Mandal, 2020). A key aspect of their influence is the production of phytohormones-chemical messengers like auxins, gibberellins, cytokinins, ethylene and abscisic acid-that are vital for regulating plant growth and development (Müller, 2021; Olanrewaju *et al.*, 2022).

Among the phytohormones, indole acetic acid (IAA), a type of auxin, stands out due to its critical role in promoting root growth, seed germination, cell division and shoot dominance. Notably, about 80% of rhizosphere bacteria are capable of producing IAA (Glick, 2020). By boosting root development and stress resistance, IAA-producing

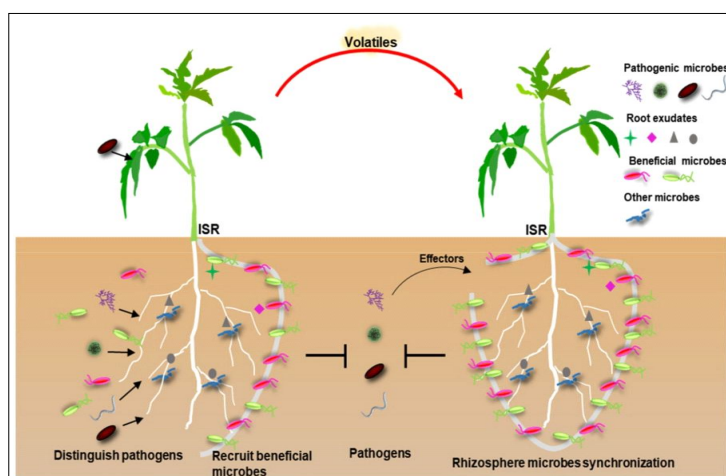


Fig 2: Effect of root exudates in the growth of beneficial microbes in the rhizosphere.

PGPB help plants better withstand both biotic and abiotic stressors, such as diseases and harsh environmental conditions (Kaushal and Wani, 2016). For instance, during drought stress, these bacteria help maintain nutrient and water transport within plants, thus safeguarding plant growth and survival (Alzate Zuluaga *et al.*, 2024; Guo *et al.*, 2021).

In addition to auxins, other phytohormones produced by PGPB, like gibberellins and cytokinins, also play crucial roles in plant development. Gibberellins contribute to processes like flowering, stem elongation and fruit ripening, while cytokinins are involved in root and vascular development, seed germination and the regulation of apical dominance (Osugi and Sakakibara, 2015). When PGPB increase cytokinin levels in the rhizosphere, it can further stimulate plant growth and improve plant vitality. Thus, the presence and activity of PGPB in the soil are essential for both enhancing plant productivity and mitigating the negative impacts of environmental stresses (Paite *et al.*, 2019).

Role of plant growth-promoting microorganisms (pgpm) in improving nutrient uptake

Nitrogen and phosphorus are two essential nutrients for plant development, particularly because they are key components of nucleic acids and energy molecules like ATP, ADP, NADP and NADPH (Bais *et al.*, 2006). Plants often rely on phosphate-solubilizing bacteria in the soil to convert insoluble forms of phosphorus into accessible forms. These beneficial bacteria, including species like *Xanthomonas*, *Klebsiella*, *Enterobacter* and *Bacillus pseudomonas*, play a crucial role in enhancing phosphorus availability and improving overall plant nutrition (Alori *et al.*, 2017) (Table 1).

For nitrogen uptake, plants primarily absorb it in the form of ammonium and nitrate. However, atmospheric nitrogen must first be converted into ammonia through the activity of nitrogen-fixing bacteria. Both free-living and symbiotic bacteria contribute to this process (Etesami *et al.*, 2017). Symbiotic nitrogen-fixing genera, such as *Rhizobium*, *Bradyrhizobium*, *Ensifer*, *Azorhizobium* and *Frankia*, form partnerships with specific plant species like legumes to supply them with usable nitrogen. Free-living bacteria like *Arthrobacter*, *Azoarcus*, *Azospirillum*, *Azotobacter*, *Enterobacter*, *Mitsuaria* and *Pseudomonas* also assist in nitrogen fixation independently of a host plant (Mahmud *et al.*, 2020; Reyes-Castillo *et al.*, 2019).

