Chapter

Rhizosphere Intelligence: Harnessing Root-Microbe Dynamics for Resilient Cropping System

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Abstract

For more than half a billion years, plants and microbes have shared their resources in a common ground known as the rhizosphere. The rhizosphere, a biologically active zone of the soil influenced by plant roots, has complex and dynamic interactions between soil microbes that shape crop plant health, resilience, and productivity. Despite decades of research, the processes of the rhizosphere remain underutilized in cropping systems management. This chapter entails the advances in rhizobiology with a focus on root-microbe dynamics, interactions, and their implications for sustainable crop management. It offers a thorough understanding of how intelligently the rhizosphere exhibits its connection between plants and microbes. The chapter further describes how rhizosphere intelligence can be viewed as an information-processing network with multiple levels of organization in which plants and microbes exchange chemical and molecular information throughout their separate life cycles. Root exudates take the highest level as a selective filter in recruiting or excluding microbes, and microbes provide services such as nitrogen fixation, phosphorus solubilization, pathogen suppression, and abiotic stress suppression. The future of rhizosphere intelligence is expected to result in a paradigm shift for sustainable agriculture, in which a combination of biology, engineering, and digital tools is anticipated to create a resilient cropping system.

Keywords: rhizosphere, root-microbes, cropping system, microbe-microbe interaction, nutrient uptake

1. Introduction

Living organisms exist as a result of interactions that occur among themselves and their environment. The rhizosphere, a biologically active zone of the soil influenced by plant roots, exhibits complex and dynamic interactions involving soil microbes and roots that shape plant health, resilience, and productivity. The whole array of signal-exchange [1] and distinct induced behavioral interconnectedness and responses within the rhizosphere are well-organized and intelligent. In fact, intelligence in plants has been described as the ability to sense and grow toward the resources surrounding them and capture them [2]. The ability of plants, like any other organism, to solve problems they experience in their life cycle forms a unique aspect of intelligence. Considering the environment as the influencing factor in intelligence, what is considered intelligent in one environment is not necessarily the same in another. Plants have developed the ability to improve behavior through long-term experience [3] and adaptively vary across a multitude of different environments while they continue development in their life cycle [2].

The concept of "rhizosphere intelligence" therefore entails the dynamic, adaptive, and synergistic interaction between soil microbes, plants through roots, and the surrounding environment in a collective manner, which enhances plant health, nutrient acquisition, and ecosystem resilience. As a system, biology, ecology, and plant-microbe interactions describe how these components act in connectedness, hence resembling a collective intelligence. Furthermore, a responsive feedback mechanism that enables the rhizosphere to adjust to changing conditions has the implication of making it a critical component in the development of resilient cropping systems [4].

Rhizosphere intelligence is governed by several key mechanisms which ensure connected communication between plants, microbes, and soil. From plants come root exudates, which contain organic acids, sugars, amino acids, and secondary metabolites, all of which attract specific microbial taxa [5, 6]. This mechanism is an initiator of the communication and guides the kind of relationship that will enhance the resilience of the plants in a specific environment. The second mechanism is microbial signaling, which involves soil microbes producing signal molecules such as quorum sensing compounds and phytohormones that govern root development, architecture, and defense [7, 8].

In this chapter, the details of how rhizosphere intelligence could change our understanding of the possibilities of utilizing the active lifeforms' mechanisms in the rhizosphere to benefit the sustainability of plants are discussed. The applications could include the development of biofertilizers and microbial consortia, breeding crops with traits that support beneficial rhizobiomes, integration of soil microbiomes in managing agroecological practices, and precision microbiome engineering using synthetic biology and artificial intelligence-based tools. Through rhizosphere intelligence as a transformative concept, the integration of plant physiology, microbial ecology, and systems thinking could leverage the understanding of complex interactions with the possibility of developing a resilient cropping system that would be productive, sustainable, and adaptive to multifarious challenges.

