



# Biofertilizers: An Integrated Approach to Improving Soil Fertility, Plant Nutrition, Forest and Environmental Sustainability

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## Abstract

Biofertilizers present a viable solution for enhancing soil fertility, improving plant nutrition, and advancing environmental sustainability in agriculture and forest ecosystems. These microorganism-based fertilizers not only supply essential nutrients to plants but also foster soil health, thereby reducing reliance on synthetic fertilizers. This review highlights various types of biofertilizers, such as mycorrhizal fungi, rhizobia, and compost, and examines their mechanisms of action and applications in sustainable agricultural and forestry practices. The potential benefits of biofertilizers include increased crop yields, enhanced soil carbon sequestration, improved biodiversity, and the promotion of forest health and resilience. However, challenges such as limited availability, standardization issues, and the need for integration with conventional practices must be addressed to maximize their effectiveness. Future research directions should focus on scaling up biofertilizer production, developing innovative formulations, and understanding the interactions between biofertilizers and soil microbial communities. By promoting the adoption of biofertilizers, we can contribute to environmentally friendly and socially responsible food systems, ultimately ensuring food security while preserving ecological balance. This review emphasizes the importance of collaborative efforts among researchers, farmers, and policymakers to integrate biofertilizers into sustainable practices, paving the way for a resilient agricultural and forest landscape that meets the needs of a growing population while safeguarding the environment for future generations.

## Subject Areas

Agroecology

## Keywords

Biofertilizers, Sustainable Agriculture, Soil Fertility, Plant Nutrition, Forest Ecology, Environmental Sustainability

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## 1. Introduction

The world's population is projected to reach 9.7 billion by 2050, placing unprecedented pressure on the global food system [1] [2]. Meeting this demand while ensuring environmental sustainability and social equity presents a significant challenge. Conventional agricultural practices, which heavily rely on synthetic fertilizers and pesticides, have contributed to soil degradation, water pollution, and loss of biodiversity [3]-[6]. In contrast, sustainable agricultural practices prioritize environmental stewardship, social responsibility, and economic viability [7] [8]. Sustainable agriculture is vital for maintaining ecosystem services, including soil formation, water cycling, and climate regulation [9]-[11]. Additionally, it promotes rural development, improves food security, and enhances the well-being of farming communities [12]-[15]. Practices such as agroecology, permaculture, and regenerative agriculture can mitigate climate change, protect biodiversity, and ensure a more equitable food system [16]-[18].

In this context, the use of biofertilizers emerges as a promising strategy for promoting sustainable agriculture. Biofertilizers are microorganism-based products that provide essential nutrients to plants, promote soil health, and reduce the need for synthetic fertilizers [19] [20]. These living microorganisms enhance soil fertility and contribute to environmental sustainability [21] [22]. The use of biofertilizers offers numerous benefits, including improved soil fertility through increased availability of essential nutrients [23]-[25], which promotes healthy plant growth [26]-[29]. They also enhance plant nutrition by providing essential micronutrients that improve overall plant health and resilience [23] [30]-[32]. Furthermore, biofertilizers reduce reliance on synthetic fertilizers and pesticides, minimizing soil pollution, water contamination, and biodiversity loss [33] [34]. Ultimately, they can lead to increased crop yields, thereby improving food security [26] [35].

Therefore, biofertilizers offer a promising solution for enhancing soil fertility, plant nutrition, and environmental sustainability in agriculture [19] [36]. This review will explore the different types of biofertilizers, their mechanisms of action, and their potential applications in sustainable agriculture.

## 2. Types of Biofertilizers and Their Applications

Biofertilizers can be classified into several types based on their composition, mode of action, and applications [22] [37]. The main types of biofertilizers include mycorrhizal fungi, rhizobia, compost [38] phosphorus-solubilizing bacteria, and Azotobacter. Each type plays a unique role in enhancing soil fertility and plant growth, contributing significantly to sustainable agricultural practices.

