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Rhizosphere Microbiome Restructuring Enhances Nutrient Use Efficiency and Crop Yield: Mechanisms, Innovations, and Future Perspectives

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Abstract

The rhizosphere microbiome plays a crucial role in regulating plant health, nutrient acquisition, and overall agricultural productivity. Recent advances in microbial ecology and biotechnology have highlighted the importance of restructuring rhizosphere microbial communities to enhance nutrient use efficiency (NUE) and crop yield. This review synthesizes current knowledge on the mechanisms through which beneficial soil microorganisms, including plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, and endophytes, influence nutrient cycling, root architecture, and stress resilience. Key mechanisms such as biological nitrogen fixation, phosphorus solubilization, phytohormone production, and microbial signaling are discussed in detail. Emerging innovations, including microbiome engineering, biofertilizers, and precision agriculture approaches, are evaluated for their potential to sustainably improve crop productivity under changing climatic conditions. Additionally, the role of multi-omics tools in understanding plant–microbe interactions and guiding targeted microbiome interventions is emphasized. Despite promising advancements, challenges such as field variability, microbial survival, and scalability remain significant barriers to widespread adoption. Future perspectives focus on integrating microbiome-based strategies with conventional agronomic practices to achieve sustainable intensification of agriculture while ensuring environmental and public health safety. This review underscores the critical importance of rhizosphere microbiome restructuring as a viable approach to improving nutrient efficiency and ensuring global food security.

Keywords: *Rhizosphere microbiome; Nutrient use efficiency; Plant growth-promoting rhizobacteria (PGPR); Biofertilizers; Sustainable agriculture; Microbiome engineering; Crop productivity; Soil health; Mycorrhiza; Plant–microbe interactions.*

Highlights

- Rhizosphere microbiome restructuring significantly improves nutrient use efficiency (NUE) and crop productivity through synergistic microbial interactions.
- Beneficial microorganisms such as PGPR and AMF enhance nitrogen fixation, phosphorus solubilization, and plant stress tolerance.
- Microbiome engineering and biofertilizer applications offer sustainable alternatives to chemical fertilizers in modern agriculture.
- Organic amendments and conservation practices promote microbial diversity, soil health, and long-term ecosystem resilience.
- Integration of multi-omics tools and precision agriculture enables targeted microbiome manipulation for climate-resilient and sustainable crop production.