Research shows that legume crops often experience improved growth and productivity when inoculated with nitrogen-fixing bacteria (Ke *et al.*, 2019). Furthermore, PGPB not only help in nitrogen fixation but also enhance the plant's ability to absorb nitrate. For example, studies on *Arabidopsis* have demonstrated that certain PGPB can stimulate the overexpression of genes related to nitrate transporters, ensuring more efficient nitrogen uptake by plants (Kechid *et al.*, 2013). Thus, PGPB are integral to improving both nitrogen and phosphorus acquisition in plants, significantly boosting agricultural productivity.

Although global food production is continually threatened by plant pathogens, the widespread use of chemical pesticides and fungicides to control these threats has raised serious environmental and health concerns (Hakim *et al.*, 2021). These chemical solutions are often unsustainable, leading to soil and water pollution. In contrast, the use of plant growth-promoting microbes (PGPM) offers a more eco-friendly and sustainable approach to disease control.

Table 1: Rhizosphere bacteria and their effect on plant productivity.

Microbial strain	Plant-growth promoting traits	Effect on plant productivity
<i>Bradyrhizobium sp.</i>	Synthesis of siderophore and indole acetic acid, nitrogen fixation and phosphate solubilization	Increases growth parameters and seed yield in mung beans plant
<i>Rhizobium meliloti</i>	Production of siderophore and nitrogen fixation	Increases peanuts growth, yield attributes, I quality of pods and efficiency in the use of nitrogen
<i>R.leguminosarum</i>	Phosphate solubilization	Increases growth of soybean and yield performance under drought stress
<i>Bacillus spp.</i>	Production of phytohormone, such as auxin, phosphate solubilization	Increases straw berry fresh and dry weight parameters, increases yield over the control plant
<i>Chryseobacterium sp.</i>	Production of siderophore, phosphate solubilization	Increases grain yield, shoot mass and nodule mass in chickpea
<i>Herbaspirillum spp.</i>	Synthesis of indole acetic acid, nitrogen fixation	Enhances mineral uptake in maize plant and increases yield
<i>Paenibacillus glucanolyticus</i>	Synthesis of indole acetic acid	Increases tissue dry weight and nutrient uptake in black pepper
<i>Streptomyces spp.</i>	Production of siderophore and synthesis of indole acetic acid	Increases tomato growth parameter and modulates metabolic activity

PGPM, particularly plant growth-promoting bacteria (PGPB), help plants resist pathogens through multiple mechanisms, including the production of ACC-deaminase, siderophores, lytic enzymes, antibiotics and by triggering induced systemic resistance in plants (Glick, 2014; Olanrewaju *et al.*, 2017) (Table 1).

How rhizosphere microbes support sustainable agriculture

Soil serves as a natural medium for plant growth and development, housing a diverse range of microorganisms such as bacteria, fungi, algae and actinomycetes. In recent years, the plant microbiome has gained significant attention due to its critical role in plant health and productivity (Hunter, 2016; Trivedi *et al.*, 2017). Microbes in the rhizosphere can form beneficial, neutral, or harmful relationships with plants, depending on the interaction type. About 5-20% of photosynthetic byproducts, known as photosynthates, are secreted by plant roots into the rhizosphere, including substances like mucilage, sloughed cells and rhizodeposits (Ray *et al.*, 2020). These root exudates largely determine the structure and composition of the rhizosphere microbiome (Durán *et al.*, 2018; Gaiero, 2013; Santoyo *et al.*, 2021).

Classic examples of beneficial plant-microbe relationships include nitrogen-fixing bacteria such as rhizobia, arbuscular mycorrhizal fungi and phosphate-solubilizing bacteria (Köhl *et al.*, 2014). These microbes enhance plant access to essential nutrients like nitrogen and phosphorus through processes like biological nitrogen fixation, phosphate solubilization and nutrient transport (Köhl *et al.*, 2014; Kumar *et al.*, 2015). Furthermore, the microbiome promotes plant growth by producing phytohormones, such as salicylic acid (SA), auxin, gibberellins, cytokinins and indole-3-acetic acid (IAA) (Hashem *et al.*, 2017; Trivedi *et al.*, 2017). Certain bacteria also produce ACC deaminase, an enzyme that lowers ethylene levels in plants, thereby reducing stress (Mohler, 2001; Suman *et al.*, 2022). The microbiome plays a crucial role in helping plants survive under extreme conditions like salinity, drought and heavy metal stress by mitigating the harmful effects of these stresses through the production of beneficial compounds (Gaiero *et al.*, 2013). Harnessing the microbiome's potential could lead to the development of targeted microbial inoculants or the manipulation of microbial populations for better plant growth (Hopkins *et al.*, 2017).

