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Review

Application of Biofertilizers for Enhancing Beneficial Microbiomes in Push–Pull Cropping Systems: A Review

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Abstract: The need for sustainable farming practices has brought attention to biofertilizers to improve soil quality and boost crop yield while minimizing environmental impacts. This study explores the potential integration of biofertilizers within push–pull cropping systems, an agroecological approach that utilizes companion cropping to repel and attract pests. This review focuses on how biofertilizers could optimize plant–microbe interactions, promoting nutrient uptake, pest control, and soil health. Key biofertilizers, including nitrogen-fixing, phosphate-solubilizing, and potassium-solubilizing bacteria, improve nutrient availability, which leads to higher crop yields and resilience. They also enhance soil water retention and drought tolerance, which are crucial under changing climate conditions. Biofertilizers support beneficial microbial communities, reducing reliance on synthetic fertilizers and pesticides while fostering disease suppression and stress tolerance in crops. Their effectiveness can be significantly increased when biofertilizers are integrated with push–pull technology (PPT). However, challenges remain, such as inconsistent biofertilizer performance and the complexity of microbial interactions. Overcoming these challenges necessitates a multidisciplinary approach to refining production and application techniques. This study emphasizes the need to investigate biofertilizer-mediated plant–microbiome dynamics further to unlock their full potential. It concludes that future research should focus on the synergies between biofertilizers and agroecological systems to enhance food security and environmental sustainability. This work advances our understanding of optimizing biofertilizers in sustainable farming practices, particularly within the PPT framework.

Keywords: biofertilizers; push–pull technology; sustainable agriculture; nutrient uptake; soil health; plant–microbe interactions

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1. Introduction

The rising need for producing food and the negative effects on the environment caused by farming methods have sparked a focus on sustainable agriculture practices. Recently, the application of biofertilizers in crop production has gained prominence as a sustainable approach to enhancing soil health and crop productivity [1,2]. Among various agroecological practices, push–pull cropping systems have emerged as a highly effective method for managing pests, improving soil fertility, and boosting crop yields [3–6]. Push–pull technology (PPT) involves the strategic use of trap and repellent crops to manage pest populations while enhancing soil health through the incorporation of beneficial microorganisms [7]. Despite its proven benefits, the effectiveness of push–pull systems can be significantly enhanced by the application of biofertilizers, which support and amplify beneficial microbiomes in the plant–soil continuum [8,9]. However, to fully realize the potential of biofertilizers in PPT, it is essential to understand the mechanisms underlying their interactions with crops and associated microbial communities [10].

Push–pull technologies have demonstrated their ability to improve crop productivity and manage pest infestations in various farming contexts [7]. These systems leverage plant–microbe interactions to create more resilient agricultural environments. Biofertilizers, including phosphate-solubilizing bacteria (PSB) [11], potassium-solubilizing bacteria (KSB) [12], and nitrogen-fixing bacteria (NFB) [13], play a crucial role in optimizing these interactions by enhancing nutrient availability and supporting microbial communities. Research has shown that biofertilizers significantly improve soil properties and plant health by fostering beneficial microbiomes that contribute to nutrient cycling, disease suppression, and stress tolerance [14–18]. The ability of biofertilizers to stimulate plant growth and defense responses further amplifies the benefits of PPT, leading to improved crop yields and reduced reliance on synthetic inputs [10]. However, successfully integrating biofertilizers into PPT hinges on understanding the intricate relationships between the crop, the associated microbial community, and surrounding environmental factors.

Recognizing these complexities, researchers have made extensive efforts to elucidate the mechanisms by which biofertilizers enhance the performance of PPT. Key mechanisms include the direct promotion of plant growth through phytohormone production, enhanced nutrient availability via biological nitrogen fixation and phosphate solubilization, and the suppression of plant pathogens through antimicrobial compound production and the induction of systemic resistance [10,18]. For instance, PSB increase phosphorus availability, a critical nutrient for plant growth [11,19–21], while KSB improve potassium availability, vital for crop resilience [12,22]. Similarly, NFB contribute to soil nitrogen content, promoting plant growth and yield [23]. Integrating these biofertilizers within PPT can enhance their effectiveness and support sustainable agricultural practices by reducing reliance on chemical fertilizers and improving soil health. Therefore, the strategic use of biofertilizers in PPT holds great promise for advancing sustainable and resilient agricultural systems [10,24–26]. However, a deeper understanding of biofertilizer-mediated changes in plant–microbiome interactions is needed to maximize their potential within PPT systems [10,18,25,27].

Furthermore, biofertilizers can improve soil water retention and plant drought tolerance—critical factors in changing climate conditions [8,28]. Recent studies have shown that applying biochar and microbial inoculants can enhance water retention and crop productivity, which can benefit push–pull systems [29,30]. Despite the growing body of evidence supporting biofertilizers in PPT, further research is needed to fully understand how these microorganisms interact with plant and soil systems [31]. The potential for biofertilizer adoption in PPT is hindered by several challenges, including variable and unpredictable performance, the complex interactions between biofertilizers and the soil–plant–microbe continuum, and the lack of robust and reliable production and application methods [10,26]. Overcoming these challenges requires a multidisciplinary approach, bringing together microbiologists, plant scientists, and agronomists to develop innovative solutions. This study aims to explore the application of biofertilizers in enhancing beneficial microbiomes within PPT, focusing on their impact on pest management, soil health, water management, and crop productivity. The research will contribute to optimizing PPT and advancing sustainable agricultural practices by bridging gaps in current knowledge.