2. Rhizosphere ecosystem

Plants invest up to 30% of their photosynthates in root exudates to ensure a conducive zone for microbial communities and biogeochemical processes in the rhizosphere. To reap the benefits of such an investment, the exudate is responsible for recruiting the right microbial assembly that ensures their growth, defense and nutrient use efficiency [9]. The structure and overall profile of the rhizosphere are significantly shaped by a complex interplay of abiotic and biotic factors. These factors, including soil type, moisture, temperature, nutrient availability, plant species, root exudates, and the presence of other organisms, collectively influence the composition, diversity, and functionality of microbial communities inhabiting the rhizosphere [10].

2.1 The chemistry of the rhizosphere

Changes in soil chemistry due to root activity and microbial processes are highly influenced by factors such as pH gradients, where roots can acidify or alkalize the rhizosphere through ion exchange and root exudation [11]. The root exudates, which are rich in organic compounds like sugars, amino acids, and phenolics, serve as chemical signals or microbial chemoattractants [12, 13]. The exudate chemistry is the language that guides partner choice and reinforcement, which can determine mutualism and invasion success [14]. The chemical profile of the rhizosphere is also influenced by nutrient concentrations, at which levels of nitrogen, phosphorus, potassium, and micronutrients are altered due to uptake and exudation [15].

2.2 Root exudates and their signaling functions

Root exudates are a complex mixture of organic and inorganic compounds secreted by plant roots into the surrounding soil and play a critical role in shaping the rhizosphere environment, especially through chemical signaling that facilitates interactions between plants, microbes, and soil components. They include sugars (glucose and sucrose) and amino acids (glutamate and aspartate) that shape microbial communities by influencing the selective growth of beneficial microbes (**Table 1**) [16]. Phenolic acids and benzoxazinoids have specific functions in allelopathy and plant competition by inhibiting the growth of neighboring plants through interference with seed germination or root development (**Table 1**). Flavonoids and strigolactones attract symbionts and affect nodulation by triggering

Compound group	Representative compound	Ecological function in the rhizosphere	Reference
Sugars and organic adds	Glucose, malate, citrate	Carbon source, nutrient mobilization, chemotaxis cues	[20]
Amino adds and peptides	Glutamate, L-serine, peptides	Microbial recruiting, signaling, and N cycling	[21]
Phenolics and flavonoids	Coumarins, flavones	Iron chelation, antimicrobial activity, microbiome filtering	[22]
Nucleotides/small RNAs	Extracellular RNAs	Cross-kingdom communication	[23]
Proteins/enzymes	Acid phosphatases, chitinases	Nutrient acquisition, defense and microbe modulation	[23]
Lipids and fatty adds	Long chain fatty acids	Biofin modulation and signaling	[24]

Table 1.
Root exudate compounds and their ecological functions.

the production of nod factors that initiate root nodule formation. At the same time, mycorrhizal colonization occurs when roots emit strigolactones to attract arbuscular mycorrhizal fungi (AMF), which colonize the roots and enhance phosphorus uptake [1, 17, 18]. The induced systemic resistance (ISR) elicitors and peptides are also parts of root exudates that provide defense and immunity, thereby enhancing plant resistance to pathogens [19]. Organic acids and phytosiderophores help in nutrient acquisition by solubilizing P, Fe, and other micronutrients from bound forms in the soil.

2.3 Biological profile of the rhizosphere

This covers the diversity, abundance, and interactions of living organisms in the rhizosphere. Microbes such as bacteria and archaea contribute to nutrient transformation (N, P, S), production of hormones, and pathogen suppression. Fungi, especially arbuscular mycorrhizae and endophytes, enhance nutrient foraging and intrinsic immunity. Protists feed on bacteria, which shape microbial networks and nutrients, while phages regulate bacterial competition and suppress diseases in the field [17, 25]. The microbiome in the rhizosphere across crops is involved in stress adaptation and productivity [13, 26]. Soil fauna, mainly nematodes, earthworms, and microarthropods, influence nutrient cycling and microbial populations.