Promoting sustainable agriculture involves leveraging the plant microbiome to reduce dependency on chemical fertilizers and pesticides (Ashraf *et al.*, 2024). Additionally, the microbiome serves as a natural biocontrol agent, suppressing pathogen activity through mechanisms such as parasitism, antibiosis and enhanced plant immune responses (Rascovan *et al.*, 2016). By improving nutrient availability (biofertilization) and controlling diseases, the microbiome can significantly contribute to sustainable farming practices, leading to increased agricultural yields, reduced chemical use and lower greenhouse gas

emissions (Mosttafiz *et al.*, 2012; Tripathi, 2015). Such approaches are crucial to meet the demands of the world's growing population.

Challenges in harnessing rhizosphere microbiomes

The rhizosphere microbiome plays a critical role in plant health and growth, but its functionality is constantly challenged by a range of environmental and biological factors. These stressors include the plant's developmental stages, its species or genotype, soil composition and conditions like moisture, temperature and pH (Ali *et al.*, 2019). External factors such as light, rainfall, pesticide use, soil-borne pathogens and farming methods further influence the microbiome's behavior, making it difficult to predict and manage its effects on plants (Liu *et al.*, 2020).

Environmental conditions and stressors can lead to changes in the plant's molecular composition, including its transcriptomics and metabolomics, which in turn affect root and leaf exudates. These alterations can shift the microbial populations in the rhizosphere, impacting their ability to support plant growth and productivity. Variations in temperature and soil moisture can particularly disturb the balance of microbial communities, directly influencing the plant's immune responses, nutrient absorption and overall health (Lemanceau *et al.*, 2017).

These disruptions in the microbiome's structure and function ultimately affect plant productivity and resilience. Abiotic and biotic factors collectively modify plant physiology, root exudation and microbial activity, creating obstacles to effectively using these microorganisms in agriculture (Trivedi *et al.*, 2022). Addressing these challenges is essential to enhancing the role of rhizosphere microbes in promoting sustainable farming and improving plant resilience to various stresses.

CONCLUSION

In the rhizosphere, plants and microorganisms interact closely, significantly affecting soil health, nutrient availability and plant productivity. These interactions are shaped by factors such as root exudates, soil properties, microbial diversity and environmental conditions. Beneficial microorganisms, including plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, play crucial roles in nutrient cycling, stress resistance and biological control of diseases. On the other hand, pathogenic microbes can negatively impact plant health, hindering agricultural sustainability.

Harnessing the positive interactions between plants and microbes offers a sustainable and natural solution for agricultural challenges. By using biofertilizers, microbial inoculants and biocontrol agents, the reliance on chemical fertilizers and pesticides can be reduced, leading to healthier soils and safer produce. PGPRs contribute to enhanced nutrient uptake through processes like nitrogen fixation and phosphorus solubilization, while also promoting phytohormone production that supports growth and improves resistance to stressors such as drought

and salinity. Furthermore, these microorganisms help plants fend off pathogens through eco-friendly biological control methods.

However, deploying beneficial microbes universally across diverse environmental conditions remains challenging. Factors like soil type, plant genotype, farming practices and climate changes all influence rhizosphere dynamics and microbial performance. To maximize the benefits of plant-microbe interactions, further research is needed in microbiome management, the development of synthetic microbial communities and advanced molecular techniques.

Ultimately, fostering natural plant-microbe relationships is key to developing a sustainable, productive and environmentally secure food system, which is essential to ensuring food security for the growing global population.

Conflict of interest

The authors confirm that there are no conflicts of interest associated with this publication.

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