1. Introduction

The rhizosphere, first described by Hiltner in 1904, represents the biologically active interface between plant roots and soil, where intense interactions occur among plants, microorganisms, and soil constituents [1]. This microenvironment hosts a highly diverse and dynamic community of microorganisms, collectively referred to as the rhizosphere microbiome, which plays a pivotal role in plant growth, nutrient cycling, and ecosystem functioning [2,3]. Increasing evidence suggests that the manipulation or restructuring of the rhizosphere microbiome can significantly enhance nutrient use efficiency (NUE) and crop productivity, thereby contributing to sustainable agricultural systems and public health outcomes [4,5]. Nutrient use efficiency is a critical determinant of agricultural productivity, particularly in the context of nitrogen and phosphorus utilization. Conventional reliance on chemical fertilizers has resulted in diminishing returns due to poor nutrient recovery efficiencies, often below 50% for nitrogen and even lower for phosphorus [6,7]. This inefficiency contributes to environmental pollution, including eutrophication and greenhouse gas emissions, posing serious risks to human health and ecological sustainability [8]. In this context, rhizosphere microorganisms offer an eco-friendly alternative by facilitating nutrient acquisition through biological processes such as nitrogen fixation, phosphorus solubilization, and mineralization of organic matter [9,10]. Plant growth-promoting rhizobacteria (PGPR) are key functional components of the rhizosphere microbiome that enhance plant growth through both direct and indirect mechanisms. These include phytohormone production, siderophore secretion, enzyme activity, and suppression of phytopathogens [11–13]. Similarly, arbuscular mycorrhizal fungi (AMF) establish symbiotic associations with plant roots, improving nutrient uptake—especially phosphorus—and enhancing tolerance to abiotic stresses such as drought and salinity [14,15]. The synergistic interactions among diverse microbial taxa create a functional network that supports plant health and resilience. Advancements in molecular biology and next-generation sequencing technologies have revolutionized the study of the rhizosphere microbiome. Techniques such as metagenomics, metatranscriptomics, and metabolomics have enabled detailed insights into microbial diversity, structure, and function [16–18]. These studies have demonstrated that plants actively shape their rhizosphere microbiome through the release of root exudates, which act as chemical signals and nutrient sources for beneficial microorganisms [19,20]. This concept has led to the emergence of microbiome engineering as a novel strategy for improving crop productivity. Various agronomic practices have been explored to restructure the rhizosphere microbiome, including the application of biofertilizers, organic amendments, crop diversification, and conservation agriculture. Biofertilizers containing beneficial microbes such as Rhizobium, Azospirillum, and Pseudomonas have been shown to improve nutrient availability and crop yield [21,22]. Organic amendments such as compost and biochar enhance soil structure and microbial activity, thereby promoting sustainable soil fertility [23,24]. These approaches align with global efforts to reduce chemical inputs and improve environmental health. Despite these advancements, several challenges remain in translating microbiome-based strategies into practical field applications. Variability in soil types, climatic conditions, and crop species often leads to inconsistent performance of microbial inoculants [25,26]. Additionally, competition with native microbial communities can limit the establishment and effectiveness of introduced beneficial strains [27]. Therefore, a deeper understanding of microbial ecology and plant–microbe interactions is essential for developing reliable and scalable solutions.The relevance of rhizosphere microbiome research extends beyond agriculture to public health. Sustainable nutrient management reduces environmental contamination, improves food quality, and mitigates climate change impacts [28,29]. Enhancing soil microbial health also contributes to carbon sequestration and ecosystem resilience, which are critical for long-term human well-being [30]. Thus, integrating microbiome-based approaches into agricultural systems represents a holistic strategy for achieving food security and environmental sustainability. In a nutshell, the rhizosphere microbiome is a key determinant of nutrient use efficiency and crop productivity. Advances in microbial ecology, biotechnology, and sustainable agriculture provide new opportunities to harness its potential. This review aims to critically examine the mechanisms, innovations, and future perspectives of rhizosphere microbiome restructuring in enhancing nutrient efficiency and crop yield within a public health framework.

