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Review Article

Functional Profiling of Beneficial Soil Microbes Improving Plant Stress Tolerance: Mechanisms, Applications, and Public Health Implications

Lahar Jyoti Bordoloi[1], Sindhuja suram[2], Abhijit Debnath[3], Ratan Das[4]

[1]KVK Kiphire-798611, ICAR Research Complex for NEH Region, Nagaland Centre, Nagaland, India.
[2]PGIHS, SKLTGHU, Siddipet, Telangana- 502279, India.
[3]Department of Horticulture, KVK Dhalai, Salema-799278, Tripura, India.
[4]Department of Horticulture, KVK Unakoti-799279, Tripura, India.

Corresponding Author
Sindhuja suram
Email: sindhusuram1234@gmail.com

Article Information:
Received: 15 December 2025 | Revised: 22 January 2026 | Accepted: 19 February 2026 | Published: March 24, 2026

Cite this article:
Lahar Jyoti Bordoloi, Sindhuja suram, Abhijit Debnath, Ratan Das (2026) Functional Profiling of Beneficial Soil Microbes Improving Plant Stress Tolerance: Mechanisms, Applications, and Public Health Implications *Public Health Open Journal*. 11(1):224–202. https://doi.org/10.17140/PHOJ.11.01.224

Abstract

Plant stress caused by abiotic and biotic factors poses a significant threat to global agricultural productivity and food security. Beneficial soil microorganisms, particularly plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, and endophytic microbes, play a critical role in enhancing plant stress tolerance through diverse functional mechanisms. This review provides a comprehensive analysis of the functional profiling of beneficial soil microbes and their contributions to improving plant resilience under stress conditions such as drought, salinity, temperature extremes, and pathogen attack. Key mechanisms include phytohormone modulation, osmolyte accumulation, antioxidant enzyme activation, induced systemic resistance, and nutrient acquisition enhancement. Advances in omics technologies, including metagenomics, transcriptomics, and metabolomics, have facilitated deeper insights into microbial functions and plant–microbe interactions. Emerging approaches such as microbiome engineering, biofertilizer development, and precision agriculture are discussed for their potential to mitigate stress impacts sustainably. Furthermore, the implications of microbial-based stress management strategies for environmental sustainability and public health are highlighted, particularly in reducing agrochemical use and improving food quality. Despite promising developments, challenges related to field variability, microbial survival, and large-scale application remain. Future research directions emphasize the integration of multi-disciplinary approaches to optimize microbial interventions for sustainable agriculture and global health.

Keywords: *Beneficial soil microbes; Plant stress tolerance; Plant growth-promoting rhizobacteria (PGPR); Mycorrhiza; Abiotic stress; Biotic stress; Biofertilizers; Microbiome engineering; Sustainable agriculture; Plant–microbe interactions.*

