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The Role of Biofertilizers in Soil Health Improvement and Sustainable Farming: A Comprehensive Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The Role of Biofertilizers in Soil Health Improvement and Sustainable Farming. Biofertilizers have emerged as a promising alternative to chemical fertilizers, contributing to sustainable agriculture by enhancing soil fertility, improving crop productivity, and minimizing environmental degradation. These natural formulations containing beneficial microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, potassium-mobilizing bacteria, and mycorrhizal fungi promote nutrient availability through various mechanisms, including nitrogen fixation, phosphate solubilization, potassium mobilization, and organic matter decomposition. Biofertilizers play a critical role in improving soil microbial diversity, enhancing soil structure, increasing organic matter content, and contributing to carbon sequestration. Despite their numerous advantages, several challenges hinder their widespread adoption, including limited awareness, inconsistent performance under field conditions, and inadequate regulatory frameworks. Variability in biofertilizer effectiveness due to environmental factors, carrier material selection, and poor formulation techniques remain significant barriers to their efficient utilization. Recent advancements in biofertilizer technology, including the development of multi-functional biofertilizers, genetic engineering, and microbial consortia, have shown promising results in improving their efficacy. Integrating biofertilizers with modern agricultural practices, such as precision agriculture, offers new opportunities for enhancing their performance and promoting large-scale adoption. Effective policy support, training programs, and public awareness initiatives are essential for promoting biofertilizer usage among farmers. Future research should focus on enhancing formulation techniques, conducting long-term impact studies on soil health, and establishing standardized guidelines for quality control. Addressing these challenges will ensure the successful implementation of biofertilizer technology, contributing to agricultural sustainability and environmental protection.

Keywords: Biofertilizers; sustainable agriculture; soil health; microbial diversity; precision agriculture; nutrient availability; genetic engineering.

1. INTRODUCTION

A. Sustainable Agriculture

Sustainable agriculture is a holistic approach to farming that seeks to meet present food and fibre demands while ensuring that future generations can fulfil their own needs. This practice emphasizes the judicious use of natural resources, conservation of biodiversity, economic viability, and social equity. According to the Food and Agriculture Organization, sustainable agriculture integrates various management practices aimed at enhancing environmental quality, preserving natural resources, and promoting socioeconomic well-being. Essential principles of sustainable agriculture include crop rotation, reduced dependency on non-renewable resources, organic farming, integrated pest management, and the utilization of natural biofertilizers (Dönmez et al., 2024). Biofertilizer was defined as a substance which contains living microorganisms which, when applied to seed, plant surfaces, or soil, colonizes the rhizosphere or the interior of the plant and promote growth by increasing the supply or availability of primary nutrients to the host plant. The application of biofertilizers in agriculture can effectively increase crop yields and reduce the use of chemical fertilizers. Studies have shown that biofertilizers, when used together with chemical fertilizers, can increase crop yields by 10%–40% and replace nearly 25%–30% of the chemical fertilizers (Zhao et al., 2024; Koushal et al., 2024).

Conventional agricultural practices, characterized by the extensive use of synthetic fertilizers, pesticides, and monoculture cropping systems, have successfully boosted food production worldwide (Crews *et.al.,* 2018). These practices have resulted in significant adverse environmental impacts. Research indicates that excessive chemical fertilizer application has led to soil degradation, water pollution, greenhouse gas emissions, and the loss of biodiversity. Continuous and imbalanced use of chemical fertilizers depletes soil organic matter, causing deterioration of soil structure and declining fertility over time. The contamination of water resources due to nitrate leaching from agricultural fields poses severe health risks, including methemoglobinemia and various chronic conditions. These negative consequences have highlighted the urgent need to explore and adopt environmentally sustainable alternatives that can reduce the dependency on chemical fertilizers while maintaining or improving crop productivity (Wang et al., 2025). The growing awareness of the detrimental effects of conventional farming practices has prompted researchers and policymakers to identify eco-friendly and economically viable solutions (Sekhar *et.al.,* 2024). Among various approaches, the use of biofertilizers has emerged as a promising alternative that aligns with the principles of sustainable agriculture. Biofertilizers contribute to soil health and fertility enhancement through natural biological processes, including nutrient cycling, organic matter decomposition, and beneficial microbial interactions within the soil-plant system. By promoting soil fertility and improving plant growth, biofertilizers offer long-term benefits such as enhanced agroecosystem resilience, reduced input costs, and decreased environmental pollution (Han et al., 2025).