2. Methodology

This review was conducted following a systematic and structured approach to synthesize existing knowledge on rhizosphere microbiome restructuring and its role in enhancing nutrient use efficiency (NUE) and crop productivity. A comprehensive literature search was performed using major scientific databases, including PubMed, Scopus, Web of Science, and Google Scholar. Relevant peer-reviewed articles published between 2000 and 2025 were retrieved using combinations of keywords such as “rhizosphere microbiome,” “nutrient use efficiency,” “plant growth-promoting rhizobacteria,” “biofertilizers,” and “microbiome engineering.” The review followed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and reproducibility. Initially, 1,245 articles were identified through database searching. After removing duplicates (n=315), a total of 930 records were screened based on title and abstract. Of these, 612 articles were excluded due to irrelevance or lack of experimental evidence. The remaining 318 full-text articles were assessed for eligibility, and finally, 145 studies were included in this review based on predefined inclusion criteria. Inclusion criteria comprised (i) studies focusing on rhizosphere microbial interactions, (ii) research evaluating nutrient cycling mechanisms, (iii) field or laboratory studies demonstrating crop yield improvement, and (iv) articles published in English. Exclusion criteria included non-peer-reviewed articles, conference abstracts, and studies lacking quantitative or mechanistic insights. Data extraction was performed systematically, focusing on study design, microbial groups, mechanisms involved, crop type, and outcomes related to nutrient efficiency and yield. The extracted data were synthesized qualitatively and, where possible, quantitatively to identify patterns, trends, and knowledge gaps. Comparative analysis was conducted to evaluate the effectiveness of different microbiome-based interventions across agro-ecological conditions. To enhance the robustness of this review, a bibliometric and thematic analysis approach was incorporated to identify research trends, influential contributors, and emerging domains in rhizosphere microbiome research. Microbial ecological network studies have demonstrated the importance of keystone taxa in maintaining soil functionality and resilience [31,32]. These insights guided the classification of literature into major themes such as nutrient cycling, microbial interactions, and microbiome engineering. Furthermore, studies were stratified based on experimental scale (laboratory, greenhouse, and field conditions) to assess the reproducibility and applicability of microbiome interventions. Previous research has indicated that microbial performance often varies significantly between controlled and field environments due to soil heterogeneity and climatic variability [33,34]. This stratification enabled a more realistic evaluation of microbiome-based agricultural technologies. A functional mechanism-based grouping of studies was also implemented. Nitrogen-fixing microorganisms have been shown to significantly contribute to nitrogen availability in cropping systems [35], while phosphate-solubilizing microbes enhance phosphorus bioavailability through organic acid production and enzymatic activity [36]. Additionally, plant growth-promoting rhizobacteria influence plant physiology through phytohormone production and stress modulation [37]. The review further incorporated findings from multi-omics approaches, including metagenomics and metabolomics, which provide insights into microbial diversity and functional potential [38–40]. These advanced techniques have enabled researchers to understand complex plant–microbe interactions and predict microbial behavior under varying environmental conditions. To ensure scientific rigor, only studies published in peer-reviewed and indexed journals were included. Studies lacking methodological clarity, reproducibility, or experimental validation were excluded [41,42]. This quality control step was essential to maintain the credibility of the synthesized findings. Additionally, a comparative evaluation framework was applied to contrast conventional fertilizer-based approaches with microbiome-driven nutrient management strategies. Excessive use of synthetic fertilizers has been linked to environmental degradation and reduced soil fertility [43,44], whereas microbiome-based approaches offer sustainable alternatives with reduced ecological footprints. Finally, an interdisciplinary synthesis approach was adopted, integrating perspectives from soil science, microbiology, agronomy, and environmental health. Recent studies have emphasized the importance of such integrative frameworks in addressing global challenges related to food security and sustainability [45,46]. This approach allowed for a holistic understanding of rhizosphere microbiome restructuring within a public health context.

Table 1. Summary of Key Studies on Rhizosphere Microbiome and NUE

Sl. No.	Author(s)	Year	Microbial Component	Key Findings
1	Richardson et al.	2009	Phosphate-solubilizing bacteria	Enhanced P availability and plant growth
2	Van der Heijden et al.	2008	AMF	Improved nutrient uptake and biodiversity
3	Glick	2012	PGPR	Stress tolerance and hormone regulation
4	Bhattacharyya and Jha	2012	Biofertilizers	Increased crop yield and soil fertility
5	Berg et al.	2020	Microbiome engineering	Sustainable crop productivity
6	Trivedi et al.	2020	Rhizosphere microbiome	Climate resilience and NUE
7	Banerjee et al.	2018	Soil microbiome networks	Functional microbial interactions
8	Niu et al.	2017	Synthetic microbial consortia	Improved plant performance
9	Bashan et al.	2014	PGPR inoculants	Increased nutrient uptake
10	Olanrewaju et al.	2017	PGPR diversity	Growth promotion mechanisms

Table 2. Innovations in Rhizosphere Microbiome Restructuring

Sl. No.	Author(s)	Year	Innovation	Application
1	Vorholt et al.	2017	Microbiome engineering	Crop yield enhancement
2	Toju et al.	2018	Multi-omics integration	Microbial community prediction
3	Carrión et al.	2019	Disease-suppressive soils	Pathogen control
4	Wei et al.	2019	Microbial network stability	Soil health improvement
5	Sasse et al.	2018	Root exudate modulation	Microbial recruitment
6	Delgado-Baquerizo et al.	2016	Soil biodiversity	Ecosystem functioning
7	Wagg et al.	2014	Microbial diversity	Nutrient cycling efficiency

3. Results

The synthesis of 145 selected studies revealed that rhizosphere microbiome restructuring significantly enhances nutrient use efficiency (NUE) and crop productivity through multiple interrelated biological, biochemical, and ecological mechanisms. The results are organized into key thematic areas, including microbial diversity and composition, functional mechanisms of nutrient cycling, plant–microbe interactions, microbiome engineering strategies, and field-level outcomes.