3. Root-microbe interactions: Mechanisms and functions in relation to cropping systems' resilience

3.1 Mutualism, symbiosis, commensalism

Plant–microbe interaction involves root architecture, mucilage, and chemotaxis toward exudate gradients, followed by recruitment, biofilm formation, and immune negotiation [8]. Plants are intelligent enough to fine-tune their exudation profile to encourage beneficial interactions (e.g., plant growth-promoting rhizobacteria [PGPR], AMF while deterring antagonists. Mutualistic interactions between plants and microbes, such as Rhizobia–Legume symbiosis, are notable examples. The mechanism works through trade-offs in which legumes secrete flavonoids, and rhizobia respond by producing nod factors, leading to nodule formation [27, 28]. Moreover, AMF and ectomycorrhizal fungi (ECM) colonize roots and form arbuscules or ectomycorrhizal sheaths, consequently improving phosphorus and water uptake, as well as increasing drought and salt tolerance. The resilience contribution of this mutualism is to improve nutrient use efficiency and reduce abiotic stress sensitivity. PGPR colonize root surfaces or interiors, producing phytohormones, solubilizing minerals, and suppressing pathogens. PGPR contribute to resilience by enhancing plant growth, stress resistance, and disease suppression [29]. Symbiosis refers to mutualistic interactions that are symbiotic, though it can also be neutral or even parasitic. In cropping systems, the beneficial forms are emphasized. The key functions in resilience include nutrient access in degraded soils, improved plant adaptation to environmental stress, increased biodiversity in the soil microbiome, and stable productivity in variable climates [30].

The interactions in which microbes benefit from root exudates, while the plant is not directly harmed or helped, are termed commensalism. Common examples include endophytic bacteria that live within roots without altering plant health [31] and rhizospheric microbes that use exudates as energy sources without influencing plant performance [32]. The resilience role of both endophytic bacteria and rhizospheric microbes is the maintenance of microbial diversity and ecosystem balance, potentially acting as a reservoir for future beneficial microbes [30, 33].

3.2 Biocontrol and antagonists

Beneficial rhizospheric microbes support cropping system resilience through biocontrol and antagonistic mechanisms. Microbes, such as pseudomonas and Azotobacter, compete effectively with pathogens for nutrients and space, preventing their establishment on plant roots [34, 35]. *Bacillus* and *Streptomyces* species produce antimicrobial compounds that directly inhibit the growth of fungi, bacteria, or nematodes [36, 37]. Trichoderma and bacteria like Pasteuria act as hyperparasites or predators, physically attacking and degrading harmful organisms [38, 39]. Some PGPR, including *Pseudomonas fluorescens*, trigger ISR, enhancing the plant's internal defense mechanisms against a broad range of pathogens. *Bacillus* and *Rhizobium* form protective biofilms on root surfaces, acting as physical barriers and further restricting pathogen access [40, 41]. These diverse mechanisms collectively enhance plant health, reduce disease incidence, and contribute significantly to the long-term resilience and sustainability of cropping systems.

3.3 Communication in the rhizosphere

The rhizosphere is a chemically dynamic and biologically interactive zone where plants and microbes continuously communicate using chemical signals. These interactions regulate colonization, cooperation, competition, and plant responses, ultimately shaping the health, productivity, and resilience of cropping systems [42]. Two major forms of communication are quorum sensing, which is the communication between microbes, and phytohormonal signaling, connecting microbes and plants.

Quorum sensing is a cell-density-dependent communication system used by bacteria. It involves the release and detection of small signaling molecules called autoinducers, such as acyl-homoserine lactones (AHLs) in gram-negative bacteria [43, 44]. Bacteria release AHLs into the environment, and as the bacterial population increases, the concentration of AHLs also rises. When a threshold is reached, AHLs bind to receptors and activate gene expression related to biofilm formation [45], antimicrobial compound production, or virulence [46, 47]. The function of quorum sensing in cropping systems' resilience includes biofilm formation that enhances root colonization and protection, antibiotic and lytic enzyme production that targets soil-borne pathogens, coordinated behavior that improves microbial efficiency in nutrient cycling, and priming ISR in plants, making them more resilient to stresses [48, 49].

