Biofertilizers in sustainable and organic agriculture: implications for soil health, environmental sustainability and future perspectives

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Abstract. Biofertilizers have emerged as promising tools for supporting sustainable and organic agriculture by improving nutrient availability, enhancing soil fertility, and promoting plant growth through natural biological processes. Increasing concerns regarding the environmental impacts of synthetic fertilizers have intensified interest in biological alternatives capable of maintaining agricultural productivity while reducing ecological pressures. This review examines the role of biofertilizers in sustainable agricultural systems, focusing on their classification, mechanisms of action, and contributions to soil health and environmental sustainability. The analysis highlights the ability of biofertilizers to improve nutrient cycling, stimulate beneficial microbial activity, enhance soil biodiversity, and reduce dependence on chemical fertilizers. Their application may contribute to water quality protection, pollution reduction, and the preservation of ecosystem services essential for long-term agricultural productivity. In addition, the review discusses the challenges associated with biofertilizer use, including variable field performance, formulation stability, regulatory constraints, and farmer adoption. Recent advances in microbial biotechnology, microbiome research, and precision agriculture have created new opportunities for improving biofertilizer effectiveness and expanding their agricultural applications. Overall, biofertilizers represent an important component of environmentally responsible farming systems and may play a significant role in the transition toward more sustainable and resilient agricultural practices.
Keywords: biofertilizers, sustainable agriculture, organic agriculture, soil health, environmental sustainability.

Introduction. Agricultural systems are increasingly challenged to ensure food security while reducing the environmental impacts associated with intensive farming practices. Although synthetic fertilizers have significantly improved crop productivity, their excessive use has contributed to soil degradation, nutrient imbalance, water contamination, eutrophication, and greenhouse gas emissions. These concerns have intensified the search for sustainable alternatives capable of maintaining agricultural productivity while preserving environmental quality (Daniel et al., 2022; Khan et al., 2024).

Biofertilizers have emerged as an important component of sustainable and organic agriculture due to their ability to improve nutrient availability and plant growth through natural biological processes. They generally contain beneficial microorganisms capable of biological nitrogen fixation, phosphorus solubilization, nutrient mobilization, and the production of plant growth-promoting substances. As a result, biofertilizers may reduce dependence on chemical fertilizers while supporting soil fertility, crop productivity, and environmentally responsible agricultural practices (Ammar et al., 2023; Daniel et al., 2022; Prisa et al., 2023).

The growing interest in sustainable agriculture has increased the adoption of biofertilizers as eco-friendly tools for improving soil quality and promoting long-term agricultural sustainability. Their application is consistent with the principles of organic farming and climate-smart agriculture, where maintaining soil health and reducing environmental pressures are considered essential objectives. However, despite their considerable potential, challenges related to field performance variability, formulation stability, and large-scale adoption continue to limit their widespread use (Pirttilä et al., 2021; Shahzad et al., 2025).

Therefore, a comprehensive understanding of the benefits, limitations, and future potential of biofertilizers is necessary to support their effective integration into modern agricultural systems. This review examines the role of biofertilizers in sustainable and organic agriculture, with particular emphasis on their implications for soil health, environmental sustainability, current challenges, and future development perspectives.

Literature Review Methodology. This review was conducted through a comprehensive analysis of scientific literature addressing the role of biofertilizers in sustainable and organic agriculture. Relevant publications were identified using several scientific databases, including Google Scholar, PubMed, ScienceDirect, Frontiers, MDPI, and PubMed Central.

The literature search focused on studies published between 2017 and 2025, using combinations of keywords such as "biofertilizers", "microbial inoculants", "plant growth-promoting rhizobacteria", "PGPR", "soil health", "soil microbiome", "organic agriculture", "sustainable agriculture", "environmental sustainability", and "biofertilizer applications". Additional references were identified through the bibliographies of selected articles.

The inclusion criteria considered peer-reviewed review articles and original research papers that provided information on the classification, mechanisms of action, agricultural applications, environmental implications, challenges, and future perspectives of biofertilizers. Priority was given to recent publications, open-access studies, and articles published in internationally recognized scientific journals.

A total of 19 scientific publications were selected and analyzed. The collected information was organized thematically to facilitate the discussion of biofertilizer classification, mechanisms of action, contributions to soil health, environmental sustainability, current limitations, and future research directions. Rather than presenting individual study summaries, the selected literature was critically synthesized to provide an integrated overview of the current state of knowledge regarding biofertilizers and their role in sustainable agricultural systems.

