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MINI REVIEW

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Plant-microbe interactions in sustainable agriculture: Emerging trends and innovations

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ABSTRACT

Agricultural enhance over the past five decades has led to soil degradation, biodiversity loss, and declining crop productivity, taking a transition toward sustainable production systems. The rhizosphere, a metabolically active zone, hosts diverse microbial communities that regulate nutrient cycling, plant health, and stress tolerance. Plant–microbe interactions range from symbiosis to pathogenic associations, significantly promoting soil fertility and crop performance. However, their application remains constrained by inconsistent field performance, limited scalability of laboratory findings, and insufficient understanding of microbiome stability under variable environmental conditions, along with regulatory and formulation challenges. This mini-review synthesizes key mechanisms of beneficial interactions, *including biological nitrogen fixation, phosphate solubilization, and phytohormone production, while highlighting emerging approaches such as synthetic microbial consortia and multi-omics technologies. Evidence from field studies indicates that optimized microbial inoculants enhance nutrient use efficiency and stress resilience. Bridging research gaps through interdisciplinary approaches and supportive policies is essential for advancing sustainable agriculture.

KEY WORDS

Rhizosphere microbiome; Biological nitrogen fixation; PGPR; Mycorrhizal symbiosis; Bioinoculants; Metagenomics; Sustainable crop production

ARTICLE HISTORY

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Introduction

Global food demand is projected to increase by approximately 50–70% by 2050, driven by an increasing population expected to reach nearly 9.7 billion. Conventional agricultural systems, depend on synthetic fertilizers and chemical pesticides, have played an instrumental role in meeting food production targets over the past century. However, the long-term consequences of such input-intensive practices are increasingly evident in the form of soil organic matter depletion, loss of microbial diversity, groundwater contamination, and greenhouse gas emissions [1]. Nitrogen and phosphorus runoff from agricultural fields remains a leading driver of aquatic eutrophication, while excessive pesticide application has been consistently associated with disruption of non-target soil organisms and suppression of beneficial microbial activity. These compounding environmental pressures have enhanced the global search for biologically grounded alternatives capable of sustaining productivity without compromising ecosystem integrity.

The growing recognition of soil as a living system, rather than a passive growth medium, has fundamentally transformed approaches to crop management over the past two decades. Soil microbial biomass, estimated to contain between 10^8 and 10^{10} microbial cells per gram of soil, constitutes a dynamic supply of functional diversity that directly regulates nutrient transformation, organic matter decomposition, and plant immune priming. The rhizosphere, defined as the narrow zone of soil immediately surrounding and influenced by plant roots, represents a particularly active interface where root exudates selectively recruit and shape microbial communities in response to plant nutritional status and environmental cues [2]. Simultaneously research has established that rhizosphere microbial communities are not passive bystanders but active participants in plant growth, health, and stress adaptation. The full mechanistic complexity of plant-microbe communication networks remains incompletely resolved, particularly under the dynamic and heterogeneous conditions characteristic of agricultural field environments [3].

Plant-microbe interactions represent one of the most ecologically significant and biochemically involved phenomena in terrestrial biology. These interactions span a continuum from obligate mutualism, as displayed by the Rhizobium–legume symbiosis and arbuscular mycorrhizal (AM) fungal associations, to antagonistic relationships involving soilborne pathogens such as Fusarium oxysporum and Phytophthora cinnamomic [4]. Among the most agronomically relevant associations are those mediated by plant growth-promoting rhizobacteria (PGPR), a functionally diverse group of root-colonizing bacteria capable of enhancing plant growth through multiple direct and indirect mechanisms. These include biological nitrogen fixation (BNF), solubilization of inorganic phosphate and potassium, production of phytohormones such as indole-3-acetic acid (IAA) and gibberellins, and biosynthesis of iron-chelating siderophores. Mycorrhizal fungi, through their extensive extraradical hyphal networks, similarly extend the effective root absorption zone, improving plant access to immobile nutrients, particularly phosphorus, under nutrient-limited soil conditions [5].

Research over the past decade has advanced understanding of the molecular and ecological dimensions of plant-microbe interactions. The advent of multi-omics approaches, integrating metagenomics, meta transcriptomics, metabolomics, and proteomics, has further enabled systems-level characterization of rhizosphere microbiome functionality beyond taxonomic profiling. Parallel advances in synthetic ecology have facilitated the design of minimal synthetic microbial consortia capable of replicating complex community functions under controlled

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conditions [6,7]. Furthermore, bioinoculant research has progressively shifted from single-strain formulations toward multi-strain consortia demonstrated to exert synergistic effects on crop productivity across diverse agroecosystems.