In phytohormonal signaling, beneficial microbes produce or modulate plant hormones (phytohormones) such as auxins, cytokinins, gibberellins, ethylene, and abscisic acid. The mechanism of phytohormonal signaling is that the microbes synthesize or alter hormone levels in response to plant exudates or environmental signals, and these hormones influence root architecture, stomatal regulation, and stress tolerance [50, 51]. Ethylene levels, for instance, are modulated by

1-aminocyclopropane-1-carboxylic acid (ACC) deaminase-producing bacteria, reducing ethylene-induced stress in roots. Functions for rhizosphere communication in cropping systems resilience include the promotion of root elongation and branching, enhancing nutrient uptake, stimulating shoot growth and delaying senescence, promoting root growth under drought, salinity, or flooding, and helping plants maintain productivity under abiotic and biotic stresses [52].

3.4 Role of rhizosphere microbes in the resilience of cropping systems

Rhizosphere microbes play a critical role in enhancing plant health and productivity by influencing various ecological and physiological processes at the soil-plant interface. These include proper nutrient cycling, where rhizosphere microbes such as bacteria, fungi, and archaea contribute to nutrient availability through nitrogen fixation, like *Rhizobium* and *Azospirillum* converting atmospheric nitrogen into forms usable by plants [53]. Secondly, through phosphorus solubilization, microbes like *Pseudomonas* and *Bacillus* release organic acids and enzymes to solubilize insoluble phosphate [54]. Lastly, potassium and micronutrient mobilization occurs, where some microbes release chelators or acids that help make micronutrients (Fe, Zn, Cu) more bioavailable [55], and decomposition of organic matter, where microbes break down organic materials, releasing nutrients like N, P, and S [56].

4. Rhizosphere intelligence: A systems biology perspective

As an intelligent system, the rhizosphere can be viewed as an information-processing network with multiple levels of organization. At the level of sensing, the roots detect soil nutrient gradients, moisture levels, pathogens, and symbiotic signals through specialized receptors [5]. The rhizosphere enters into signaling level after the establishment of sensing, which leads to plants secreting diverse exudates (sugars, amino acids, organic acids, flavonoids) that act as chemical messages to recruit beneficial microbes or deter pathogens [7, 42]. After sharing the chemical messages, another level of decision-making is attained. This level decides, based on microbial and environmental feedback, in which plants reprogram their root architecture, secondary metabolism, and immune responses [57].

Holistically, as a systems biology approach, the plant-microbe-soil interaction in its nature could be understood by integrating various “omics” approaches, which include metagenomics, metatranscriptomics, proteomics, metabolomics, fluxomics, and network analysis. Through metagenomics, the microbial community structure and genetic potential in the rhizosphere can be revealed [7, 47]. Such studies pave the way to understanding the active microbial pathways and plant responses during specific interactions through metatranscriptomics and proteomics by analyzing different proteins expressed during the interaction [58, 59]. The root exudates and microbial metabolites, which shape plant health and soil processes, are also an area of interest in which metabolomics studies provide evidence for understanding the close interactions that occur between plant roots and microbes within the root zone, the rhizosphere [60]. Furthermore, one could explore the dynamics of the flow of nutrients and metabolites across the rhizosphere network through fluxomics and network analysis [61]. The connectedness that exists between the above-mentioned datasets in systems biology would uncover unique parameters, such as adaptability and resilience as a system, which cannot be predicted from isolated components.