2. Push–Pull Technology

Push–pull technology (PPT) is an agroecological strategy that involves the intercropping of companion crops to manage pests without heavy reliance on chemical pesticides [3,5,6,32]. This approach combines "push" crops that repel pests and "pull" crops that attract pests away from the main crop. The most popular PPT practiced in East Africa involves maize or sorghum intercropped with leguminous plants of the genus *Desmodium* (Fabaceae), surrounded by *Napier grass* (*Pennisetum purpureum*) or *Brachiaria* species (both Poaceae) [33]. The *Desmodium* intercrop protects cereal crops by repelling stem borer pests, including the emerging *Spodoptera frugiperda* (fall armyworm), through a "push" effect while attracting parasitoids such as *Cotesia ruficrus*, *Cotesia sesamiae*, and *Trichogramma* spp. These parasitoids further reduce pest populations by parasitizing the pests, laying their eggs on or inside them, with the larvae consuming the host from within [34,35]. Additionally, microbial parasites are crucial in pest management within push–pull systems. For example, *Bacillus thuringiensis* (Bt) produces toxins that are lethal to specific insect larvae [3], while entomopathogenic fungi, such as *Beauveria bassiana* and *Metarhizium anisopliae,* infect and kill insects by penetrating their cuticles and growing inside them [36]. Furthermore, *Pythium* spp., a group of oomycetes, can parasitize insect larvae by infecting their tissues. The peripheral grasses act as a "pull" factor, attracting pests away from the crops for oviposition but preventing full larval development, thereby functioning as ecological traps.

In addition to pest control, PPT provides other agroecosystem benefits, such as reducing the need for synthetic chemical pesticides and fertilizers—an essential step toward sustainable agriculture. The allelopathic effects of *Desmodium* root exudates help control parasitic weeds, such as *Striga hermonthica* [7]. *Desmodium* is a leguminous species that also improves soil health by fixing nitrogen, facilitating carbon sequestration, solubilizing phosphorus, and depositing organic matter [37]. Plant-associated microbiomes further enhance productivity and overall plant health by regulating nutrient availability and uptake, improving tolerance to abiotic stress and increasing disease resistance. The root-mediated mechanisms that promote microbial species diversity in the soil within PPT systems can be further amplified by applying biofertilizers.

3. Beneficial Microbes in the Plant–Soil Continuum

Plant–soil microbiomes are crucial for plant health, stress tolerance, nutrient acquisition, and interactions with agricultural practices (Table 1). Research by [38] has demonstrated that plant-associated microbes enhance plant growth, disease resistance, and overall health by interacting with roots and influencing nutrient uptake. However, the specific mechanisms through which these interactions occur, particularly under varying environmental conditions, remain insufficiently understood. The role of the rhizosphere microbiome in suppressing soil-borne pathogens and enhancing disease resistance through various mechanisms has been well established [39–43]. S. Compant et al. [40] emphasize that the rhizosphere microbiome plays a critical role in plant health by influencing root growth, nutrient uptake, and disease resistance. Another study highlights the complexity of interactions within the rhizosphere, where beneficial microorganisms suppress plant pathogens through various mechanisms, including producing secondary metabolites, competition for nutrients and space, and modulation of the plant immune system [42]. P.A.H.M Bakker et al. [43] show that specific strains of fluorescent *Pseudomonas* can induce systemic resistance in plants, providing enhanced defense against a wide range of pathogens. Their study explains that the bacteria trigger plant immune responses without directly killing pathogens, leading to more robust and sustained disease resistance. S. Compant et al. [40] highlight that those beneficial microbes in the rhizosphere, such as mycorrhizal fungi and nitrogen-fixing bacteria, can help plants tolerate abiotic stresses, like drought and heat, which may also indirectly improve their resistance to pathogens. Nevertheless, more detailed studies are needed to understand how plant species and soil types influence these microbial communities.

Endophytic microorganisms have improved plant tolerance to environmental stresses such as drought, salinity, and metal toxicity [44–46]. For example, *Piriformospora indica* has been demonstrated to enhance drought tolerance in crops, like wheat and barley, by promoting root growth, increasing water and nutrient uptake, and boosting the expression of stress-responsive genes [45]. *Bacillus subtilis* has been found to improve drought tolerance in maize by stimulating the production of plant growth hormones, such as auxins, which increase root biomass and water retention [46]. Similarly, *Pseudomonas fluorescens* and *Azospirillum brasilense* have been reported to enhance salinity tolerance in rice and wheat by improving ion homeostasis, reducing oxidative stress, and facilitating nutrient uptake [44]. *Enterobacter cloacae* has been found to increase plant salt tolerance by producing phytohormones and enhancing antioxidant enzyme activities, which help plants cope with the osmotic stress induced by high salt levels [47]. *Pseudomonas putida* has also been reported to reduce heavy metal toxicity (such as cadmium and lead) in plants by sequestering metals in root tissues and promoting the production of stress-related proteins [48]. Despite these findings, the precise pathways through which endophytes alleviate these stresses, as well as their potential applications in sustainable agriculture, require further exploration.