1. Introduction

Plant growth and productivity are increasingly threatened by a wide range of abiotic and biotic stress factors, including drought, salinity, temperature extremes, heavy metals, and pathogenic infections. These stressors significantly reduce crop yield and quality, posing serious challenges to global food security and public health [1,2]. Climate change has further intensified the frequency and severity of these stresses, necessitating the development of sustainable and environmentally friendly strategies to enhance plant resilience [3,4]. The rhizosphere, defined as the narrow zone of soil influenced by plant roots, is a dynamic and biologically active interface where complex interactions occur between plants and microorganisms [5]. This region hosts a diverse community of beneficial soil microbes, including plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and endophytes, which play a crucial role in improving plant stress tolerance [6–8]. Early work by Hiltner established the concept of the rhizosphere, while subsequent studies demonstrated the ability of PGPR to enhance plant growth and mitigate stress effects [9–11]. Beneficial soil microorganisms employ multiple functional mechanisms to improve plant tolerance to stress conditions. One of the key mechanisms involves the production of phytohormones such as indole-3-acetic acid, gibberellins, and cytokinins, which regulate plant growth and development under adverse conditions [12,13]. In addition, several PGPR produce 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which reduces stress-induced ethylene levels in plants, thereby alleviating growth inhibition [14,15]. These mechanisms have been widely reported to enhance plant tolerance to drought, salinity, and other abiotic stresses [16,17]. Another important adaptive response involves the accumulation of osmolytes such as proline, glycine betaine, and soluble sugars, which help maintain cellular osmotic balance during stress [18,19]. Microbial inoculation has been shown to enhance osmolyte accumulation and improve water retention capacity in plants subjected to drought and salinity conditions [20]. Furthermore, beneficial microbes stimulate antioxidant defense systems, increasing the activity of enzymes such as superoxide dismutase, catalase, and peroxidase, thereby reducing oxidative damage caused by stress [21–23]. Nutrient acquisition is also significantly enhanced by soil microbes, contributing to improved plant health under stress conditions. Nitrogen-fixing bacteria such as Rhizobium, Azotobacter, and Azospirillum convert atmospheric nitrogen into plant-available forms, thereby improving nitrogen use efficiency [24,25]. Phosphate-solubilizing microorganisms release organic acids and enzymes that increase phosphorus availability in soils [26,27]. In addition, AMF form symbiotic associations with plant roots, extending the effective root surface area and enhancing the uptake of water and nutrients, particularly under drought conditions [28,29]. Apart from abiotic stress mitigation, beneficial soil microbes also play a vital role in protecting plants against biotic stress caused by pathogens. Mechanisms such as induced systemic resistance (ISR), production of antimicrobial compounds, and competitive exclusion contribute to disease suppression [30–32]. Microorganisms such as Pseudomonas and Trichoderma have been extensively studied for their biocontrol properties and ability to enhance plant immunity [33,34]. Recent advances in high-throughput sequencing and omics technologies, including metagenomics, transcriptomics, and metabolomics, have significantly improved our understanding of plant–microbe interactions [35–37]. These technologies provide insights into microbial diversity, functional capabilities, and metabolic pathways involved in stress tolerance. Plants actively shape their rhizosphere microbiome through the release of root exudates, which serve as signaling molecules and nutrient sources for beneficial microbes [38,39]. Microbiome engineering has emerged as a promising approach to enhance plant stress tolerance by manipulating microbial communities [40]. The development of synthetic microbial consortia and biofertilizers offers new opportunities for sustainable agriculture and reduced dependence on chemical inputs [41,42]. These strategies are particularly important in the context of climate change and environmental sustainability. The application of beneficial soil microbes also has important implications for public health. Reducing the use of chemical fertilizers and pesticides minimizes environmental contamination, improves soil health, and enhances food safety [43,44]. Microbial-based agricultural practices contribute to sustainable food production systems and support global efforts to mitigate climate change [45]. Despite the promising potential of beneficial soil microbes, several challenges remain in their practical application. Environmental variability, soil heterogeneity, and competition with native microbial communities can affect the survival and effectiveness of introduced microbes [46,47]. Additionally, the lack of standardized formulations and delivery systems limits large-scale adoption of microbial technologies [48]. In conclusion, functional profiling of beneficial soil microbes provides critical insights into their role in enhancing plant stress tolerance. Harnessing these microbial functions through innovative and sustainable approaches can significantly improve agricultural productivity while ensuring environmental sustainability and public health safety.

2. Mechanisms of Beneficial Soil Microbes in Enhancing Plant Stress Tolerance

Beneficial soil microorganisms play a critical role in enhancing plant resilience to environmental stresses through complex physiological, biochemical, and molecular interactions within the rhizosphere. These microbes, including plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and endophytes, contribute to stress tolerance by modulating plant metabolism, improving nutrient acquisition, and activating defense pathways. Recent advances in plant–microbe interaction studies have demonstrated that these mechanisms function synergistically to mitigate the effects of abiotic and biotic stresses [49–52].

2.1 Phytohormone Modulation and Ethylene Regulation

One of the most significant mechanisms employed by beneficial microbes is the modulation of plant phytohormones. PGPR synthesize hormones such as indole-3-acetic acid (IAA), cytokinins, and gibberellins, which regulate root architecture, enhance lateral root formation, and improve nutrient uptake under stress conditions [49–53]. A key microbial adaptation involves the production of ACC deaminase, which lowers the levels of stress-induced ethylene in plants. Elevated ethylene levels are known to inhibit root elongation and overall plant growth under stress conditions. By degrading ACC, the precursor of ethylene, microbes alleviate stress-induced growth inhibition and enhance plant tolerance to drought, salinity, and temperature extremes [54–57]. Furthermore, microbial signaling molecules influence hormonal cross-talk within plants, enabling better adaptation to environmental stressors [58,59].