Biofertilizers: Definition, Classification and Mechanisms of Action. Biofertilizers are biological products containing living microorganisms or biologically active substances that enhance nutrient availability and promote plant growth through natural biological processes. Unlike synthetic fertilizers, which directly supply nutrients to crops, biofertilizers improve soil fertility by stimulating microbial activity, nutrient cycling, and plant–microbe interactions. Consequently, they are increasingly recognized as environmentally friendly alternatives that support sustainable and organic agricultural systems (Daniel et al., 2022; Ammar et al., 2023).

These comprise a diverse group of beneficial organisms that contribute to plant nutrition and soil health. Based on their biological characteristics and primary functions, they can be broadly classified into nitrogen-fixing microorganisms, phosphate-solubilizing microorganisms, potassium-mobilizing microorganisms, mycorrhizal fungi, plant growth-promoting rhizobacteria (PGPR), and microbial consortia. Nitrogen-fixing microorganisms, such as species of *Rhizobium*, *Azotobacter*, and *Azospirillum*, convert atmospheric nitrogen into forms available to plants. Phosphate-solubilizing and potassium-mobilizing microorganisms increase nutrient availability by transforming insoluble compounds into accessible forms, while mycorrhizal fungi improve nutrient and water uptake through symbiotic associations with plant roots. In addition, PGPR and microbial consortia provide multiple agronomic benefits by combining several growth-promoting mechanisms within a single biological product (Pirttilä et al., 2021; Shahwar et al., 2023; dos Reis et al., 2024).

Biofertilizers promote plant growth through several complementary mechanisms that improve nutrient availability, plant development, and soil biological activity. One of the most important processes is biological nitrogen fixation, whereby specific microorganisms convert atmospheric nitrogen into forms that can be utilized by plants. Other microorganisms contribute to phosphorus solubilization and potassium mobilization, thereby increasing the availability of essential nutrients that are often present in soils in inaccessible forms (Prisa et al., 2023; de Andrade et al., 2023)(Table 1, Figure 1).

Table 1

Classification of biofertilizers and their principal functions

Biofertilizer group	*Representative microorganisms*	*Main function*
Nitrogen-fixing microorganisms	*Rhizobium*, *Azotobacter*, *Azospirillum*	Biological nitrogen fixation
Phosphate-solubilizing microorganisms	*Bacillus*, *Pseudomonas* spp.	Increase phosphorus availability
Potassium-mobilizing microorganisms	*Bacillus* spp.	Improve nutrient and water uptake
Mycorrhizal fungi	*Glomus* spp.	Improve nutrient and water uptake
PGPR	Various bacterial species	Plant growth promotion and stress tolerance
Microbial consortia	Mixed microbial inoculants	Multiple agronomic functions

Source: Adapted from Ammar et al. (2023), Shahwar et al. (2023), and dos Reis et al. (2024).

In addition to nutrient mobilization, many beneficial microorganisms produce plant growth-promoting substances, including auxins, gibberellins, and cytokinins, which stimulate root development and enhance nutrient uptake. Several microbial species also produce siderophores that improve micronutrient acquisition and support plant growth under nutrient-limited conditions. Furthermore, biofertilizers can enhance plant tolerance to environmental stresses and contribute to the maintenance of a biologically active soil environment (Aloo et al., 2022; Shahwar et al., 2023).

Recent advances in agricultural microbiology have encouraged the development of microbial consortia that combine different groups of beneficial microorganisms to achieve multiple functions simultaneously. Such approaches may improve biofertilizer effectiveness and represent an important strategy for reducing dependence on synthetic fertilizers while supporting sustainable agricultural production systems (Díaz-Rodríguez et al., 2025; Sabater et al., 2025).

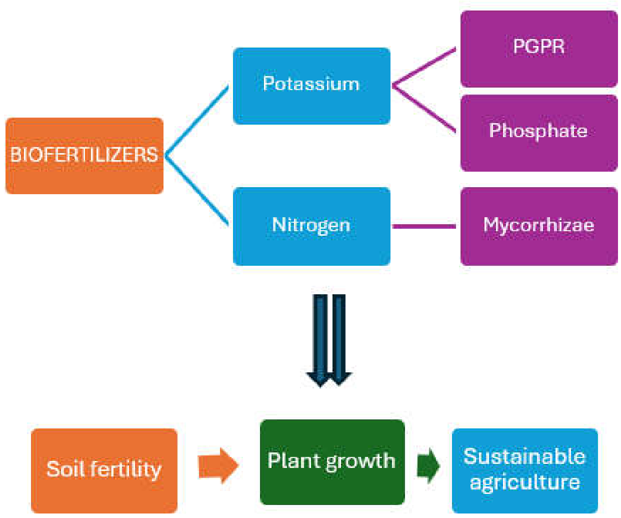

Figure 1. Classification and mechanisms of action of biofertilizers. Source: based on Daniel et al. (2022), Ammar et al. (2023), Shahwar et al. (2023), and Prisa et al. (2023).