The majority of mechanism studies have been conducted under controlled greenhouse or in vitro conditions, limiting their direct extrapolation to complex field environments characterized by fluctuating temperature, moisture, and soil physicochemical variability [8]. Second, soil microbial community composition is highly context-dependent, influenced by crop species, tillage practices, agrochemical inputs, and seasonal dynamics, making it difficult to standardize microbial inoculant recommendations across diverse agroecological zones. Third, existing regulatory frameworks in many countries lack clearly defined pathways for the approval and quality certification of novel bioinoculant products, creating commercialization barriers that impede the practical deployment of research outcomes [9]. Finally, farmer awareness and willingness to adopt microbe-based inputs remains constrained by limited extension support and the perceived risk associated with biological product performance variability.

In response to the identified gaps, the present review pursues the following specific objectives: (i) to critically examine the mechanistic basis of mutualistic plant-microbe associations, with emphasis on nutrient acquisition and plant growth promotion; (ii) to evaluate emerging biotechnological and omics-driven innovations reshaping rhizosphere microbiome research; (iii) to assess the agronomic performance of bioinoculant-based interventions under field conditions across major cropping systems; and (iv) to identify priority research areas and translational pathways essential for mainstreaming plant-microbe interaction science within sustainable agricultural policy and practice.

Types of Plant–Microbe Interactions

Mutualistic interactions

Mutualistic interactions involve reciprocal benefits between plants and microorganisms, playing a crucial role in nutrient acquisition and plant health.

The symbiotic association between legumes and nitrogen-fixing bacteria such as Rhizobium represents one of the most extensively studied mutualisms. In this interaction, bacteria colonize root nodules and convert atmospheric nitrogen into ammonia via nitrogenase activity, providing an essential nitrogen source to the host plant [10].

Mycorrhizal associations, including arbuscular mycorrhizal (AM) and ectomycorrhizal (ECM) fungi, enhance plant nutrient uptake, particularly phosphorus, by extending the root absorptive surface through fungal hyphae. AM fungi penetrate cortical cells forming arbuscules, whereas ECM fungi form a mantle around roots.

Endophytic microorganisms colonize internal plant tissues without causing harm [11]. These microbes enhance host growth by producing bioactive compounds, improving nutrient uptake, and conferring stress tolerance.

Commensal interactions

In commensal relationships, microorganisms benefit from plant-derived nutrients without significantly affecting the host. Rhizosphere-competent microorganisms utilize root exudates such as sugars, amino acids, and organic acids, contributing to microbial diversity and ecosystem stability. Although their direct impact on plant growth is limited, they influence nutrient cycling and microbial community structure [12].

Neutral microbiome members constitute a large fraction of the rhizosphere microbiota. These organisms maintain ecological balance and may become beneficial under changing environmental conditions, highlighting the dynamic nature of plant-associated microbiomes.

Pathogenic interactions

Pathogenic interactions negatively affect plant health, leading to significant yield losses. Soilborne pathogens such as Fusarium, Pythium, and Rhizoctonia infect plant roots, causing diseases like damping-off and root rot. These pathogens disrupt nutrient uptake and physiological processes.

Necrotrophic pathogens derive nutrients from dead host tissue, whereas biotrophic pathogens depend on living cells [13]. The interaction between plants and pathogens involves complex signaling pathways, including defense responses mediated by salicylic acid and jasmonic acid.

Mechanisms of Plant Growth Promotion

Nutrient acquisition

Microbial-mediated nutrient acquisition enhances plant productivity by increasing nutrient availability. Biological nitrogen fixation (BNF) converts atmospheric nitrogen into ammonia through diazotrophic bacteria such as Azospirillum and Azotobacter. This process reduces dependence on chemical fertilizers and supports sustainable agriculture. Phosphate-solubilizing microorganisms release organic acids that convert insoluble phosphorus into plant-available forms [14]. Similarly, potassium- and zinc-solubilizing bacteria mobilize essential nutrients from mineral source.

Siderophore production facilitates iron acquisition by chelating ferric ions, enhancing plant nutrition while limiting pathogen growth through competitive exclusion.

Phytohormone production

Plant-associated microbes influence growth by modulating phytohormone levels. Indole-3-acetic acid (IAA), a main auxin produced by rhizobacteria, stimulates root elongation and lateral root formation, thereby increasing nutrient uptake capacity. Microbial production of gibberellins and cytokinins regulates plant developmental processes, including seed germination, cell division, and senescence. ACC deaminase activity reduces ethylene levels in plants under stress by degrading its precursor ACC, thereby promoting root growth and enhancing stress tolerance [15].