2.2 Osmotic Adjustment and Cellular Homeostasis

Abiotic stresses such as drought and salinity disrupt cellular osmotic balance, leading to dehydration and reduced metabolic activity. Beneficial microbes promote the accumulation of compatible solutes, including proline, glycine betaine, trehalose, and soluble sugars, which play a crucial role in osmotic adjustment [60–63]. These osmolytes stabilize cellular membranes, protect proteins from denaturation, and maintain enzyme activity under stress conditions. Microbial inoculation has been shown to significantly enhance water-use efficiency and maintain cellular turgor pressure, thereby improving plant survival under water-deficit conditions [64–66].

2.3 Activation of Antioxidant Defense Systems

Environmental stresses often result in excessive production of reactive oxygen species (ROS), which cause oxidative damage to lipids, proteins, and nucleic acids. Beneficial soil microbes enhance the plant's antioxidant defense system by increasing the activity of key enzymes such as superoxide dismutase, catalase, peroxidase, and ascorbate peroxidase [67–70]. This enhanced antioxidant activity reduces oxidative stress and protects cellular components, thereby improving plant resilience. Studies have also shown that microbial inoculation can upregulate genes associated with antioxidant pathways, further strengthening plant defense mechanisms [71,72].

2.4 Nutrient Acquisition and Rhizosphere Engineering

Nutrient limitation is a major factor affecting plant stress tolerance. Beneficial microbes enhance nutrient availability through various processes, including nitrogen fixation, phosphorus solubilization, potassium mobilization, and micronutrient chelation [73–76]. Nitrogen-fixing bacteria such as Rhizobium, Azotobacter, and Azospirillum convert atmospheric nitrogen into plant-available forms, thereby improving nitrogen use efficiency [77,78]. Phosphate-solubilizing bacteria release organic acids and enzymes that convert insoluble phosphorus into accessible forms [79,80]. Arbuscular mycorrhizal fungi (AMF) establish symbiotic associations with plant roots, extending hyphal networks into the soil and enhancing the uptake of water and nutrients, particularly under drought conditions [81–83]. Additionally, microbial activity contributes to improved soil structure, organic matter decomposition, and enhanced microbial biomass, collectively referred to as rhizosphere engineering [84–86].

2.5 Induced Systemic Resistance (ISR) and Biocontrol Mechanisms

Beneficial microbes play a crucial role in protecting plants against pathogens through induced systemic resistance (ISR). This mechanism involves the activation of plant defense pathways mediated by signaling molecules such as jasmonic acid, salicylic acid, and ethylene [87–89]. Microorganisms such as Pseudomonas, Bacillus, and Trichoderma produce antimicrobial compounds, siderophores, and lytic enzymes that suppress pathogen growth [90–92]. In addition, competitive exclusion and niche occupation by beneficial microbes reduce pathogen colonization in the rhizosphere. These biocontrol mechanisms are essential for managing biotic stress in a sustainable and environmentally friendly manner [93–95].

ISSN: 2472-3878 | Vol 11 | Issue 1 | 2026

2.6 Molecular Signaling and Plant–Microbe Communication

Recent studies have highlighted the importance of molecular signaling in plant–microbe interactions. Root exudates act as chemical signals that attract beneficial microbes and regulate microbial colonization [96–98]. Microbial signaling molecules, including quorum-sensing compounds and volatile organic compounds (VOCs), influence plant gene expression and stress responses [99–101]. This bidirectional communication between plants and microbes plays a crucial role in establishing symbiotic relationships and enhancing stress tolerance.