Soil Health and Microbiome Restoration*.* Soil fertility is a fundamental component of sustainable agricultural systems, directly influencing crop productivity and ecosystem stability. The long-term application of synthetic fertilizers may increase nutrient availability in the short term; however, excessive use has often been associated with soil degradation, nutrient imbalances, and a decline in biological activity. In contrast, biofertilizers improve soil fertility through natural biological processes that enhance nutrient cycling and increase the availability of essential elements for plant growth (Daniel et al., 2022; Khan et al., 2024).

Beneficial microorganisms present in biofertilizers contribute to soil fertility by fixing atmospheric nitrogen, solubilizing phosphorus, mobilizing potassium, and producing plant growth-promoting substances. These processes improve nutrient use efficiency and support plant development without the environmental burdens commonly associated with chemical fertilizers. In addition, biofertilizers contribute to the gradual improvement of soil structure and biological activity, creating conditions that favor sustainable crop production (Prisa et al., 2023; Shahwar et al., 2023).

The soil microbiome plays a crucial role in maintaining soil health and ecosystem functioning. Diverse microbial communities participate in nutrient cycling, organic matter decomposition, disease suppression, and the regulation of plant–soil interactions. Agricultural intensification and excessive agrochemical inputs may disrupt these communities, leading to reduced soil resilience and biodiversity (Suman et al., 2022).

Biofertilizers support the restoration and maintenance of beneficial microbial populations by enhancing microbial diversity and promoting positive interactions within the rhizosphere. The introduction of beneficial bacteria, fungi, and microbial consortia can improve soil biological activity and strengthen ecological processes that contribute to sustainable agricultural production. Consequently, biofertilizer application is increasingly considered an effective strategy for preserving soil biodiversity while improving soil functionality (Shaaban et al., 2025; Sabater et al., 2025).

One of the main advantages of biofertilizers is their potential to reduce dependence on synthetic fertilizers. By improving nutrient availability and enhancing nutrient uptake efficiency, biofertilizers can partially replace conventional fertilizers while maintaining crop productivity. Reduced chemical fertilizer inputs may decrease nutrient losses, lower production costs, and minimize adverse environmental impacts associated with fertilizer overuse (Ammar et al., 2023; Shahzad et al., 2025).

Although biofertilizers are not intended to completely replace mineral fertilizers under all agricultural conditions, their integration into sustainable and organic farming systems represents an important approach for improving resource-use efficiency and supporting long-term soil health. Their combined use with other sustainable agricultural practices may contribute to the development of more resilient and environmentally responsible production systems (Khan et al., 2024; Díaz-Rodríguez et al., 2025).

Biofertilizers in Organic Agriculture and Environmental Sustainability*.* The excessive application of synthetic fertilizers is one of the major causes of nutrient losses to aquatic ecosystems, frequently resulting in water contamination and eutrophication. Nitrogen and phosphorus runoff from agricultural fields can negatively affect freshwater quality, aquatic biodiversity, and ecosystem functioning. By improving nutrient use efficiency and reducing the need for high fertilizer inputs, biofertilizers may contribute to lower nutrient losses and support the protection of water resources (Ammar et al., 2023; Khan et al., 2024).

Biofertilizers are increasingly recognized as environmentally friendly alternatives to conventional fertilizers because they reduce the dependence on synthetic agrochemicals. Their application may decrease the accumulation of chemical residues in soils and reduce the environmental pressures associated with fertilizer production, transportation, and intensive use. Furthermore, the replacement of part of the chemical fertilizer input with biological alternatives may contribute to reducing greenhouse gas emissions associated with agricultural activities (Ammar et al., 2023; Shaaban et al., 2025).

The environmental benefits of biofertilizers extend beyond nutrient management. By promoting biological processes and improving soil functionality, they contribute to more sustainable nutrient cycling and support agricultural systems that are less dependent on external chemical inputs. These characteristics are consistent with the principles of organic agriculture and climate-smart farming strategies (Khan et al., 2024; Sabater et al., 2025).