Symbiotic relationships between plants and microbes, such as mycorrhizae and NFB, significantly enhance nutrient uptake [49]. Arbuscular mycorrhizal fungi (AMF) have been shown to improve the uptake of phosphorus (P), which is typically immobile in soil. *Glomus intraradices* extend the root system by forming hyphal networks that explore the soil more efficiently than plant roots alone, thereby enhancing P uptake in wheat by facilitating nutrient transport [50]. *Pisolithus tinctorius*, an ectomycorrhizal fungus commonly associated with trees, such as pine, oak, and birch, enhances nitrogen (N) and P uptake, promoting tree growth in nutrient-poor soils [51]. *Rhizobium leguminosarum* forms nodules on pea roots, providing the plant with fixed N in exchange for carbon compounds from the plant [52]. *Azospirillum* is associated with the roots of grasses (maize, wheat, rice, etc.), enhancing N availability and stimulating root growth by producing plant growth hormones such as auxins, gibberellins, and cytokinins [53]. *Herbaspirillum seropedicae* is an endophytic nitrogen fixer associated with sugarcane productivity in low-N soils [54]. However, the genetic and environmental factors that optimize these symbioses for different crops are not yet fully understood.

Agricultural practices such as crop rotation, tillage, and fertilization can significantly alter plant-associated microbiomes [55–57]. Crop rotation, the practice of alternating different crops (e.g., soybean and maize) in the same field, promotes a more diverse soil microbiome. During the legume phase, the populations of *Rhizobium* and *Bradyrhizobium* increase, enhancing N availability and microbial diversity [55]. Additionally, crop rotation can reduce soil pathogen populations, as non-host crops interrupt the life cycles of pathogens specific to certain crops. For instance, rotating cereal crops with brassicas (e.g., mustard) have been shown to reduce populations of soil-borne pathogens, like *Rhizoctonia* and *Fusarium* spp., thereby allowing beneficial microbes to thrive [58]. Conversely, conventional tillage can disrupt microbial communities and reduce the abundance of fungi, such as AMF. In contrast, no-tillage practices promote the growth of beneficial microbes, like *Pseudomonas* and *Bacillus* spp., which support crop growth and enhance disease resistance [59]. The impact of fertilization on the soil microbiome depends on the fertilizer used. Synthetic nitrogen fertilizers alter microbial community composition by favoring fast-growing bacteria that thrive in nitrogen-rich environments while reducing the abundance of nitrogen-fixing bacteria and mycorrhizal fungi [60]. Organic fertilizers, by contrast, enhance soil microbial diversity by providing a slow-release nutrient source and increasing organic matter content. Studies have shown that applying compost to fields increases populations of beneficial microbes, such as *Trichoderma* spp., which can suppress soil-borne pathogens, and promote the growth of phosphate-solubilizing bacteria that improve phosphorus availability to plants [61]. However, there remains a gap in understanding how specific agricultural practices can be optimized to maintain or enhance beneficial microbial communities.

Table 1. Studies on beneficial microbes in the plant–soil continuum.

Microbes Studied	Key Benefits	References
Rhizobia	Nitrogen fixation, improved soil fertility, increased crop yield	[13,18,23,52]
Mycorrhizal fungi	Enhanced nutrient uptake (phosphorus, nitrogen), improved drought resistance, increased crop yield	[50,51,62,63]
Pseudomonas	Disease suppression, enhanced root growth, increased nutrient uptake	[41,43]
Bacillus	Biocontrol of soil-borne pathogens, enhanced plant growth, improved stress tolerance	[17,53,64]
Trichoderma	Biocontrol of plant pathogens, improved seedling vigor, increased crop yield	[16,65,66]
Azospirillum	Nitrogen fixation, improved root architecture, increased nutrient uptake and growth	[13,43,53,66]
Endophytic fungi	Enhanced growth, increased resistance to biotic and abiotic stress	[40,45,67,68]

Table 1. *Cont.*

Microbes Studied	Key Benefits	References
Phosphate-solubilizing bacteria	Improved phosphorus availability, enhanced root development, increased yield	[11,12,20,24,29]
Actinomycetes	Biocontrol of pathogens, enhanced nutrient cycling, improved plant growth	[39,40,66]
Plant growth-promoting rhizobacteria (PGPR)	Enhanced disease resistance, improved nutrient uptake, increased plant growth	[10,39]
Nitrogen-fixing bacteria	Improved nitrogen availability, enhanced plant growth, increased yield	[13,52,69]
Siderophore-producing bacteria	Enhanced iron uptake, improved plant health, increased resistance to pathogens	[10,39,48,66]
Lactic acid bacteria	Improved plant growth, enhanced nutrient uptake, biocontrol of soil pathogens	[47,66,70]
Cyanobacteria	Nitrogen fixation, improved soil health, increased crop productivity	[1,48,71]
Vesicular–arbuscular mycorrhiza (VAM)	Improved nutrient and water uptake, enhanced soil structure, increased plant resilience	[50,51,62,63]