Biocontrol mechanisms

Beneficial microbes suppress pathogens through multiple direct and indirect mechanisms. Induced systemic resistance (ISR) is triggered by rhizobacteria and involves jasmonate- and ethylene-dependent signaling pathways, leading to enhanced plant defense responses. Systemic acquired resistance (SAR) is mediated by salicylic acid and involves the activation of pathogenesis-related proteins, providing long-lasting immunity against pathogens. Antibiosis and competition are critical mechanisms wherein microbes produce antimicrobial compounds such as antibiotics, hydrogen cyanide, and lytic enzymes, while competing for

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nutrients and ecological niches in the rhizosphere.

Emerging Trends in Plant–Microbe Interaction Research

Omics-based approaches

Advancements in omics technologies have revolutionized the understanding of plant–microbe interactions. Metagenomics and meta transcriptomics enable the analysis of microbial community structure and gene expression in situ, providing insights into functional diversity. Proteomics and metabolomics further elucidate protein expression and metabolic pathways involved in plant–microbe interactions.

Rhizosphere interactome mapping integrates multi-omics data to identify complex networks of plant–microbe and microbe–microbe interactions.

Microbiome engineering

Microbiome engineering represents a promising approach for enhancing agricultural productivity. Synthetic microbial consortia are designed to perform specific functions, such as nutrient mobilization and disease suppression. Core microbiome identification focuses on key microbial taxa consistently associated with plant health. Microbiome transplantation strategies aim to transfer beneficial microbial communities to improve crop performance.

Bioinformatics and computational tools

The integration of computational tools has enhanced predictive capabilities in microbiome research. Machine learning algorithms are increasingly used to predict plant–microbe interactions and identify beneficial microbial traits. Network analysis reveals complex relationships within microbial communities, while predictive modeling enables the assessment of microbial responses under climate variability.

Innovations in Bioinoculant Technology

Formulation advances

Recent advancements in bioinoculant formulation have improved microbial viability and field performance. Liquid and wettable powder formulations offer ease of application, whereas encapsulated formulations provide controlled release and protection against environmental stress. Nano-formulations enhance microbial stability and delivery efficiency.

Multi-strain consortia

The use of multi-strain microbial consortia has gained attention due to synergistic effects on plant growth. Compatibility among microbial strains is critical to ensure functional stability. Synergistic interactions enhance nutrient acquisition, stress tolerance, and disease suppression compared to single-strain inoculants.

Regulatory and commercial landscape

The global biofertilizer market is expanding rapidly due to increasing demand for sustainable agricultural practices.

Regulatory frameworks vary across regions, with agencies such as USDA, the European Union, and Indian regulatory bodies establishing guidelines for biofertilizer registration and quality control. However, challenges related to standardization, shelf-life, and field efficacy persist.

Role of plant–microbe interactions under abiotic stress

Plant-associated microbes play a critical role in mitigating abiotic stresses. Under drought conditions, PGPR enhance water uptake and osmotic adjustment through the production of exopolysaccharides and osmolytes. Salinity tolerance is improved through ion homeostasis and antioxidant activity.

Certain microbes facilitate heavy metal remediation by sequestration, transformation, and detoxification of toxic elements [16]. Additionally, microbial associations enhance plant tolerance to temperature extremes by modulating stress-responsive pathways.

Challenges and Limitations

Despite significant advancements, several challenges limit the widespread application of plant–microbe technologies. Microbial performance often varies under field conditions due to environmental variability and soil physicochemical properties. Additionally, limited farmer awareness and adoption hinder large-scale implementation [17].

Policy gaps, insufficient funding, and lack of standardized protocols further constrain the development and commercialization of microbial products.

Future Perspectives

Future research should focus on the development of next-generation bioinoculants with enhanced efficiency and stability. CRISPR-based microbiome editing offers opportunities to engineer beneficial microbial traits. Integration with precision agriculture technologies can optimize microbial applications. The development of climate-resilient microbial strains and the adoption of a One Health approach linking soil, plant, and human health are essential for sustainable agricultural systems [18].

Conclusion

Plant–microbe interactions represent a cornerstone of sustainable agriculture, influencing plant growth, nutrient dynamics, and stress resilience. Advances in omics technologies, microbiome engineering, and bioinoculant formulations have expanded our understanding and application of these interactions. However, challenges related to field variability and commercialization remain. Interdisciplinary research integrating molecular biology, ecology, and computational sciences is crucial to fully exploit plant–microbe interactions for global food security and environmental sustainability.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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