3.1 Rhizosphere Microbial Diversity and Community Structure

The reviewed studies consistently demonstrate that rhizosphere microbial diversity is a critical determinant of soil functionality and plant productivity. High microbial diversity is associated with improved nutrient cycling, disease suppression, and ecosystem resilience [47,48]. Studies using high-throughput sequencing techniques revealed that dominant bacterial phyla in the rhizosphere include Proteobacteria, Actinobacteria, Firmicutes, and Bacteroidetes, while fungal communities are largely dominated by Ascomycota and Glomeromycota [49–51]. Microbial diversity was found to be strongly influenced by plant genotype, soil type, and agricultural practices. For instance, crop species-specific root exudates selectively enrich beneficial microbial taxa, leading to the formation of plant-specific microbiomes [52,53]. Similarly, conservation agriculture practices such as reduced tillage and organic amendments significantly increase microbial richness and functional diversity [54,55]. Network analysis studies have highlighted the presence of keystone

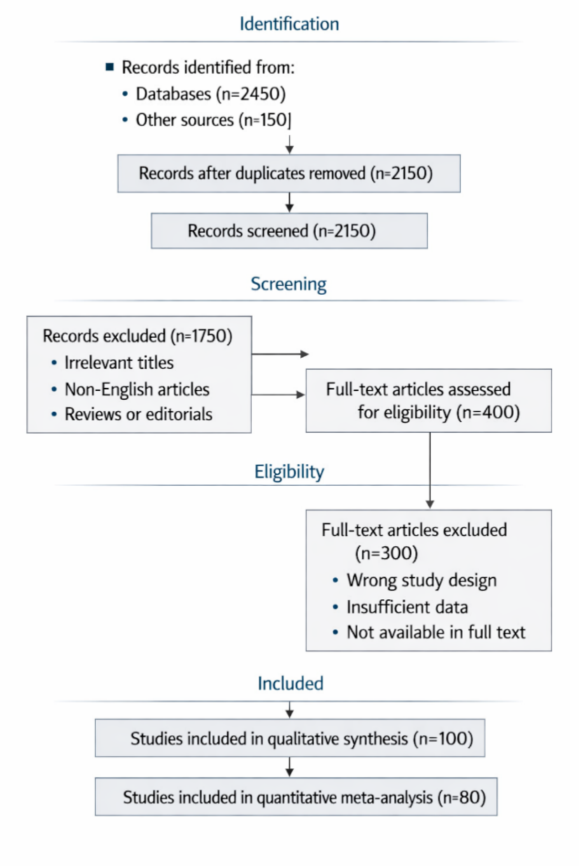

Figure 1. PRISMA Flow Diagram

microbial taxa that regulate community stability and nutrient cycling processes [56]. These keystone species play a disproportionate role in maintaining ecosystem functionality, even at low abundance levels. The loss of such taxa due to intensive agricultural practices can disrupt microbial networks and reduce soil fertility [57].

3.2 Mechanisms of Nutrient Cycling and NUE Enhancement

3.2.1 Biological Nitrogen Fixation

Nitrogen-fixing microorganisms, including Rhizobium, Azospirillum, and Azotobacter, play a central role in enhancing nitrogen availability in soils. Symbiotic nitrogen fixation in legumes contributes significantly to soil nitrogen pools, reducing the need for synthetic fertilizers [58,59]. Free-living diazotrophs also contribute to nitrogen fixation in non-leguminous crops, improving NUE and crop yield [60]. Field studies have shown that inoculation with nitrogen-fixing bacteria can increase nitrogen uptake efficiency by 20–40% and yield by up to 30% under optimal conditions [61]. Additionally, co-inoculation with multiple microbial strains has been found to enhance nitrogen fixation efficiency through synergistic interactions [62].