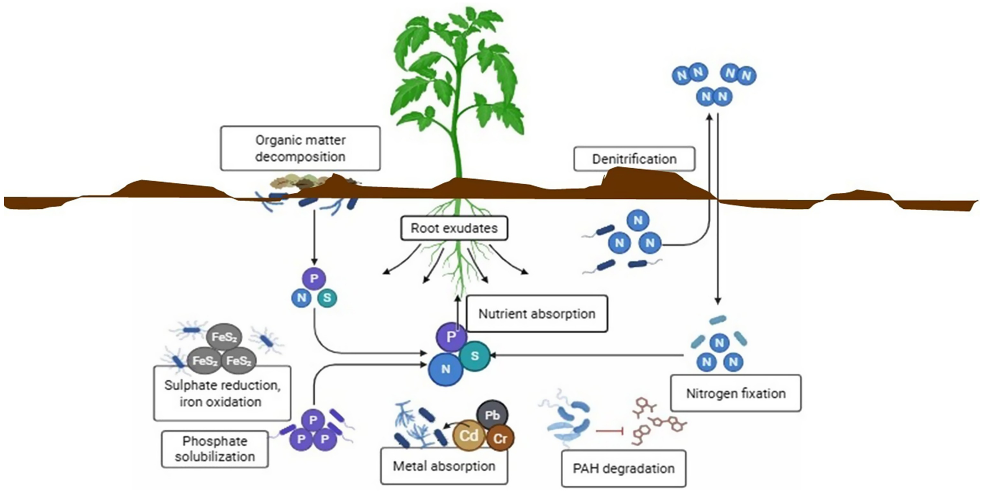

Figure 1.
A coordinated rhizospheric interaction as guided and supported by root exudates.

The rhizosphere intelligence operates through a well-established mechanism, which altogether compounds toward achieving sustainability and resilience. These mechanisms include chemical signaling through root exudates (**Figure 1**) which act as a selective cue assisting plants in recruiting PGPR or mycorrhizal fungi while deterring harmful microbes [62]. Similarly, microbial crosstalk through quorum sensing has been a well-established mechanism that helps coordinate activities related to biofilm formation, antibiosis, and/or pathogenesis [7]. In areas where nutrient limitation has been experienced, microbes establish symbiotic relationships as a mechanism to enhance nutrient acquisition and share metabolic benefits with host plants [63]. Legume-Rhizobium symbiosis is one of the broadly known mechanisms in which root-secreted flavonoids induce nod gene expression in rhizobia and ultimately initiate nodule formation for biological nitrogen fixation [64]. In areas where phosphorus is low in soils, plants secrete organic acids as a chemoattractant to recruit microbes with the ability to solubilize bound phosphates [65]. In circumstances of stress, plants and microbes have established a mechanism for adaptation in which microbes induce systemic resistance and modulate plant hormone signaling such as ABA, JA, and SA, to mitigate drought, salinity, or pathogen attack [66]. Some PGPR strains, like *Pseudomonas* and *Bacillus,* have been shown to have the ability to induce systemic plant defenses thereby reducing susceptibility to pathogens [67]. In desert and arid environments, plants tend to host microbial consortia that enhance water use efficiency and osmotic adjustment [68]. Holistically, past interactions imprint memory in the microbiome, which remains persistent and confers long-term resilience [69].

Harnessing rhizosphere intelligence exhaustively would offer new strategies for sustainable agriculture by providing new avenues for microbiome engineering, in which synthetic microbial consortia tailored to crop needs would be obtained [70]. Crop breeders would have enough knowledge to breed with respect to rhizosphere traits by selecting crop varieties with favorable root exudation patterns and microbial recruitment abilities [71]. Therefore, focusing through a systems biology lens, the rhizosphere broadens by not being just a nutrient exchange zone but rather a cognitive-like ecosystem responsible for communication, adaptation capacity, and memory recording. Rhizosphere intelligence holds a future transformative potential in agriculture, enabling resilient and sustainable cropping systems that harness the full capacity of plant-microbe-soil interaction.

5. Agro-ecological and technological applications

The increasing demand for sustainable farming systems has led to an increase in the use and commercialization of biofertilizers and biostimulants as ecologically friendly agro-inputs [72]. Biofertilizers include living microorganisms such as phosphate solubilizers, mycorrhizal fungi, and nitrogen-fixing bacteria, which enhance nutrient availability and their accessibility to plants, hence reducing dependence on synthetic fertilizers [73]. Biostimulants include seaweed extracts, humic substances, protein hydrolyzates, and microbial metabolites, which function differently by stimulating plant physiological processes [74]. The use of biostimulants has been associated with improved root growth, stress tolerance, nutrient use efficiency, and overall crop performance [75]. Unlike conventional agrochemicals, these biological inputs operate through complex ecological interactions, enhancing soil biodiversity and resilience. Inoculation of Rhizobium in legumes, for instance, not only fixes atmospheric nitrogen but also improves soil fertility for subsequent crops. Similarly, AMF establish symbioses that extend root absorptive capacity, particularly for phosphorus and micronutrients [74]. Biostimulants enhance hormonal signaling pathways, helping crops withstand drought, salinity, and temperature extremes, which are increasingly critical under climate change scenarios [76]. Importantly, the use of biostimulants aligns with agroecological principles by minimizing environmental footprints, maintaining soil health, and fostering long-term sustainability. However, their adoption is often constrained by limited farmer awareness, variability in product quality, and inadequate policy frameworks to regulate standards [77]. Strengthening research, extension, and regulatory mechanisms is, therefore, crucial to unlock the full potential of biofertilizers and biostimulants in modern agro ecosystems.