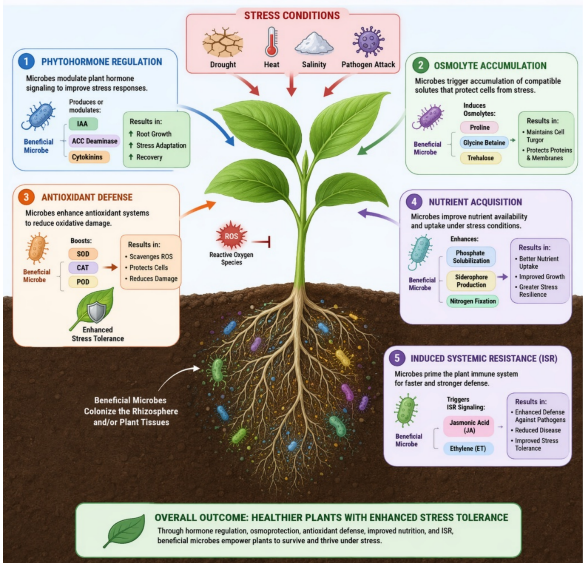

Figure 1. Microbial Mechanisms Enhancing Plant Stress Tolerance

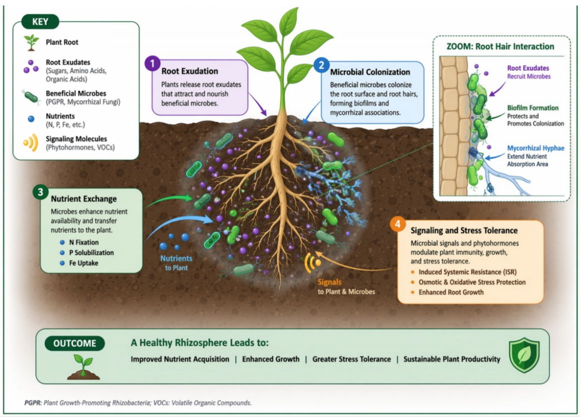

Figure 2. Rhizosphere Interactions Between Plants and Beneficial Microbes

3. Applications of Beneficial Soil Microbes in Sustainable Agriculture and Stress Management

The functional understanding of beneficial soil microbes has led to their widespread application in modern agriculture as eco-friendly tools for improving crop productivity and stress resilience. These applications are increasingly important in the context of climate change, soil degradation, and the need to reduce dependence on chemical inputs. Microbial-based technologies offer sustainable solutions that integrate plant health, soil fertility, and environmental safety [102].

3.1 Biofertilizers and Microbial Inoculants

Biofertilizers containing beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR), phosphate-solubilizing bacteria (PSB), and arbuscular mycorrhizal fungi (AMF) are widely used to enhance nutrient availability and plant growth. These inoculants improve nitrogen fixation, phosphorus solubilization, and overall nutrient cycling, leading to increased crop productivity under stress conditions [103,104]. The use of microbial consortia has been shown to be more effective than single-strain inoculants, as synergistic interactions among microbes enhance their functional efficiency and adaptability in diverse soil environments [105–107]. Additionally, biofertilizers contribute to improved soil organic carbon and microbial biomass, which are critical indicators of soil health [108].

3.2 Microbiome Engineering and Synthetic Microbial Communities

Microbiome engineering involves the manipulation of soil microbial communities to optimize plant performance and stress tolerance. Advances in microbial ecology and omics technologies have enabled the design of synthetic microbial consortia tailored to specific environmental conditions and crop requirements [109,110]. These engineered microbial communities can enhance nutrient acquisition, regulate plant hormone levels, and improve stress resilience through coordinated functional activities [111–113]. This approach represents a promising frontier in sustainable agriculture, allowing precise targeting of beneficial microbial functions.

3.3 Climate-Resilient Agriculture

Beneficial soil microbes play a vital role in climate-resilient agriculture by enhancing plant tolerance to drought, salinity, temperature extremes, and other stress factors. Microbial inoculation improves water-use efficiency, maintains plant physiological stability, and reduces yield losses under adverse climatic conditions [114–116]. In regions with fragile ecosystems, such as rainfed and semi-arid areas, microbial interventions have been shown to significantly improve crop survival and productivity [117]. These approaches are

Table 1. Beneficial Soil Microbes and Their Roles in Stress Tolerance

Microbial Group	Representative Genera	Functional Role	Stress Type Mitigated
PGPR	*Pseudomonas, Bacillus*	Hormone production, ACC deaminase	Drought, salinity
Nitrogen-fixers	*Rhizobium, Azotobacter*	Nitrogen fixation	Nutrient stress
PSB	*Bacillus, Pseudomonas*	Phosphorus solubilization	Nutrient deficiency
AMF	*Glomus spp.*	Nutrient & water uptake	Drought
Biocontrol agents	*Trichoderma*	Pathogen suppression	Biotic stress

Table 2. Key Mechanisms and Their Physiological Effects

Mechanism	Microbial Action	Plant Response
Phytohormone production	IAA, GA synthesis	Root growth enhancement
ACC deaminase activity	Ethylene reduction	Stress alleviation
Osmolyte accumulation	Proline, sugars increase	Osmotic balance
Antioxidant activation	ROS scavenging enzymes	Reduced oxidative damage
ISR activation	Defense signaling pathways	Disease resistance

essential for ensuring food security under changing climate scenarios.