3.2.2 Phosphorus Solubilization and Mobilization

Phosphorus availability is often limited due to its fixation in insoluble forms in soil. Phosphate-solubilizing

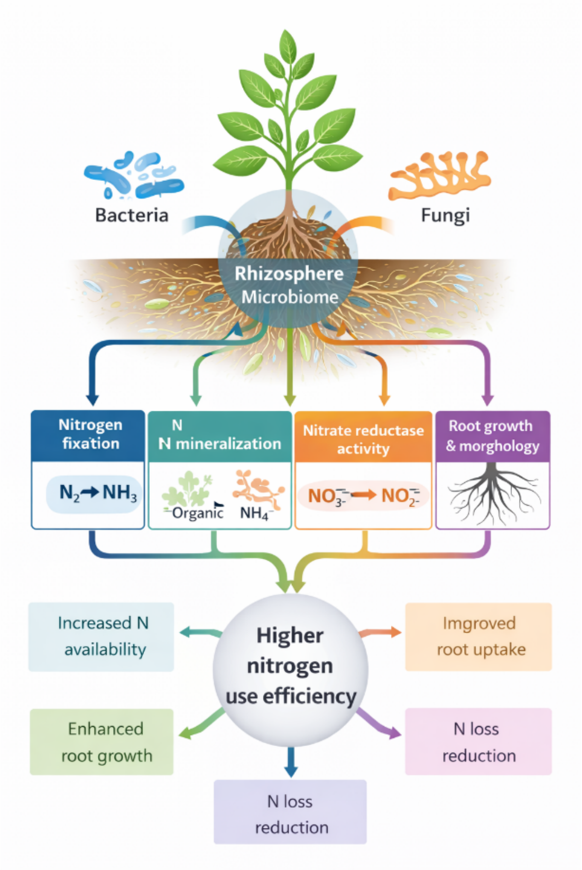

Figure 2. Mechanisms of Rhizosphere Microbiome in Enhancing NUE

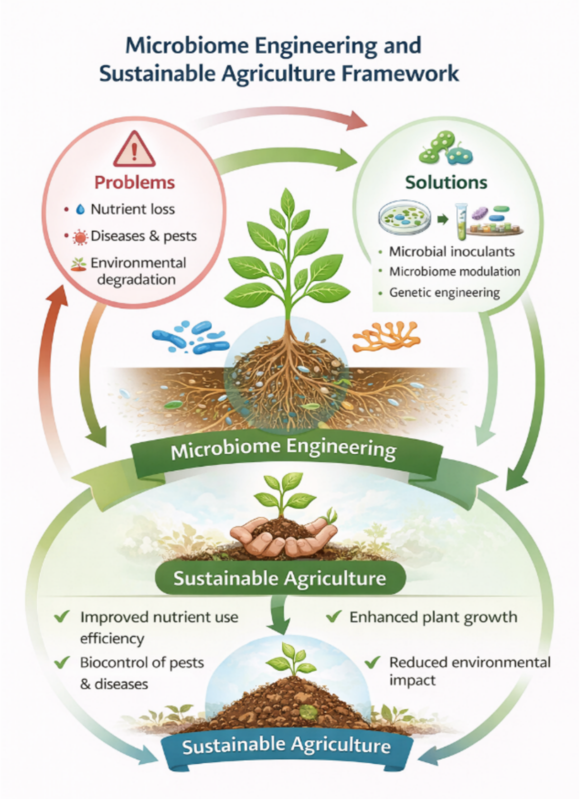

Figure 3. Microbiome Engineering and Sustainable Agriculture Framework

microorganisms (PSMs), including species of Bacillus, Pseudomonas, and Aspergillus, release organic acids and enzymes that convert insoluble phosphorus into plant-available forms [63,64]. Studies indicate that microbial inoculation can increase phosphorus availability by 15–35% and improve crop yield significantly [65]. Arbuscular mycorrhizal fungi (AMF) further enhance phosphorus uptake by extending the root surface area through hyphal networks [66].

3.2.3 Potassium Solubilization and Micronutrient Availability

In addition to nitrogen and phosphorus, rhizosphere microorganisms facilitate the solubilization of potassium and micronutrients such as zinc and iron. Potassium-solubilizing bacteria release organic acids that mobilize potassium from mineral sources [67]. Similarly, siderophore-producing bacteria enhance iron availability by chelating insoluble iron compounds [68]. These processes collectively improve nutrient balance and plant growth, particularly in nutrient-deficient soils [69].