Agricultural sustainability depends not only on crop productivity but also on the maintenance of ecosystem services that support long-term environmental stability. Soil microorganisms play a key role in nutrient cycling, organic matter decomposition, soil structure formation, and plant health. The use of biofertilizers may enhance these ecological functions by promoting beneficial microbial communities and increasing biological activity within the soil environment (Suman et al., 2022; Sabater et al., 2025). By supporting soil biodiversity and improving plant–microbe interactions, biofertilizers contribute to the resilience of agroecosystems and help maintain ecological processes essential for sustainable crop production. Their integration into agricultural management practices may therefore provide benefits that extend beyond yield improvement, including biodiversity conservation and ecosystem stability (Shaaban et al., 2025; Pirttilä et al., 2021).

Despite their numerous advantages, biofertilizers should not be regarded as entirely risk-free. The introduction of non-native microbial strains may alter existing microbial communities and potentially affect ecological interactions within the soil ecosystem. In addition, environmental factors such as soil type, climate conditions, and agricultural management practices can influence the effectiveness and ecological behavior of introduced microorganisms (Pirttilä et al., 2021; Díaz-Rodríguez et al., 2025).

Current evidence suggests that the ecological risks associated with biofertilizers are generally lower than those linked to intensive chemical fertilizer use. Nevertheless, further research is required to better understand the long-term ecological consequences of large-scale biofertilizer application and to ensure their safe integration into sustainable agricultural systems (Shahzad et al., 2025; dos Reis et al., 2024) (Figure 2).

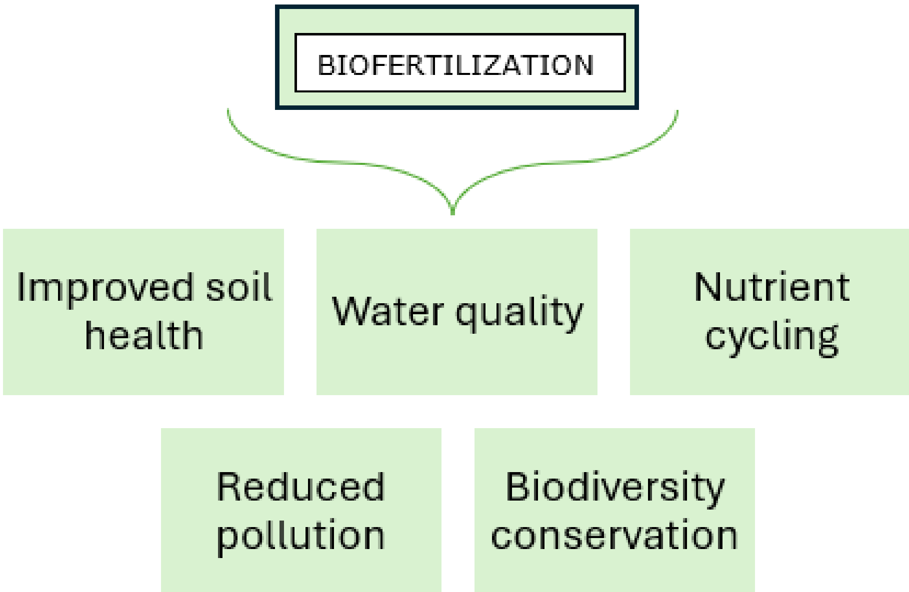

Figure 2. Contribution of biofertilizers to sustainable and organic agriculture. Source: Based on Daniel et al. (2022), Khan et al. (2024), Shaaban et al. (2025), Suman et al. (2022), and Sabater et al. (2025).

Current Challenges and Limitations. One of the major challenges associated with biofertilizer application is the variability of their performance under field conditions. Although many microorganisms demonstrate promising results under laboratory and greenhouse environments, their effectiveness may be influenced by soil properties, climatic conditions, crop species, and agricultural management practices. Consequently, inconsistent performance remains one of the principal obstacles limiting the widespread adoption of biofertilizers in commercial agriculture (Pirttilä et al., 2021; Shahzad et al., 2025).

The viability of microorganisms during storage and transportation represents another important limitation. Biofertilizers contain living organisms whose survival may be affected by temperature, humidity, formulation techniques, and storage conditions. Reduced microbial viability can decrease product effectiveness and limit farmer confidence in biofertilizer-based technologies. Therefore, the development of stable formulations with extended shelf-life remains a priority for both researchers and manufacturers (dos Reis et al., 2024; Díaz-Rodríguez et al., 2025).