## 2.1. Mycorrhizal Fungi

Mycorrhizal fungi are symbiotic organisms that form associations with plant roots, significantly enhancing nutrient uptake and promoting plant growth [39]-[42]. These fungi extend the root system through their hyphae, allowing plants to access water and nutrients that are otherwise unavailable. Their applications are diverse; in forestry, mycorrhizal fungi improve tree growth, enhance nutrient uptake, and increase drought tolerance [43]-[46]. In agricultural settings, they can boost crop yields, enhance nutrient uptake, and reduce soil erosion, which is particularly beneficial in areas prone to degradation [47]-[49]. Additionally, in horticulture, mycorrhizal fungi promote overall plant health, improve nutrient uptake [42] [50], and enhance flower and fruit production, making them valuable for commercial growers [51]-[54].

## 2.2. Rhizobia

Rhizobia are another critical type of biofertilizer, consisting of symbiotic bacteria that establish relationships with legume plants to convert atmospheric nitrogen into a biologically usable form [50] [55]-[57]. This nitrogen fixation process is vital for enhancing soil fertility, as it enriches the soil with nitrogen that can be utilized by subsequent crops. The applications of rhizobia are especially important for legume crops, where they enhance nitrogen fixation, improve plant growth, and increase crop yields [58]-[60]. Furthermore, rhizobia contribute to soil fertility improvement by enhancing nutrient cycling and reducing soil degradation, which is crucial for maintaining healthy ecosystems [61]-[63].

## 2.3. Compost

Compost, a mixture of decomposed organic matter, contains a diverse range of microorganisms that contribute to soil health [64]-[66]. Its applications are particularly significant in organic farming, where compost enhances soil fertility, promotes nutrient cycling, and reduces soil degradation [67]-[69]. Composting also plays a vital role in waste management by reducing waste disposal costs, minimizing environmental pollution, and producing a valuable nutrient-rich soil amendment that supports plant growth [70]-[72].

## 2.4. Phosphorus-Solubilizing Bacteria

Phosphorus-solubilizing bacteria (PSB) are another important category of biofertilizers. These bacteria can solubilize inorganic phosphorus from soil minerals, making it available for plant uptake [73] [74]. By improving phosphorus availability, PSB play a crucial role in supporting plant growth and enhancing crop yields, particularly in phosphorus-deficient soils [75] [76].

## 2.5. Azotobacter

Azotobacter, a genus of free-living nitrogen-fixing bacteria, also contributes to soil fertility by fixing atmospheric nitrogen and making it available to plants [77]

[78]. These bacteria are suitable for a wide range of crops and can improve plant growth and yield by enhancing nutrient availability in the soil [79].

Collectively, these biofertilizers offer a range of benefits for sustainable agriculture, forestry, and horticultural practices [19] [80] [81]. By understanding the unique roles and applications of each type, we can promote their adoption and contribute to a more sustainable food system that meets the needs of a growing population while preserving environmental health.

Biofertilizers are living microorganisms that, when applied to soil or plants, promote plant growth, enhance soil fertility, and contribute to environmental sustainability. These microorganisms encompass a range of beneficial organisms, including bacteria, fungi, and algae, which interact with plants and the soil ecosystem [82] [83]. Understanding the various types of biofertilizers and their mechanisms of action can enhance soil fertility, improve plant nutrition, and promote environmental sustainability.