Soil microbiomes are crucial in plant growth, nutrient uptake, overall plant health, and soil structure [31]. Organic farming practices promote greater diversity and activity of soil microbiomes, leading to improved soil health and increased crop productivity compared to conventional farming methods [56,57,61,72]. Over the long term, organic farming significantly influences the diversity and activity of soil microbial communities, enhancing soil health and crop productivity compared to mineral-based fertilization strategies [61]. K. Hartman et al. [56] demonstrated that organic farming boosts the abundance and diversity of soil microbiomes, improving soil health and enhancing crop productivity. Additionally, J. Nelkner et al. [57] reported that organic farming practices lead to a higher diversity and functional activity of beneficial soil microbiomes than conventional farming, resulting in improved soil health and increased crop yields. L. Qiu et al. [72] further showed that organic farming practices can mitigate soil erosion and improve microbial diversity and network complexity, which are essential for maintaining soil health and productivity compared to conventional methods. Specific soil microbiomes can suppress plant diseases by outcompeting pathogens, producing antimicrobial compounds, and inducing plant systemic resistance [14]. Several studies [21,26,68] have highlighted the essential roles of soil microorganisms in nutrient cycling, particularly N, P, and carbon, which are crucial for soil fertility and plant growth. Soil health is closely tied to microbiome diversity, with more diverse microbiomes contributing to improved soil structure, nutrient availability, and disease suppression [41,56]. The activities of soil microbiomes regulate the decomposition of organic matter and soil carbon sequestration [63,68]. Microbial communities can also adapt to degrade pollutants in contaminated environments, enhancing bioremediation processes [40,48,73]. Furthermore, microbiomes contribute to soil stability and resistance to erosion by influencing soil aggregation and structure [72,74]. Microbes' secretion of extracellular polysaccharides promotes soil particle aggregation, thereby enhancing soil structure [56,61]. Additionally, soil microbiomes play a significant role in soil respiration through the decomposition of organic matter and microbial activity, both of which affect soil carbon fluxes [68,72].

4. Applications of Biofertilizers in Push–Pull Technologies

4.1. Biofertilizers

A biofertilizer refers to a microbial inoculant formulation that contains cultures of dormant or live cells from beneficial strains, such as nitrogen-fixing and phosphorus-solubilizing microorganisms [2,70]. From a cellular perspective, biofertilizers are typically applied in three ways: to seeds, plants, or soil. Most biofertilizer applications aim to enable beneficial microorganisms to colonize the rhizosphere or the plant's interior, promoting growth by increasing the supply or availability of primary nutrients to the host plant [75]. Microbiomes beneficial for plant production in biofertilizers are commonly referred to as plant growth-promoting microbes (PGPMs), plant growth-promoting bacteria (PGPB), or plant growth-promoting rhizobacteria (PGPR) [2]. A recent study detailed the primary mechanisms of biofertilizers, including improved nutrient supply, regulation of plant growth, and enhancement of soil quality and microbiome health [2].

Biofertilizers can have multiple impacts through various roles and mechanisms across the soil–plant continuum, promoting sustainable agriculture (Table 2). In agroecological systems, biofertilizers are integrated into push–pull farming techniques, enhancing beneficial microbial communities while contributing to pest management and soil health [7,76]. Biofertilizers reduce the need for synthetic fertilizers and pesticides, promoting sustainable farming by enhancing soil fertility and plant resilience [17,49,70]. Studies have shown that biofertilizers, such as AMF and vesicular–arbuscular mycorrhizae (VAM), improve soil structure and nutrient availability, thereby enhancing soil quality [62]. Additionally, cyanobacteria have been effective in boosting soil health by improving N fixation and overall soil productivity [71]. PGPR and endophytic fungi have been shown to enhance plant health by increasing nutrient uptake, promoting growth, and improving resistance to biotic and abiotic stresses [67,77]. Specifically, *Pseudomonas* species have proven beneficial in promoting plant growth and controlling soil-borne pathogens, aiding in pest management [41,43]. Collectively, these studies underscore the vital role of biofertilizers in advancing sustainable agricultural practices by improving soil conditions, strengthening plant health, and managing pests.

Table 2. Synthesized insights on the roles and mechanisms of biofertilizers in sustainable agriculture.

Biofertilizer Impact	Key Insights	References
Nutrient uptake enhancement	Nitrogen-fixing bacteria (e.g., *Azospirillum, Rhizobia*) improve nitrogen and phosphorus uptake, reducing dependence on chemical fertilizers.	[20,26,54,77]
Plant growth and yield improvement	PGPRs (*Pseudomonas, Trichoderma*) promote plant growth by producing plant hormones, enhancing nutrient absorption, and protecting against pathogens, leading to increased yields.	[43,53,69]
Abiotic stress tolerance	Help plants cope with drought and salinity by promoting beneficial root–microbe interactions, improving water uptake, and enhancing root growth.	[8,44,46]
Soil microbial health	Enhance microbial diversity and interactions in the rhizosphere, improving soil health, structure, and long-term fertility.	[41,61,78]
Disease suppression	Biofertilizers containing *Pseudomonas* and *Trichoderma* induce systemic resistance, reducing crop disease incidence and minimizing chemical pesticide use.	[43,65,79,80]
Phosphorus solubilization	Biofertilizers with PSB enhance phosphorus availability, which is critical for crop nutrition and productivity, especially in phosphorus-limited soils.	[12,24]
Climate resilience	Biofertilizers containing climate-resilient microbes can help plants withstand environmental stresses, such as temperature fluctuations and extreme weather.	[16,28,40]
Phytoremediation	Siderophore-producing bacteria and other PGPRs assist in the phytoremediation of heavy metals, contributing to soil detoxification and rehabilitation of polluted lands.	[48,53]
Greenhouse gas reduction	Improved nutrient use efficiency with biofertilizers reduces nitrous oxide (N_2O) emissions, a potent greenhouse gas associated with synthetic fertilizer overuse.	[13,60]
Crop quality enhancement	Biofertilizers improve the nutritional quality of crops (e.g., higher vitamin, protein, and mineral content) by improving nutrient absorption, especially phosphorus and potassium.	[22,81]
Synergy with organic amendments	Biofertilizers work synergistically with organic matter (compost, manure) to enhance microbial activity, nutrient availability, and sustainable nutrient release.	[19,61,80]
Biofertilizers as microbial carriers	Biofertilizers can act as carriers for diverse microbial communities, improving soil microbiome composition and stability, particularly when combined with amendments like biochar.	[30,61]
Marginal climate applications	Cold-tolerant microbial strains in biofertilizers enhance crop performance in cold or marginal soils, improving yield and plant health in difficult growing conditions.	[15]