The commercialization and large-scale adoption of biofertilizers are also influenced by regulatory frameworks. Differences in product registration procedures, quality standards, and biosafety requirements among countries may complicate the development and distribution of biofertilizer products. Furthermore, the absence of harmonized regulations can create uncertainty for producers and users, slowing the integration of biological alternatives into agricultural systems (Shahzad et al., 2025; Pirttilä et al., 2021).

Despite growing scientific evidence supporting the benefits of biofertilizers, their adoption by farmers remains uneven. Limited awareness, insufficient technical knowledge, concerns regarding product reliability, and the perceived risks associated with replacing conventional fertilizers may discourage implementation. In addition, economic considerations, including production costs and market availability, can influence adoption decisions, particularly in regions where chemical fertilizers remain readily accessible and relatively inexpensive (Samanta et al., 2025; Díaz-Rodríguez et al., 2025) (Table 2).

Table 2

Environmental benefits and limitations of biofertilizers

Environmental benefits	*Current limitations*
Improved soil fertility	Variable field performance
Enhanced nutrient cycling	Limited shelf-life and microbial viability
Reduced dependence on chemical fertilizers	Sensitivity to storage and transport conditions
Reduced environmental pollution	Regulatory and registration barriers
Improved soil microbial diversity	Inconsistent effectiveness under different field conditions
Protection of water resources	Limited farmer awareness and technical knowledge
Support for sustainable and organic agriculture	Economic and market constraints

Source: based on Pirttilä et al. (2021), dos Reis et al. (2024), Shahzad et al. (2025), Samanta et al. (2025), and Díaz-Rodríguez et al. (2025).

Future Perspectives. Recent research has increasingly focused on the development of microbial consortia that combine multiple beneficial microorganisms within a single biofertilizer formulation. Unlike single-strain inoculants, microbial consortia may perform complementary functions, including nutrient mobilization, plant growth promotion, stress mitigation, and disease suppression. Such integrated approaches have the potential to improve biofertilizer effectiveness under diverse environmental conditions and enhance their reliability in agricultural applications (Díaz-Rodríguez et al., 2025; Sabater et al., 2025).

Advances in molecular biology and sequencing technologies have significantly improved the understanding of soil microbial communities. Emerging approaches such as microbiome engineering, metagenomics, transcriptomics, and other omics technologies provide new opportunities to identify beneficial microorganisms and optimize their interactions with crops. These tools may facilitate the development of more efficient biofertilizers tailored to specific environmental conditions and agricultural systems (Pirttilä et al., 2021; dos Reis et al., 2024).

The growing need to adapt agricultural systems to climate change is expected to further increase interest in biofertilizers. Their capacity to improve nutrient use efficiency, support soil health, and reduce dependence on chemical inputs aligns with the objectives of climate-smart agriculture. In addition, the integration of biofertilizers with precision agriculture technologies may improve application efficiency and contribute to more sustainable resource management. Future agricultural strategies will likely combine biological inputs, digital technologies, and advanced soil management practices to enhance productivity while minimizing environmental impacts (Khan et al., 2024; Shaaban et al., 2025).

Overall, continued research, technological innovation, and supportive regulatory frameworks will be essential for expanding the role of biofertilizers in sustainable and organic agriculture. The combination of advances in microbial biotechnology, precision farming, and ecological management is expected to strengthen the contribution of biofertilizers to future agricultural systems.

Conclusions. Biofertilizers represent an important component of sustainable and organic agriculture due to their ability to enhance nutrient availability, improve soil fertility, and support plant growth through natural biological processes. Their application contributes to the maintenance of soil health, promotes beneficial microbial communities, and may reduce dependence on synthetic fertilizers, thereby supporting environmentally responsible agricultural practices.

Beyond their agronomic benefits, biofertilizers can contribute to environmental sustainability by improving nutrient use efficiency, reducing pollution risks, and supporting ecosystem functions essential for long-term agricultural productivity. These characteristics make biofertilizers valuable tools for addressing current challenges related to food production, environmental protection, and sustainable resource management.
However, several limitations continue to influence their large-scale adoption, including variability in field performance, formulation challenges, regulatory constraints, and economic considerations. Addressing these issues will be essential for maximizing the effectiveness and reliability of biofertilizer technologies.

Future advances in microbial biotechnology, microbiome research, and precision agriculture are expected to further expand the role of biofertilizers in agricultural systems. Their integration with sustainable farming practices may contribute to the development of more resilient, productive, and environmentally sustainable agricultural systems capable of meeting future food demands while preserving ecosystem integrity.

Authors Contributions. Robert Raul Papp contributed to all aspects of the work.

Conflicts of Interest. The author declares that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the author upon reasonable request.

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