### 3. Molecular and Biochemical Processes Involved in Biofertilizer-Plant Interactions

The interactions between biofertilizers and plants involve complex molecular and biochemical processes that promote plant growth and development. Biofertilizers, which contain beneficial microorganisms such as bacteria and fungi, interact with plants through various mechanisms, including symbiotic relationships, hormone regulation, and nutrient uptake [25] [84] [85]. One primary mechanism of interaction is through symbiotic relationships. For example, Rhizobia form nodules on legume roots and fix atmospheric nitrogen into a usable form for the plant. This relationship involves a complex exchange of signals, including flavonoids released by the plant, which induce the production of nodulation factors by the bacteria, triggering nodule formation [86]-[89]. Biofertilizers also influence plant growth through hormone regulation. Certain bacteria, such as *Azospirillum*, produce plant growth-promoting hormones, including auxins and cytokinins. These hormones regulate various aspects of plant growth, such as cell elongation and division, which are crucial for root and shoot development [90]-[92]. Additionally, biofertilizers enhance nutrient uptake in plants. Mycorrhizal fungi, for example, form symbiotic relationships with plant roots, increasing the uptake of phosphorus and other nutrients. These fungi produce enzymes that break down complex nutrients, making them more accessible to the plant in exchange for carbohydrates produced during photosynthesis [93]-[95]. Several specific pathways and mechanisms are involved in biofertilizer-plant interactions. The nitrogen fixation pathway involves the enzyme nitrogenase, which converts atmospheric nitrogen into ammonia, a process that is energy-intensive and requires a microaerobic environment [96]. The phosphate solubilization pathway includes the production of phosphatases, which break down organic phosphorus compounds into inorganic phosphate available for plant use [97] [98]. Hormone production pathways involve the biosynthesis of plant growth-promoting hormones, such as auxins and cytokinins, oc-

curing through complex pathways regulated by various environmental and developmental cues [99] [100]. The molecular and biochemical processes involved in biofertilizer-plant interactions offer several benefits for plant growth and development, including enhanced nutrient uptake and utilization, promoted root growth and development, increased shoot growth, improved stress tolerance, and enhanced plant defense against pathogens. In summary, understanding these processes can provide valuable insights into how biofertilizers promote plant growth and development. By elucidating these specific pathways and mechanisms, researchers can develop more effective biofertilizers that support sustainable agricultural practices [101] [102].

#### **4. Benefits of Biofertilizers**

Biofertilizers offer numerous benefits to agriculture, the environment, and human well-being, including improved soil fertility and structure, enhanced plant nutrition and growth, increased crop yields and quality, and various environmental advantages [27] [103]. They contribute to increased nutrient availability by solubilizing phosphorus, fixing nitrogen, and mobilizing other essential nutrients, thereby making them accessible to plants [26] [104] [105]. Additionally, biofertilizers improve soil structure by enhancing soil aggregation, aeration, and water-holding capacity, all of which lead to better overall soil health [106] [107]. They also promote the growth of beneficial microorganisms in the soil, which further improves soil fertility and ecosystem services [26] [108].

In terms of plant nutrition and growth, biofertilizers enhance nutrient uptake, which supports plant development and overall health [26] [109]. They produce plant growth-promoting substances that improve plant health and increase resistance to diseases [110]. Furthermore, biofertilizers help plants tolerate abiotic stressors such as drought, heat, and cold [21] [111].

Biofertilizers also contribute to increased crop yields and quality. They can enhance crop yields by improving plant nutrition and health [26] [112]. Additionally, they improve crop quality by increasing essential nutrient content while reducing toxic substances [26] [105].

From an environmental perspective, biofertilizers can significantly reduce the reliance on chemical fertilizers, which in turn lessens soil pollution and water contamination [33] [113] [114]. They promote soil carbon sequestration, leading to reduced greenhouse gas emissions and enhanced soil fertility [115]-[117]. Moreover, biofertilizers support the growth of beneficial microorganisms, thereby promoting biodiversity within the soil ecosystem [26] [37] [118].

Overall, biofertilizers present a promising solution for enhancing soil fertility, improving plant nutrition, and promoting environmental sustainability in agriculture.