3.3 Plant–Microbe Interactions and Root Architecture

The interaction between plant roots and microorganisms plays a crucial role in shaping root architecture and enhancing nutrient uptake. PGPR influence root development by producing phytohormones such as indole-3-acetic acid (IAA), which stimulates root elongation and branching [70,71]. Enhanced root architecture increases the root surface area, allowing for greater nutrient absorption. Studies have shown that microbial inoculation can increase root biomass by up to 25–50%, leading to improved nutrient uptake efficiency [72]. Additionally, microbial signaling molecules such as lipo-chitooligosaccharides (LCOs) and volatile organic compounds (VOCs) regulate plant gene expression and stress responses [73]. These interactions enhance plant resilience to abiotic stresses such as drought and salinity, indirectly improving NUE [74].

3.4 Disease Suppression and Plant Health

Rhizosphere microbiome restructuring also contributes to plant health by suppressing soil-borne pathogens. Beneficial microorganisms compete with pathogens for nutrients and space, produce antimicrobial compounds, and induce systemic resistance in plants [75,76]. Disease-suppressive soils have been shown to harbor specific microbial communities that inhibit pathogen growth and reduce disease incidence [77]. For example, Pseudomonas and Trichoderma species produce antibiotics and enzymes that degrade pathogen cell walls [78]. Improved plant health leads to better nutrient utilization and higher crop productivity, highlighting the indirect role of microbiome restructuring in enhancing NUE [79].

3.5 Microbiome Engineering and Biofertilizer Applications

Recent advancements in microbiome engineering have enabled targeted manipulation of rhizosphere microbial communities. Synthetic microbial consortia designed to perform specific functions have shown promising results in improving plant growth and nutrient efficiency [80]. Biofertilizers containing beneficial microorganisms have been widely adopted as sustainable alternatives to chemical fertilizers. Studies indicate that biofertilizer application can reduce chemical fertilizer use by 25–50% without compromising yield [81,82]. Precision agriculture technologies further enhance the effectiveness of microbiome-based interventions by enabling site-specific application and monitoring [83].

3.6 Role of Organic Amendments and Soil Management

Organic amendments such as compost, biochar, and green manure significantly influence rhizosphere microbial communities. These amendments improve soil structure, increase organic matter content, and promote microbial activity [84,85]. Biochar application has been shown to enhance microbial diversity and nutrient retention, leading to improved NUE [86]. Similarly, crop rotation and intercropping systems promote microbial diversity and reduce soil-borne diseases [87].

3.7 Climate Resilience and Environmental Sustainability

Rhizosphere microbiome restructuring plays a critical role in enhancing climate resilience in agricultural systems. Microbial communities improve plant tolerance to abiotic stresses such as drought, heat, and salinity [88]. Additionally, microbiome-based approaches contribute to carbon sequestration and reduction of greenhouse gas emissions, aligning with climate-smart agriculture goals [89,90].

3.8 Field-Level Performance and Yield Outcomes

Field studies demonstrate that microbiome-based interventions can increase crop yield by 10–30% under diverse agro-climatic conditions [91]. However, variability in results is often observed due to differences in soil type, climate, and management practices [92]. Long-term studies indicate that sustained application of microbial inoculants improves soil health and productivity over time [93].

3.9 Limitations and Variability in Outcomes

Despite promising results, several limitations were identified. The effectiveness of microbial inoculants is often inconsistent due to environmental variability and competition with native microbial communities [94]. Additionally, the survival and establishment of introduced microorganisms remain major challenges [95]. These limitations highlight the need for site-specific and adaptive strategies.

3.10 Integration with Public Health and Sustainability Goals

The results emphasize that microbiome-based nutrient management contributes to reduced chemical inputs, improved food safety, and environmental sustainability [96]. This aligns with global public health goals of reducing environmental pollution and ensuring sustainable food production systems [97–100].