3.4 Integration with Precision Agriculture

The integration of microbial technologies with precision agriculture systems has opened new avenues for efficient resource management. Precision application of microbial inoculants using advanced tools such as remote sensing, soil sensors, and GPS-based systems ensures optimal delivery and effectiveness [118,119]. This approach minimizes input wastage, enhances nutrient use efficiency, and improves crop performance under variable field conditions. Moreover, data-driven decision-making allows for site-specific management of soil microbial populations, leading to more sustainable agricultural practices [120–122].

3.5 Biocontrol and Integrated Pest Management (IPM)

Beneficial microbes are widely used as biocontrol agents in integrated pest management (IPM) systems. Microorganisms such as Trichoderma, Pseudomonas, and Bacillus suppress plant pathogens through mechanisms including antibiotic production, competition for nutrients, and induced systemic resistance [123–125]. The use of microbial biocontrol agents reduces reliance on chemical pesticides, thereby minimizing environmental contamination and promoting ecological balance [126,127]. These strategies are particularly important for sustainable crop protection and reducing the emergence of pesticide-resistant pathogens.

3.6 Soil Health Restoration and Carbon Sequestration

Microbial-based approaches contribute significantly to soil health restoration by enhancing soil structure, increasing organic matter content, and promoting nutrient cycling. Beneficial microbes play a key role in

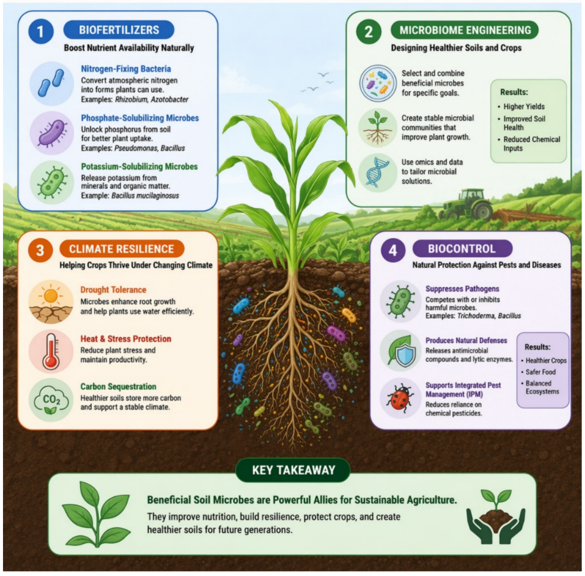

Figure 3. Applications of Beneficial Soil Microbes in Sustainable Agriculture

carbon sequestration by stabilizing soil organic carbon and improving soil aggregation [128–130]. These processes not only improve soil fertility but also contribute to climate change mitigation by reducing greenhouse gas emissions associated with intensive agricultural practices [131].

3.7 Role in Food Quality and Nutritional Security

The application of beneficial soil microbes has been linked to improvements in crop quality and nutritional content. Enhanced nutrient uptake results in higher concentrations of essential minerals and vitamins in crops, contributing to better human nutrition [132,133]. Furthermore, reduced use of chemical fertilizers and pesticides lowers the risk of harmful residues in food products, thereby improving food safety and public health outcomes [134–136].

Table 3. Microbial Contributions to Nutrient Cycling

Process	Microbial Agents	Nutrient Impact	Agricultural Benefit
Nitrogen fixation	*Rhizobium, Azotobacter*	Increases N availability	Reduced fertilizer use
Phosphorus solubilization	PSB	Improves P availability	Enhanced growth
Organic matter decomposition	Soil microbes	Nutrient release	Soil fertility
Mycorrhizal symbiosis	AMF	Nutrient uptake	Stress tolerance

Table 4. Applications of Beneficial Soil Microbes in Agriculture

Application Area	Microbial Role	Outcome
Biofertilizers	Nutrient mobilization	Increased crop yield
Microbiome engineering	Functional enhancement	Improved stress tolerance
Climate-resilient agriculture	Stress mitigation	Stable productivity
Precision agriculture	Targeted application	Resource efficiency
Biocontrol/IPM	Pathogen suppression	Reduced pesticide use
Soil restoration	Carbon sequestration	Improved soil health