#### **5. Forest Ecology and Environmental Sustainability**

Forest ecosystems are critical components of the global environment, providing

essential ecological services such as carbon sequestration, biodiversity conservation, and soil and water regulation [119]-[121]. However, these ecosystems face increasing threats from deforestation, climate change, and unsustainable land management practices [104] [122]. In this context, biofertilizers emerge as a promising tool for promoting forest health and resilience, contributing to overall environmental sustainability [80] [123].

One of the key benefits of biofertilizers in forest ecosystems is their role in enhancing carbon sequestration [123] [124]. As trees and plants grow, they absorb carbon dioxide from the atmosphere and store it in their biomass and soil [125] [126]. By promoting robust plant growth, biofertilizers ensure that more carbon is sequestered and stored within the forest ecosystem [115] [124]. Utilizing extremophilic microorganisms enhances forest carbon sequestration [127]-[129] by altering the rhizosphere, improving nutrient cycling, and increasing stress tolerance in trees [127] [130] [131].

Biofertilizers also play a crucial role in promoting biodiversity conservation within forest ecosystems [132]. By supporting sustainable growth processes, these microorganisms help maintain diverse plant species, which, in turn, support various forms of wildlife dependent on specific plants for food and habitat [133]. Mycorrhizal fungi, for instance, are essential for nutrient cycling and overall forest vitality, suggesting that their preservation should be a key component of forest management practices [134]-[136].

Furthermore, biofertilizers contribute to soil rehabilitation in degraded forest lands by accelerating sapling growth [133] [137] and ensuring the success of tree plantation programs critical for combating deforestation and climate change [133] [138]. The application of biofertilizers can increase biological activity indicators, stimulating self-seeding and aiding forest regeneration [139] [140].

Despite their potential, challenges exist in the effective application of biofertilizers within forest ecosystems. The effectiveness of biofertilizers can vary depending on climate, soil type, and the presence of native microbial communities [141] [142]. A holistic approach to biofertilizer research and development is necessary, considering the intricate interactions among microorganisms, plants, and their environments [105] [143].

Future research should focus on understanding the complex interactions among microorganisms, plants, and the environment, including studies on plant microbiomes [144]-[146]. Additionally, high-throughput methods for identifying and characterizing novel microbial strains and consortia are needed [147] [148]. Conducting field tests of biofertilizers across diverse environments is essential to evaluate their efficacy and sustainability [149] [150].

In summary, biofertilizers offer a promising approach for enhancing forest ecology and promoting environmental sustainability. By improving carbon sequestration [151] [152], conserving biodiversity, and rehabilitating degraded lands, biofertilizers can contribute to the long-term health and resilience of forest ecosystems. Addressing the challenges and limitations associated with their use, along

with continued research and development, is crucial for realizing their full potential.

## 6. Case Studies and Examples of Practical Applications of Biofertilizers

Researchers have developed a *Rhizobia* inoculant containing *Bradyrhizobium japonicum*, which promotes nitrogen fixation in soybeans and has been shown to increase soybean yields by up to 20% [153]. In Brazil, over 90% of soybean farmers now use this inoculant, leading to improved crop yields and reduced reliance on synthetic nitrogen fertilizers, resulting in cost savings and a lower environmental impact [154] [155]. Additionally, a mycorrhizal fungus-based biofertilizer featuring *Glomus intraradices* has been developed to enhance phosphorus uptake in crops, increasing yields by up to 30% while decreasing the need for synthetic phosphorus fertilizers [156] [157]. Small-scale farmers in Kenya have adopted this biofertilizer, resulting in improved productivity and a reduced environmental footprint [47] [158]. Furthermore, an inoculant containing *Azospirillum brasilense* has been developed to enhance maize growth, increasing yields by up to 25%. Its use has become widespread in Mexico, where farmers report improved yields and lower fertilizer costs [159]-[161]. Studies indicate significant agronomic benefits under various conditions [162] [163]. Biofertilizers positively affect various crops, enhancing nitrogen fixation in legumes such as *Rhizobia* and *Bradyrhizobium*, which leads to improved yields and reduced fertilizer costs [164]. In cereals, biofertilizers like *Azospirillum* and *Azotobacter* promote growth, resulting in better yields and lower fertilizer expenditures [92] [165]. Mycorrhizal fungi also enhance phosphorus uptake in fruits and vegetables, improving yields [166] [167]. Moreover, biofertilizers contribute positively to broader farming systems by providing a natural alternative to synthetic fertilizers, which is essential in organic farming [168] [169], and promoting soil health and reducing erosion in conservation agriculture [170] [171]. Many small-scale farmers utilize biofertilizers to boost crop yields and lower fertilizer costs, thereby enhancing livelihoods and food security [15] [172] [173]. The use of biofertilizers offers numerous benefits, including significantly improved crop yields [28] [174], reduced reliance on synthetic fertilizers leading to cost savings for farmers [114] [175] [176], environmental benefits that mitigate the impact of synthetic fertilizers and support sustainable agricultural practices [19] [177], and improved soil health through better structure and fertility. In sum, biofertilizers positively influence crop yields, farming systems, and the environment, and their adoption is likely to play an increasingly crucial role in promoting sustainable agriculture and ensuring food security as global food demand rises.