4.2. Pest Management

There is growing interest in integrating beneficial microbes with PPT to develop sustainable pest management systems. Endophytic fungi in PPT could offer systemic protection against fall armyworm infestations [5,35]. F. Chidawanyika et al. [5] suggested that incorporating endophytic fungi into PPT could provide additional protection against pests like the fall armyworm. I.S. Sobhy et al. [35] examined the effectiveness of PPT in controlling fall armyworms through the use of volatile compounds. Although their study did not focus on endophytic fungi, it provides a solid foundation for considering how endophytes could complement existing pest management strategies in PPT. Other studies have highlighted the potential of endophytic fungi in enhancing plant resistance against pests and diseases [67,73]. These studies emphasize the need for further research to assess the long-term effectiveness of such biological control agents.

Z.R. Khan et al. [7] indicated that specific microbial inoculants significantly boosted plant growth and pest resistance, particularly for controlling stem borers and Striga weed in maize. Nevertheless, the interaction between microbial strains and their combined effects on multiple pest species requires further investigation. If integrated with PPT, PGPR could improve crop growth and pest resistance [39]. However, research gaps include identifying the most effective PGPR strains and understanding their interaction with other components of PPT across various agroecological zones.

D.E. Conlong et al. [4] suggested that entomopathogenic nematodes (EPNs) could significantly reduce stemborer populations and enhance crop yields. Z.R. Khan et al. [34] evaluated the effectiveness of PPT in increasing natural parasitism of maize stemborers. Although their study does not specifically evaluate EPNs, it provides a context in which EPNs could be effectively integrated to control stemborers. Further studies are needed to optimize application methods and assess the long-term sustainability and non-target effects of EPNs in diverse farming systems. C.A. Midega et al. [76] found that AMF inoculation improved plant growth and nutrient uptake, thereby increasing resilience to pest attacks. However, more detailed research is required to identify the specific AMF strains that offer the best protection and to understand how they interact with other soil microorganisms and agricultural practices. M. Dong et al. [82] found that microbial inoculants enhanced the production of volatile organic compounds (VOCs), which attracted natural enemies of pests and improved pest control efficacy. Similarly, I.S. Sobhy et al. [35] highlighted how PPT companion crops, when combined with microbial inoculants, produce bioactive VOCs that repel pests, such as the fall armyworm, and attract natural enemies, like parasitoids, enhancing pest control. Future research should focus on identifying which microbial inoculants are most effective at enhancing VOC production and how environmental factors influence VOC release and pest attraction. While these studies underscore the potential benefits of integrating beneficial microbes with PPT, several research gaps remain. These include understanding the specific interactions and synergies between different microbes, optimizing inoculation methods, assessing long-term sustainability, and adapting these systems to diverse environmental conditions and crop varieties. Addressing these gaps will be key to fully harnessing the potential of microbial inoculants in enhancing the efficacy and sustainability of push–pull technology in pest and soil fertility management.

4.3. Disease Suppression

Several studies have consistently demonstrated that biofertilizers play a significant role in suppressing soil-borne pathogens through various mechanisms, including the production of microbial antagonistic compounds, direct competition with pathogens, and the induction of systemic resistance in plants [2,65,73,79,82]. Biofertilizers have also been shown to enhance soil microbial diversity, supporting disease suppression and promoting sustainable disease management [82]. For example, biofertilizers effectively controlled Panama disease in banana cultivation by promoting beneficial microbial communities that outcompete the pathogenic fungus *Fusarium oxysporum* [79]. M. Dong et al. [82] explored the role of biofertilizers in suppressing bacterial wilt in tomatoes, demonstrating how biofertilizer application alters microbial communities in soil microaggregates to combat the disease. Similarly, applying plant PGPR in mustard reduced the severity of Alternaria blight through the induction of systemic resistance and the production of pathogen-inhibiting secondary metabolites [64]. Additionally, *Trichoderma virens*, a well-known biofertilizer, has proven effective in controlling soil-borne diseases and enhancing crop resilience by promoting root colonization and producing lytic enzymes that degrade pathogen cell walls [65]. Z. Shen et al. [80] demonstrated how compost and biofertilizers can suppress Fusarium wilt in bananas, enhancing yield and quality while modifying the soil microbiome to resist pathogen proliferation. C. Tao et al. [73] investigated fungal interactions within biofertilizers and their combined effects in suppressing Fusarium wilt, revealing the additive effects of fungal components in promoting plant growth while controlling disease. The synergistic interaction of multiple fungal species in biofertilizers further underscores the effectiveness of diverse microbial consortia for disease suppression, offering better results than single-strain treatments [73]. These findings highlight the importance of utilizing diverse biofertilizer formulations for comprehensive disease management in agricultural systems, which can be integrated with PPT and ensure sustainable agroecosystems.