5.1 Integration of conservation agriculture and regenerative practices

Conservation agriculture (CA) and regenerative practices represent cornerstone approaches to building resilient and climate-smart farming systems. CA is based on three interlinked principles: (i) minimal soil disturbance through direct seed and/or fertilizer placement, which reduces soil erosion and preserves soil organic matter; (ii) permanent soil cover of at least 30% with crop residues and/or cover crops, which provides a protective layer of vegetation on the soil surface with the aim of suppressing weeds, protecting the soil from the impact of extreme weather patterns, preserving soil moisture, and avoiding compaction of the soil; and (iii) diversified crop rotations. Well-designed crop rotation promotes good soil structure, fosters a diverse range of soil flora and fauna that contribute to nutrient cycling and improved plant nutrition, and helps to prevent pests and diseases [78]. Regenerative agriculture (RA) and soil conservation are critical approaches to enhancing ecosystem health, soil fertility, and biodiversity while improving agricultural productivity and resilience to climate change. These sustainable land management practices address environmental degradation and promote long-term agricultural sustainability. This study explores the principles and benefits of RA, emphasizing its role in soil health restoration, carbon sequestration, and climate change mitigation. It examines key RA practices, including CA, organic farming, minimum tillage, crop rotation, cover cropping, agroforestry, composting, and livestock integration. A systematic review of RA practices was conducted, analyzing their ecological, agronomic, and economic impacts across diverse agricultural landscapes. Case studies and empirical data were assessed to evaluate the effectiveness of different RA strategies in improving soil structure, enhancing nutrient cycling, and increasing resilience to climate variability. Findings indicate that RA significantly improves soil organic matter content, reduces soil erosion, enhances water retention, and supports biodiversity. CA, a foundational RA practice, minimizes soil disturbance, maintains permanent soil cover, and promotes crop diversification, leading to improved soil health and reduced greenhouse gas emissions. Organic farming fosters soil fertility and microbial diversity by eliminating synthetic inputs, while agroforestry enhances ecosystem resilience through tree integration. Additionally, composting and livestock integration contribute to nutrient cycling and soil structure enhancement. The widespread adoption of RA and soil conservation practices is essential for ensuring global food security, mitigating climate change, and preserving natural resources. Governments, policymakers, and stakeholders must promote RA through policy support, financial incentives, and knowledge dissemination to encourage sustainable agricultural transitions. Future research should focus on region-specific RA strategies, long-term soil health monitoring, and economic viability assessments to facilitate global implementation [75]. These practices not only conserve soil structure and moisture but also enhance biological activity and carbon sequestration.

RA is an agricultural approach that aims to improve the current state of the soil and includes the combination of two or more of the following practices: reduced or no till, increased complexity of crop diversity, addition of carbon through organic amendments or grazing animals, and/or inclusion of legumes, with the specific aim of restoring soil health and/or sequestering carbon [78]. RA expands on these foundations by emphasizing soil health restoration, biodiversity enhancement, and closed-loop nutrient cycling. Practices such as cover cropping, agroforestry, compost application, and reduced tillage contribute to improved soil organic matter, reduced erosion, and enhanced water infiltration. From an agroecological perspective, these approaches optimize ecological interactions between plants, soil microbes, and beneficial fauna, thereby reducing dependence on external inputs. For instance, integrating legumes into rotations provides biological nitrogen fixation, reducing fertilizer needs while supporting soil microbial diversity. Similarly, cover crops suppress weeds, provide habitat for natural enemies of pests, and improve nutrient cycling [79]. Regenerative practices also align with carbon farming initiatives, positioning agriculture as a potential sink for atmospheric carbon [80].