## 7. Challenges and Limitations of Biofertilizers

While biofertilizers offer numerous benefits for sustainable agriculture, several challenges and limitations must be addressed [19] [177]. One significant challenge

is the availability and accessibility of biofertilizers. Production and distribution are often limited, making these products inaccessible to many farmers [178]-[180]. Additionally, biofertilizers can be more expensive than chemical fertilizers, which makes them less attractive to farmers who are budget-conscious [180]-[182]. A lack of awareness regarding the benefits and availability of biofertilizers further exacerbates this issue, as many farmers remain uninformed about their potential advantages [183] [184].

Another challenge lies in the standardization and quality control of biofertilizer products. The quality of biofertilizers can vary widely depending on the production process and the ingredients used [185]-[188]. There is also a pressing need for standardized protocols for biofertilizer production, testing, and labeling to ensure consistency and reliability [189] [190]. Furthermore, contamination risks exist, as biofertilizers can be contaminated with pathogens or other microorganisms that may harm plants or pose risks to human health [37] [82] [191].

The integration of biofertilizers with conventional farming practices presents additional challenges. Compatibility issues may arise, as biofertilizers might not work well alongside chemical fertilizers, necessitating separate application and management strategies [82] [192] [193]. The adoption of biofertilizers may also require changes in farming practices, such as reduced tillage or altered irrigation schedules [194]-[196]. Moreover, many farmers lack access to extension services that can provide guidance on the use of biofertilizers and their integration with conventional practices [6] [149].

Addressing these challenges and limitations is crucial for promoting the adoption of biofertilizers and realizing their potential benefits for sustainable agriculture.

## **8. Highlights of Research Gaps and the Need for Improved Biofertilizer Research and Development**

The development of biofertilizers has gained significant attention in recent years due to their potential to promote sustainable agriculture and reduce the environmental impact of chemical fertilizers [19] [21]. However, despite the growing interest, substantial research gaps remain that need to be addressed to realize the potential of biofertilizers fully.

One major gap is the lack of understanding of the complex interactions among microorganisms, plants, and the environment [144]. Most studies have primarily focused on the individual effects of specific microorganisms on plant growth, while the interactions among multiple microorganisms and the plant microbiome as a whole are not well understood. Further research is necessary to elucidate the mechanisms by which microorganisms interact with plants and the environment, optimizing these interactions for improved crop yields and sustainability [25].

Another critical research gap is the limited exploration of novel microbial strains and consortia that can serve as biofertilizers. Although some microorganisms like *Rhizobia* and *Azospirillum* have been extensively studied, many others with po-

tential benefits for plant growth remain unexplored. Identifying and characterizing these novel microbial strains and consortia is essential for developing effective biofertilizers [82].