4.4. Soil Health

Biofertilizers have been applied to promote beneficial microbes, enhancing the availability and uptake of essential soil minerals, thereby contributing to the overall success of push–pull technologies in sustainable agriculture. One of soil microbes' most important agroecosystem services is improving nutrient bioavailability. For instance, plant roots cannot absorb insoluble phosphate, potassium salts, or certain forms of phosphorus and potassium in the soil [83,84]. Nitrogen-fixing microbes utilize the enzyme nitrogenase to convert atmospheric nitrogen into forms like NH_4^+ or NO_3^-, which plant roots can readily absorb [83]. Although organic phosphorus compounds (such as phosphoinositides, phospholipids, and nucleic acids) and inorganic sources (like phosphate rock and insoluble phosphate) dominate in the soil, they are not directly accessible to plants.

Research has demonstrated various benefits. C.A. Midega et al. [76] found that nitrogen-fixing bacteria in PPT improved soil nitrogen levels and plant health, leading to better pest resistance and higher yields. Rhizobium can symbiotically form root nodules with the roots of legume crops and fix nitrogen efficiently in these nodules [15]. Azospirillum, however, is less effective in fixing nitrogen than the symbiotic fixation in legume nodules but can fix nitrogen in non-legume crops such as maize, rice, and wheat [85]. B. Vanlauwe et al. [19] showed that phosphate-solubilizing bacteria in legume-based cropping systems enhanced phosphorus availability and uptake, improving plant vigor and reducing pest damage. Similarly, W. Janati et al. [11] reported that phosphate-solubilizing bacteria in maize cropping systems significantly increased phosphorus solubility, improving phosphorus uptake by maize plants and enhancing pest resistance.

P.N. Bhattacharyya et al. [69] found that zinc-solubilizing bacteria increased zinc solubility, enhancing zinc uptake by maize plants and improving plant health and pest resistance. H. Etesami et al. [12] reviewed the role of potassium-solubilizing bacteria in biofertilizers, which improve soil health by making essential nutrients more accessible to plants and increasing overall soil fertility. A.A. Mahmud et al. [1] reported that silicon-solubilizing bacteria increased silicon uptake in rice plants, improving their structural integrity and resistance to pest attacks. Z.R. Khan et al. [7] indicated that certain microbial inoculants significantly boosted plant growth and pest resistance by improving nutrient uptake, particularly nitrogen and phosphorus. J. Nelkner et al. [57] examined the effects of long-term farming practices on soil microbiomes using metagenomically assembled genomes (MAGs), finding that biofertilizer applications in these systems promoted beneficial microbes that play key roles in enhancing nutrient availability and soil health. D. Francioli et al. [61] compared mineral and organic amendments, including biofertilizers, and found that biofertilizers significantly improved soil microbial activity and community structure. This increase in agriculturally relevant microbes was directly linked to improved soil health and fertility. S. Bolan et al. [30] reviewed the potential of biochar as a microbial carrier in biofertilizers, finding that biochar improves the efficiency of biofertilizers by providing a habitat for beneficial microbes, thereby enhancing soil fertility and health over the long term. These comprehensive findings highlight the benefits of various biofertilizers in enhancing nutrient availability and uptake. However, further research is needed to better understand the specific interactions and synergies between different biofertilizers and their combined effects on plant health and pest resistance in PPT across diverse agroecosystems.

4.5. Water Management

Several studies have demonstrated the potential of beneficial microbes in crop production, which can be integrated with PPT to improve drought resilience, water use efficiency, and crop yields across various cropping systems. AMF inoculation has been shown to enhance root water absorption, increasing drought resilience and crop yields in water-limited environments [51,62], which could benefit rainfed PPT in semi-arid regions. When combined with optimized irrigation schedules, nitrogen-fixing bacteria improved water use efficiency and crop performance under varying water availability conditions [13,19]. J. Li et al. [28] observed that microbial inoculants enhanced wheat growth under low soil water availability, leading to more efficient water use and improved crop resilience during dry spells. Microbial inoculants in biofertilizers improve wheat's drought tolerance by colonizing the root zone and enhancing soil water retention. M. Rafique et al. [29] demonstrated that integrating biochar and microbial inoculants improved soil water retention capacity and overall crop yield under fluctuating rainfall conditions. O.A. Fasusi et al. [70] emphasized that biofertilizers improve rhizosphere management, enhancing the soil's ability to retain water and resist drought conditions. A.A. Mahmud et al. [1] discussed how biochar and microbial inoculants work together to improve soil structure and water retention capacity. These improvements in soil conditions contribute to higher crop yields, particularly in areas with variable rainfall. Additionally, S. Bolan et al. [30] reviewed the role of biochar-enhanced biofertilizers in improving water retention in soils. Biochar acts as a microbial carrier, improving the ability of soils to retain moisture, especially in dry or degraded soils. P.N. Bhattacharyya et al. [69] reviewed how water-efficient irrigation techniques combined with beneficial microbes in rice fields resulted in significant water savings, improved plant water status, and enhanced pest control efficacy. S. Compant et al. [40] examined how climate change affects plant–microbe interactions, noting that biofertilizers can mitigate the impacts of water stress by improving plant water-use efficiency and promoting microbial communities that help retain soil moisture. Integrating cover crops, beneficial microbes, and optimized water management practices improved soil moisture dynamics and crop productivity, enhancing soil moisture retention, reducing irrigation requirements, and improving overall crop performance [56,61]. However, more research is needed to better understand the specific interactions and synergies between microbial inoculants and their combined effects on water use efficiency and crop resilience across different cropping systems and environmental conditions.