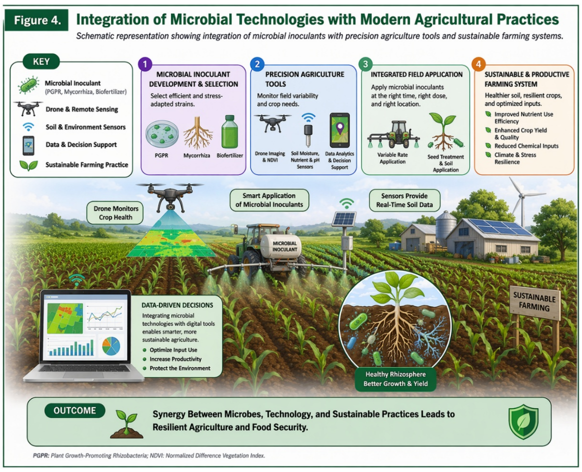

Figure 4. Integration of Microbial Technologies with Modern Agricultural Practices

4. Public Health Implications

The application of beneficial soil microbes in agriculture extends beyond crop productivity and environmental sustainability, with significant implications for public health. The excessive use of chemical fertilizers and pesticides has been linked to environmental pollution, food contamination, and adverse health effects in humans. Microbial-based agricultural practices offer a viable alternative by reducing dependency on synthetic inputs and promoting eco-friendly farming systems [137]. The use of biofertilizers and microbial inoculants minimizes the accumulation of toxic residues in food products, thereby improving food safety and reducing health risks associated with long-term exposure to agrochemicals [138,139]. Additionally, enhanced nutrient uptake facilitated by beneficial microbes leads to improved crop nutritional quality, contributing to better human health outcomes and addressing micronutrient deficiencies [140]. Microbial interventions also play a crucial role in maintaining soil and environmental health, which are fundamental components of the One Health framework that integrates human, animal, and ecosystem health [141–143]. By improving soil fertility, reducing greenhouse gas emissions, and minimizing water contamination, beneficial soil microbes contribute to sustainable ecosystems and long-term public health benefits [144].

5. Challenges and Future Perspectives

.Despite the promising potential of beneficial soil microbes, several challenges hinder their large-scale adoption and consistent field performance. Environmental variability, soil heterogeneity, and climatic factors significantly influence microbial survival and effectiveness in different agroecosystems [145,146]. Another major limitation is the competition between introduced microbial inoculants and native soil microbial communities, which can reduce the establishment and persistence of beneficial strains [147]. Furthermore, the lack of standardized formulations, storage stability, and efficient delivery systems poses challenges for commercial application [148,149]. Future research should focus on the development of robust, stress-tolerant microbial strains with enhanced adaptability to diverse environmental conditions. Advances in multi-omics technologies, including metagenomics, transcriptomics, and metabolomics, offer opportunities to better understand plant–microbe interactions and optimize microbial interventions [150–152]. The integration of microbial technologies with precision agriculture and digital farming tools is another promising direction. Such integration can enable site-specific application of microbial inoculants, improving their efficiency and scalability. Long-term field studies across different agroecological zones are essential to validate laboratory findings and promote wider adoption of microbial-based solutions.

6. Conclusion

Beneficial soil microbes represent a sustainable and innovative approach to enhancing plant stress tolerance, improving crop productivity, and ensuring environmental and public health safety. Through diverse mechanisms such as phytohormone regulation, osmotic adjustment, antioxidant defense, nutrient acquisition, and induced systemic resistance, these microorganisms significantly enhance plant resilience under both abiotic and biotic stress conditions. The functional profiling of soil microbial communities, supported by advances in omics technologies, has provided deeper insights into the complex interactions between plants and microbes. These insights have facilitated the development of practical applications such as biofertilizers, microbiome engineering, and climate-resilient agricultural systems. Importantly, the adoption of microbial-based agricultural practices contributes to reduced agrochemical use, improved food quality, and enhanced environmental sustainability, thereby supporting global public health goals. However, challenges related to field variability, microbial survival, and large-scale implementation must be addressed to fully realize their potential. In conclusion, integrating beneficial soil microbes into modern agricultural systems offers a promising pathway toward sustainable food production, ecological balance, and improved human health. Continued interdisciplinary research and innovation will be critical in harnessing the full potential of these microbial resources for future agricultural and public health advancements.

7. 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.

8. 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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