Technologically, advancements such as no-till planters, precision cover crop seeders, and compost inoculants are facilitating adoption at scale. Despite proven benefits, challenges include labor demands, knowledge gaps, and short-term yield trade-offs during the transition phase. Nonetheless, when effectively implemented, conservation and regenerative practices offer a transformative pathway toward resilient food systems that integrate ecological sustainability with farmer profitability.

5.2 Precision agriculture and smart root-zone management

Precision agriculture and smart root zone management are two innovative approaches that aim to increase agricultural productivity and sustainability by leveraging advanced technologies for better management of farming operations. Precision agriculture utilizes digital technologies, data analytics, and sensor-based tools to optimize farm inputs with spatial and temporal accuracy [26, 81].

Smart root-zone management becomes a crucial area of focus within the soil–plant continuum, guaranteeing that nutrients and water are delivered in the appropriate amounts and at the appropriate times. Site-specific management is achieved through technologies such as fertigation systems, variable-rate irrigation, soil moisture monitors, and unmanned aerial vehicles (UAVs), which lower waste and increase crop output [82]. Root-zone monitoring using IoT-enabled probes and imaging techniques provides real-time insights into nutrient availability, salinity levels, and root dynamics. Such information supports targeted interventions that not only maximize nutrient-use efficiency but also reduce leaching and greenhouse gas emissions [83]. In arid situations, combining drip irrigation with automatic fertilizer dosing guarantees ideal root-zone conditions while conserving water. Predictive capacities are further improved by artificial intelligence and machine learning, which enable farmers to foresee nutrient deficits or stressful situations before obvious symptoms manifest. Apart from efficiency, by monitoring the spatial efficacy and interactions of biofertilizers and organic amendments with local microbial populations, precision technologies make integration easier. The long-term economic and environmental advantages are strong, even though initial investment and technical know-how continue to be obstacles [84]. Smart root-zone management, which combines ecological principles with cutting-edge technologies, is an essential tactic for sustainable intensification that keeps agriculture productive while protecting soil and water resources.

6. Achievements made so far in understanding the benefits within the rhizosphere

The rhizosphere has been recognized as a key interface where plants and roots interact with a diverse microbial community, influencing plant growth, health, and resilience. There has been a significant achievement in understanding the benefits associated with root-microbe dynamics, which include stress tolerance, pest suppression, and improved ecosystem services. The rhizosphere, being a very complex, dynamic, and intelligent system, regulates plant-microbe-soil interactions. Currently, with advances in microbial ecology, molecular biology, and agronomic practices, the benefits of PGPR are increasingly being harvested for sustainable and resilient cropping systems [85].

In nutrient cycling and uptake, there have been breakthroughs, which include nitrogen fixation, phosphorus solubilization, and mobilization of micronutrients by rhizospheric microbes. Numerous inoculants have been developed, such as *Rhizobium*, *Azospirillum,* and mycorrhizal fungi, with successful applications for cereal and legume systems to reduce fertilizer dependence [86, 87]. The application in major cropping systems, like rice and maize production, by using cyanobacteria

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and nitrogen fixers, has led to improved yields and reduced greenhouse emissions [88].

The impact of climate change, such as drought, salinity, and temperature fluctuations, significantly affects crops. AMF and PGPR have shown the ability to help plants tolerate some of these biotic stresses by regulating water use efficiency, osmotic adjustment, and antioxidant activities [89].

PGPR have been associated with the suppression of soil-borne pathogens through competition, antibiotic production, and ISR. Biocontrol agents such as Trichoderma spp. and Bacillus spp. have been developed and are integrated into pest management strategies [90, 91].

Lastly, in recent technological advancements in genomics, metagenomics, and metabolomics, there has been a great achievement in understanding the complex functional roles of PGPR. Such technologies have enabled the identification of microbial consortia tailored for specific crops and environments, which increases precision in microbiome engineering [92]. The overall understanding of rhizosphere intelligence and its role in resilient cropping systems has achieved considerable progress.