5. Microbial Mechanisms for Sustainable Crop Production in Challenging Soils

Several studies show that biofertilizers consistently increase microbial diversity, especially in challenging soils such as those that are arid, saline, alkaline, or polluted [86–90]. F. Zhang et al. [87] explored the application of the fungal biofertilizer *Trichoderma* in saline and alkaline soils. *Trichoderma* improved plant growth and soil nutrient availability by altering the soil microbiome to favor salt-tolerant and pH-resilient microbial populations. The application of *Trichoderma* increased the abundance of *Firmicutes* and *Proteobacteria*, two phyla that are well known for their tolerance to saline and alkaline conditions. Specifically, salt-tolerant species, such as *Bacillus* (Firmicutes), were promoted. Enhanced microbial diversity was observed, with a higher proportion of bacteria involved in nutrient solubilization, particularly phosphorus, which is often limited in saline–alkaline soils.

X. Wei et al. [88] combined the use of *Bacillus* and microalgae biofertilizers, significantly improving the growth and biomass of *Salvia miltiorrhiza* by altering soil microbial communities. The study found an increase in *Firmicutes* (due to introducing *Bacillus* strains) and *Cyanobacteria*, known to enhance N fixation and nutrient availability in nutrient-poor or stressed environments. Introducing biofertilizers promoted microbial biodiversity, mainly by enriching beneficial nitrogen-fixing and phosphorus-solubilizing microorganisms. Additionally, N. Sivaprakasam et al. [90] used metagenomics to assess the dynamics of PGPMs in soils where pathogens like *Phytophthora* are prevalent. Biofertilizer application increased *Firmicutes* and *Proteobacteria* and especially beneficial PGPMs, such as *Bacillus* (Firmicutes) and *Pseudomonas* (Proteobacteria). These bacteria enhance plant growth by producing enzymes and compounds that suppress pathogens and improve nutrient availability. The application of biofertilizers enriched microbial diversity, promoting beneficial microbial communities involved in disease suppression and nutrient cycling, particularly in soils with poor health or pathogen issues. M. Mącik et al. [89] emphasized the role of phosphorus biofertilizers in regenerating soils suffering from nutrient deficiencies, including those in arid regions. The application of phosphorus biofertilizers led to an increase in *Actinobacteria*, a phylum well-adapted to nutrient-poor and dry soils, and *Proteobacteria*, which are crucial for phosphorus solubilization. These microbial changes significantly improved nutrient cycling and soil health, enhancing microbial diversity and particularly favoring microbial communities involved in phosphorus solubilization and drought resilience.

Sun et al. [86] assessed the application of *Bacillus subtilis* biofertilizer in agricultural soils with high ammonia emissions, a problem often exacerbated by poor management or pollution. The application led to a shift in soil microbiomes, with an increase in *Firmicutes* (particularly *Bacillus subtilis*), which are known for their role in reducing ammonia emissions through enhanced nitrogen cycling. *Nitrospirae*, crucial for nitrification, also increased. The biofertilizer enhanced overall microbial diversity, significantly increasing functional microbes in N cycling, reducing ammonia loss, and promoting healthier soil conditions. These studies demonstrate that biofertilizers promote the growth of resilient phyla such as *Firmicutes, Proteobacteria*, *Nitrospirae*, and *Actinobacteria* in extreme soils. These bacterial groups are essential for nutrient cycling, stress tolerance, and soil remediation. Additionally, biofertilizer applications lead to increased microbial diversity in arid, saline, alkaline, and polluted soils. This diversity is crucial for improving soil functionality, promoting plant growth, and enhancing ecosystem resilience under stress. Furthermore, in challenging soil environments, biofertilizers enhance the presence of functional microbial groups involved in nutrient solubilization (e.g., phosphorus and nitrogen), salt tolerance, and pollutant degradation, all of which contribute to the restoration of soil health.

6. Biofertilizer-Mediated Changes in Microbial Diversity

Several studies have reported mixed results regarding the effects of biofertilizers on microbial diversity and ecosystem functioning [9,78,91]. A.A. Jalloh et al. [9] highlighted that biofertilizers increased microbial diversity, including beneficial bacterial and fungal genera, which enhanced soil resilience and overall crop performance in farmers' fields. Although beneficial microorganisms thrived and contributed to improved ecosystem functions, such as nutrient availability, there were instances where microbial diversity did not increase uniformly. This variability suggests that the success of biofertilizers may depend on bacterial phyla.

A.A. Otaiku et al. [91] demonstrated that biofertilizers enhanced soil microbiome diversity by introducing beneficial microorganisms, which improved soil health and nutrient cycling in a cassava system. The application of *Bacillus subtilis* biofertilizer increased the relative abundance of *Proteobacteria* and *Firmicutes*, particularly *Bacillus* spp., and also increased the abundance of *Nitrospirae*, responsible for ammonia oxidation [86]. This shift suggests improved N cycling and reduced ammonia loss, where biofertilizers enhanced overall microbial biodiversity, supporting functional groups that improved N retention and soil health. M. Mącik et al. [89] reported a marked increase in *Actinobacteria*, which play a critical role in P solubilization. *Firmicutes* and *Proteobacteria* also increased, while the abundance of *Bacteroidetes* decreased, indicating improved P cycling, nutrient availability, and enhanced soil fertility. The application of *Trichoderma* biofertilizers in *Medicago sativa* (alfalfa) cultivation in alkaline–saline soils led to changes in microbial diversity, particularly favoring bacteria capable of surviving in stressed environments [87]. *Firmicutes* and *Proteobacteria* showed an increase, indicating enhanced tolerance to saline–alkaline conditions, while *Bacteroidetes* and *Acidobacteria* exhibited shifts that were context specific, depending on soil salinity and pH levels.