Additionally, there is a need for more versatile biofertilizers that can be applied across a wide range of agricultural systems and environments. Most current formulations are designed for specific crops or conditions [110]. A holistic approach to biofertilizer research and development is necessary, considering the intricate interactions among microorganisms, plants, and their environments [105] [143].

To address these research gaps, a multidisciplinary approach should be adopted. This approach should integrate microbiology, ecology, plant physiology, and agronomy, focusing on:

- *Microbiome Analysis*: Studying plant microbiomes and the interactions among microorganisms, plants, and the environment [145] [146].
- *High-Throughput Screening*: Utilizing high-throughput methods to identify and characterize novel microbial strains and consortia [147] [148].
- *Formulation Development*: Creating more effective formulations and application methods for biofertilizers [188].
- *Field Testing*: Conducting field tests of biofertilizers in diverse environments to evaluate their efficacy and sustainability [149] [150].
- *Collaboration and Knowledge Sharing*: Promoting collaboration and knowledge sharing between researchers, farmers, and industry stakeholders to enhance the development and adoption of biofertilizers.

By adopting this multidisciplinary approach, we can unlock the full potential of biofertilizers and promote sustainable agricultural practices that significantly reduce the environmental impacts associated with chemical fertilizers.

## 9. Future Perspectives and Research Directions

As the world faces the challenges of sustainable agriculture, biofertilizers are positioned to play an increasingly vital role [33]. However, several key challenges must be addressed to fully realize their potential. One significant area of focus is scaling up biofertilizer production and use. Developing cost-effective and scalable production methods is essential to meet the growing demand for biofertilizers [144]. Additionally, improving distribution and marketing channels will be critical for making biofertilizers widely accessible to farmers [131] [178]. Enhancing farmer adoption through training, education, and support is also vital to promote the use of biofertilizers [178].

Another important aspect is integrating biofertilizers with other sustainable agriculture practices. For instance, combining biofertilizers with agroecological practices, such as crop rotation and conservation tillage, can enhance their effectiveness and support more sustainable agricultural systems. In organic farming systems, where synthetic fertilizers are prohibited, biofertilizers can play a crucial role. Furthermore, integrating biofertilizers with precision agriculture techniques, such as precision application and monitoring, can optimize their use and reduce

waste.

Research also plays a crucial role in the future of biofertilizers. Understanding the mechanisms by which biofertilizers interact with plants and the soil ecosystem requires further investigation [26] [196]. Additionally, enhancing the efficacy and consistency of biofertilizers through the development of more effective strains and application methods is essential [142] [144] [197] [198]. Addressing scalability and cost issues by developing cost-effective and scalable production methods, as well as improving distribution and marketing, is also vital [144].

By tackling these research needs and challenges, we can unlock the full potential of biofertilizers and promote more sustainable, equitable, and productive agricultural systems.

## 10. Critical Analysis of the Literature

The use of biofertilizers has gained significant attention in recent years due to their potential to promote sustainable agricultural practices and reduce the environmental impact of synthetic fertilizers. A comprehensive analysis of the existing literature reveals that biofertilizers positively impact crop yields, soil health, and the environment. However, several areas of disagreement and limitations in current research warrant further exploration. The literature presents several points of consensus regarding the benefits of biofertilizers. Firstly, biofertilizers promote plant growth and development, resulting in improved crop yields [199] [200]. Secondly, they can reduce reliance on synthetic fertilizers, leading to cost savings for farmers and a diminished environmental impact [21] [201]. Lastly, biofertilizers enhance soil health by improving soil structure and fertility [202]. Despite these acknowledged benefits, there are notable disagreements within the literature. One contentious issue is the effectiveness of different types of biofertilizers; some studies indicate that Rhizobia inoculants outperform *Azospirillum* inoculants in promoting nitrogen fixation in legumes [203]-[205], while others report the opposite. Additionally, the impact of biofertilizers on soil microbial communities is debated; some research shows that biofertilizers can alter these communities, affecting soil ecosystem functioning [206] [207], while other studies find no significant impact [208]. Current research on biofertilizers has several limitations that need to be addressed. Firstly, many studies focus on short-term effects, with few examining the long-term impacts on soil health and crop yields [84] [209]. Secondly, there is a lack of standardization in methods used to evaluate biofertilizer effectiveness, complicating comparisons across studies [25] [210]. Finally, much of the research has been conducted in controlled environments, with limited studies assessing biofertilizer effectiveness in real-world agricultural settings. To address these limitations, several future research directions can be proposed. Long-term studies are essential to evaluate the impacts of biofertilizers on soil health and crop yields over multiple growing seasons. Additionally, developing standardized evaluation methods will facilitate more accurate comparisons across studies. More field-based research is needed to assess biofertilizer effectiveness in practical agricultural contexts. Un-