7. Challenges

7.1 Performance of microbial products under controlled and open-field conditions and the scalability aspect

The commercialization of microbial products such as biofertilizers, biopesticides, and biostimulants faces significant challenges, particularly when transitioning from controlled environments to open-field applications [93]. In laboratory and greenhouse settings, conditions such as temperature, humidity, and soil type are carefully regulated, allowing microbial inoculants to perform optimally. However, because of environmental unpredictability, competition with native microbial communities, and shifting soil physicochemical qualities, their efficacy is frequently uneven in open-field settings. For example, a strain of Trichoderma or Bacillus may have robust growth-promoting or biocontrol activity in vitro, but field tests usually reveal reduced effectiveness [93]. The presence of UV rays, desiccation, soil fauna predation, and incompatibility with specific agronomic techniques are some of the causes of this disparity. Furthermore, it is challenging to generalize performance across geographies and cropping systems due to the high context-specificity of microbial survival and colonization. Scalability adds another layer of complexity, as small-scale trials may demonstrate promising outcomes, but large-scale adoption requires reliable mass production, formulation stability, and extended shelf life [94]. Many microbial products are sensitive to storage and transport conditions, losing viability under high temperatures or prolonged storage. Ensuring consistent product quality is further hampered by the lack of harmonized standards and regulatory frameworks, particularly in developing regions [95]. From the farmer's perspective, variable field performance undermines trust and willingness to invest in microbial solutions, especially when compared to the immediate and predictable effects of chemical inputs. Addressing these challenges calls for integrated strategies: developing robust microbial consortia rather than single strains, improving carrier materials and encapsulation technologies, and designing context-specific formulations adapted to local agroecologies. Strengthening farmer education, policy support, and investment in cold-chain infrastructure will also be pivotal. Ultimately, bridging the gap between controlled research conditions and diverse field realities remains a key bottleneck in scaling microbial technologies for sustainable agriculture.

8. Future perspective

From various studies of the plant-microbe-soil interaction that exist in the rhizosphere, there is substantial evidence of direct and indirect benefits among the interacting components. Our limited knowledge of certain aspects, such as the full information required to achieve the full potential of microbes under field conditions as opposed to controlled environments, remains to be explored. The constant need to explore the unknown potential sustainability outcomes of plant-microbe-soil interaction is a pressing subject if we are to achieve a resilient cropping system.

Currently, the use of biofertilizers is increasingly being adapted, with much development in legumes where inoculants have become the best practice in increasing productivity while ensuring minimal use of chemical fertilizers. The uptake efficiency of plants for chemical fertilizers is generally 30–50%; this leads to economic losses, with large quantities remaining as residuals being leached into water bodies and evaporated into the atmosphere, impacting the environment negatively. The use of microbes as biofertilizers could replace chemical fertilizers in an ecofriendly manner because of their wider potential to increase crop production and food safety more sustainably. Bearing all this in mind, the continual use of biofertilizers is a progressively needed process, since preparation ahead of time is not optional. The future of cropping systems, resilient meaningfully, will depend on a better understanding of PGPR in relation to plants in the rhizosphere, conferring biotic and abiotic stress alleviation; hence, it is essential to intentionally devise ways to effectively introduce them under field conditions, which will provide the same results that are observed under controlled environment conditions.

9. Conclusion

The rhizosphere is increasingly being recognized not only as the usual site for nutrient acquisition but also as a hub for decision-making, where plants and microbes exchange chemical and molecular information. Rhizosphere intelligence represents a paradigm shift in sustainability. If the root-microbe interaction is achieved by combining biology, engineering, and artificial intelligence digital tools, the ultimate creation of a resilient cropping system capable of meeting global food security challenges under climate change will be realized. The future of rhizosphere intelligence should not only focus on biological knowledge but should also be coupled with digital and engineering solutions intentionally to harness root-microbe dynamics with the global goal of reducing chemical inputs, increasing crop production under climate stress, and finally achieving a sustainable cropping system.

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Conflict of interest

The authors declare that the development of this chapter was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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