In another study, X. Wei et al. [88] observed an increase in *Cyanobacteria*, Actinobacteria, and *Firmicutes*. *Bacillus* strains dominated the bacterial community, with a noticeable shift in N-fixing and P-mobilizing bacterial phyla. N. Sivaprakasam et al. [90] showed a rise in *Firmicutes* and *Proteobacteria*, particularly those linked to pathogen suppression, such as *Bacillus* spp. A decrease in *Bacteroidetes* and *Chloroflexi* was observed, possibly due to competitive exclusion by beneficial PGPMs. D. Agustiyani et al. [27] explored the biofertilizer potential of PGPR from different plant ecosystems. They identified shifts in dominant bacterial phyla such as *Proteobacteria*, *Firmicutes*, and *Actinobacteria* across various ecosystems. The introduction of PGPR increased the abundance of beneficial bacterial groups, which promoted plant growth and altered microbial biodiversity. M. Dong et al. [82] investigated biofertilizer applications in relation to soil microbial assembly. They found that biofertilizers triggered a shift in microbial communities, particularly increasing the abundance of *Proteobacteria*, *Acidobacteria*, and *Firmicutes*, which are often linked to disease suppression. This microbial shift contributed to the suppression of bacterial wilt in tomato plants. D. Francioli et al. [61] studied the impact of long-term fertilization strategies (mineral vs. organic amendments) on microbial communities. Their findings demonstrated that organic amendments significantly increased microbial diversity, particularly in the phyla *Actinobacteria*, *Bacteroidetes*, and *Proteobacteria*. Organic inputs fostered a more diverse and functionally active microbial community than mineral fertilizers. P.P. Bittencourt et al. [8] examined the role of bacterial inoculants under drought stress. They observed that inoculants, including species from the *Bacillus* and *Pseudomonas* genera, led to significant changes in microbial biodiversity. There was an increase in the abundance of stress-tolerant bacterial phyla, such as *Firmicutes* and *Actinobacteria*, enhancing plant drought tolerance. These studies show that biofertilizer application often shifts bacterial community composition, with increased abundance in beneficial phyla like *Proteobacteria*, *Actinobacteria*, *Firmicutes*, *Bacteroidetes*, and *Nitrospirae* while often suppressing harmful or less beneficial bacterial groups. These shifts contribute to improved soil health, plant growth, and ecosystem functioning.

7. Future Directions and Research Needs

Several key areas of research require attention to advance the application of biofertilizers and enhance sustainable agricultural practices. One priority is the integration of biofertilizers with agroecological systems like PPT. This involves optimizing the synergy between biofertilizers, companion crops, and microbial inoculants to improve pest management, soil fertility, and overall system sustainability. Additionally, developing reliable and scalable methods for biofertilizer production and application is essential. Research should focus on refining biofertilizer formulations, delivery mechanisms, and compatibility with various crop varieties and soil conditions to facilitate broader farmer adoption. Despite the potential of biofertilizers to enhance soil health and crop productivity, their performance remains variable and unpredictable. To address this, research must explore improving their consistency and effectiveness across different environmental conditions and soil types. This requires a deeper understanding of microbial interactions within the plant–soil continuum and the specific roles of microbial consortia in nutrient cycling, disease suppression, and stress tolerance, particularly within PPT systems. As climate change increasingly impacts agricultural systems, biofertilizers could be vital in boosting crop resilience to environmental stresses such as drought, salinity, and extreme weather events. Research should investigate how biofertilizers enhance soil water retention and plant tolerance to these abiotic stresses, which will be critical for developing sustainable cropping systems in vulnerable regions. While short-term studies have shown the benefits of biofertilizers, long-term field trials are necessary to assess their effects on crop yields, soil health, and ecosystem services over time. This will provide a more comprehensive understanding of the sustainability of biofertilizer use across diverse agroecosystems.

8. Conclusions

Applying biofertilizers in agroecological systems, particularly in conjunction with PPT, has significant potential to advance sustainable agricultural practices. This review highlights the ability of biofertilizers to enhance nutrient availability, improve soil health, and boost crop productivity by fostering beneficial plant–microbe interactions. In addition, biofertilizers play a critical role in improving pest management and crop resilience, especially under environmental stress conditions like drought. However, the practical implementation of biofertilizers faces challenges such as variability in performance, complex interactions within the soil–plant–microbe continuum, and inconsistent outcomes across different agroecological contexts. Addressing these challenges will require refining biofertilizer formulations, improving production methods, and optimizing application techniques. This review also demonstrates that biofertilizers can significantly reduce farmer's reliance on synthetic inputs, contributing to more sustainable and resilient cropping systems. Therefore, farmers can better integrate these tools into their practices to improve crop yields and support ecosystem services. However, a multidisciplinary approach involving agronomists, microbiologists, and farmers is crucial to advancing biofertilizer technology for successful adoption. Long-term studies and field trials are essential to validate the benefits of biofertilizers in diverse environments and ensure their scalability for widespread use. Ultimately, biofertilizers offer a promising path toward enhancing sustainable agriculture, improving food security, and mitigating the environmental impacts of modern farming practices.

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