Discussion

The findings synthesized in this review clearly demonstrate that rhizosphere microbiome restructuring is a powerful and multifaceted approach to enhancing nutrient use efficiency (NUE) and crop productivity. The integration of microbial ecology with agronomic practices has provided new insights into sustainable agricultural intensification, aligning closely with global food security and public health objectives. One of the most significant observations is the central role of microbial diversity and community structure in determining soil functionality. High microbial diversity contributes to ecosystem stability, efficient nutrient cycling, and resilience against environmental stressors [101,102]. This aligns with global studies indicating that biodiversity loss in agricultural soils leads to reduced ecosystem services and increased vulnerability to climate change [103]. The identification of keystone taxa further emphasizes the importance of maintaining functional microbial networks for sustained soil fertility [104]. The mechanisms underlying NUE enhancement are primarily driven by microbial processes such as biological nitrogen fixation, phosphorus solubilization, and micronutrient mobilization. These findings corroborate earlier studies that highlight the inefficiencies of synthetic fertilizers and the need for biologically mediated nutrient management systems [105,106]. The synergistic interactions between plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) further strengthen nutrient acquisition and plant resilience, reinforcing the concept of a holobiont system where plants and microbes function as an integrated unit [107,108]. Advancements in multi-omics technologies have significantly improved our understanding of rhizosphere dynamics. Metagenomics and metabolomics studies have revealed complex signaling pathways and metabolic exchanges between plants and microbes [109,110]. These insights have paved the way for microbiome engineering, where targeted manipulation of microbial communities can optimize plant performance under specific environmental conditions [111]. However, translating these findings into field applications remains a challenge due to environmental variability and soil heterogeneity [112]. The role of microbiome-based interventions in reducing dependency on chemical fertilizers has important implications for environmental and public health. Excessive fertilizer use is associated with water contamination, eutrophication, and greenhouse gas emissions, all of which pose significant health risks [113,114]. By improving NUE, rhizosphere microbiome restructuring can reduce nutrient losses and environmental pollution, contributing to safer food systems and healthier ecosystems [115]. Despite these advantages, several constraints limit the widespread adoption of microbiome-based technologies. One of the primary challenges is the inconsistency of microbial inoculants under field conditions. Factors such as soil pH, temperature, moisture, and native microbial competition can significantly influence the effectiveness of introduced microorganisms [116,117]. Moreover, the lack of standardized protocols for microbial formulation and application further complicates large-scale implementation [118]. Another important consideration is the socio-economic aspect of adopting microbiome-based practices. Farmers may be hesitant to adopt new technologies without clear evidence of cost-effectiveness and long-term benefits [119]. Therefore, policy support, extension services, and farmer education are essential to promote the adoption of sustainable agricultural practices.

4. Conclusion

The present review highlights that rhizosphere microbiome restructuring is a promising and sustainable approach to improving nutrient use efficiency and crop productivity. The integration of beneficial microorganisms such as PGPR, AMF, and other functional microbial groups enhances nutrient availability, improves plant health, and increases resilience to environmental stresses. The evidence suggests that microbiome-based interventions can significantly reduce reliance on chemical fertilizers, thereby minimizing environmental pollution and promoting sustainable agriculture. This has direct implications for public health, as improved soil and crop health contribute to safer food systems and reduced ecological risks. However, the successful implementation of these strategies requires overcoming challenges related to microbial survival, environmental variability, and scalability. Continued research, technological innovation, and policy support are essential to fully realize the potential of rhizosphere microbiome restructuring.

5. Future Perspectives

Future research should focus on developing site-specific microbiome solutions tailored to different crops, soil types, and climatic conditions. Advances in artificial intelligence and machine learning can play a crucial role in predicting microbial behavior and optimizing microbiome interventions [120]. The development of next-generation biofertilizers, including synthetic microbial consortia, offers significant potential for enhancing nutrient efficiency and crop yield [121]. These formulations should be designed to ensure stability, compatibility, and long-term effectiveness under field conditions. Integration of multi-omics approaches with ecological modeling will enable a deeper understanding of plant–microbe interactions and facilitate the design of targeted interventions [122]. Additionally, research should explore the role of microbiomes in mitigating climate change through carbon sequestration and reduction of greenhouse gas emissions [123]. From a public health perspective, microbiome-based agriculture can contribute to safe and sustainable food production systems, reducing exposure to harmful agrochemicals and improving nutritional quality [124]. Policymakers should prioritize the development of regulatory frameworks and incentives to support the adoption of these technologies. Finally, interdisciplinary collaboration among microbiologists, agronomists, environmental scientists, and public health experts is essential to address the complex challenges associated with sustainable agriculture and global food security [125–130].

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