derstanding the mechanisms by which biofertilizers interact with soil microbial communities is also crucial, alongside the development of more effective biofertilizer formulations. The literature thus indicates that biofertilizers hold promise for promoting sustainable agricultural practices and mitigating the environmental impact of synthetic fertilizers. However, ongoing disagreements and limitations in current research necessitate further investigation. Future research should prioritize long-term studies, standardized methodologies, and field-based evaluations to deepen our understanding of biofertilizers, ultimately contributing to more effective and sustainable agricultural practices. Based on the analysis of the literature, several recommendations are proposed: conduct long-term studies to assess the impacts of biofertilizers on soil health and crop yields over multiple growing seasons; develop standardized methods for evaluating biofertilizers, enhancing comparability across studies; increase the number of field-based studies to evaluate biofertilizer effectiveness in real-world agricultural settings; investigate the mechanisms through which biofertilizers interact with soil microbial communities; and focus on developing more effective biofertilizer formulations suitable for a diverse array of agricultural environments. By following these recommendations, we can advance our understanding of biofertilizers and foster the development of more effective and sustainable agricultural practices that enhance soil health, crop productivity, and environmental sustainability.

## 11. Conclusions

Biofertilizers represent a promising solution for enhancing soil fertility, improving plant nutrition, and fostering environmental sustainability within agricultural systems. They provide essential nutrients, promote soil health, and reduce reliance on synthetic fertilizers, addressing the pressing challenges posed by a growing global population and the environmental degradation associated with conventional farming practices [19] [36]. The diverse benefits of biofertilizers include improved crop yields, enhanced nutrient availability, and better soil structure, which collectively contribute to healthier ecosystems and agricultural sustainability [23] [26].

However, to fully leverage the potential of biofertilizers, significant barriers must be overcome. These include enhancing awareness among farmers, ensuring the affordability and accessibility of biofertilizers, and addressing the need for standardization and quality control in biofertilizer production [19] [178]. Furthermore, ongoing research is essential to elucidate the mechanisms through which biofertilizers interact with soil and plants, as well as to develop more effective formulations suited to various agricultural contexts [25] [144].

Promoting the adoption of biofertilizers requires collaborative efforts involving farmers, researchers, and policymakers to facilitate education and support systems that encourage sustainable practices (Adnan *et al.*, 2018; [36]). By prioritizing biofertilizers in agricultural strategies, we can pave the way for a more sustainable and productive food system that meets the demands of a growing population while

preserving environmental health for future generations [2] [19].

Moreover, integrating biofertilizers within the broader context of forest ecology enhances ecosystem resilience and biodiversity. Healthy soils foster robust plant growth, which in turn supports diverse wildlife habitats and mitigates climate change impacts. By embracing practices that value both agricultural productivity and forest health, we can create interconnected landscapes that promote ecological balance and sustainability—ensuring that our agricultural systems thrive alongside thriving ecosystems for generations to come.

## Conflicts of Interest

The authors declare no conflicts of interest.

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