B. Introduction to Biofertilizers

Biofertilizers are defined as natural formulations containing live microorganisms that colonize the rhizosphere or the interior of plants to enhance nutrient availability through biological processes such as nitrogen fixation, phosphate solubilization, and organic matter decomposition (Sahu *et.al.,* 2016). Unlike chemical fertilizers that directly supply nutrients to plants, biofertilizers facilitate nutrient cycling by improving the availability of essential elements in the soil. Their application contributes significantly to soil fertility, plant growth, and overall productivity without causing harmful environmental impacts (Dzvene & Chiduza, 2024). Biofertilizers can be broadly classified based on their functional attributes and the microbial groups involved. Nitrogen-fixing biofertilizers, such as *Rhizobium*, *Azospirillum*, and *Azotobacter*, play a crucial role in converting atmospheric nitrogen into ammonia, making it accessible to plants. Studies have demonstrated that the application of nitrogen-fixing biofertilizers can enhance crop yield by 20-30% compared to chemical fertilizers alone (Suhag, 2016). Phosphate-solubilizing biofertilizers, including *Pseudomonas* and *Bacillus* species, facilitate the release of phosphorus from insoluble compounds, thereby enhancing plant growth and improving soil health (Billah *et.al.,* 2019).

Potassium-mobilizing biofertilizers are another category that involves microorganisms capable of releasing potassium from insoluble minerals, increasing its availability for plant uptake. Mycorrhizal biofertilizers, particularly *Arbuscular Mycorrhizal Fungi (AMF)*, form symbiotic associations with plant roots, significantly enhancing nutrient uptake, especially phosphorus while improving plant tolerance to abiotic stresses such as drought and salinity. Organic matter decomposers, including *Trichoderma* species, are effective in breaking down organic matter, thus promoting soil fertility and improving soil structure through the production of humus and other beneficial organic compounds (Khaliq et al., 2022). The concept of utilizing beneficial microorganisms to enhance plant growth can be traced back to the early 20th century with the discovery of *Rhizobium* and its nitrogen-fixing properties (Rashid *et.al.,* 2015). Early research focused on developing inoculants containing effective *Rhizobium* strains for improving legume crop productivity. Over the years, technological advancements in microbial biotechnology have expanded the scope of biofertilizers to include various microbial groups involved in nutrient cycling, disease suppression, and plant growth promotion.

Recent innovations have led to the development of more efficient biofertilizer formulations, including microbial consortia that combine multiple beneficial microorganisms, liquid formulations that enhance shelf-life and field performance, and improved carrier materials that ensure viability during storage and application. These advancements have made biofertilizers more viable for commercial use and large-scale agricultural practices (Negi et al., 2024). The application of biofertilizers aligns well with the principles of sustainable agriculture by enhancing soil fertility, promoting crop productivity, and reducing the dependency on chemical inputs (Masso *et.al.,* 2015). Research suggests that biofertilizers can improve soil health by enhancing microbial diversity and activity, which are essential for achieving long-term agricultural sustainability. Moreover, their ability to restore soil fertility and promote ecological balance makes them a valuable tool in promoting agroecosystem resilience (Sharma et.al., 2023; Wei et al., 2024).

C. Objective and Scope of the Review

The primary objective of this review is to provide an extensive analysis of the role of biofertilizers in improving soil health and enhancing crop productivity (Bhardwaj *et.al.,* 2014). Emphasis is placed on understanding the mechanisms through which biofertilizers contribute to nutrient cycling, organic matter decomposition, and plant-microbe interactions. By summarizing recent research findings, the review aims to highlight the potential of biofertilizers as a viable alternative to chemical fertilizers in promoting sustainable agricultural practices. This review also seeks to discuss various challenges and limitations associated with biofertilizer application, including factors affecting their efficacy, commercial production, and farmer adoption. Potential solutions and future research directions are suggested to improve the effectiveness of biofertilizers and ensure their widespread utilization in agricultural systems.

2. BIOFERTILIZERS

A. Classification

Biofertilizers are natural substances containing living microorganisms that, when applied to the soil or plant surfaces, promote plant growth by enhancing the availability of essential nutrients (Table 1). Unlike chemical fertilizers that directly provide nutrients, biofertilizers work through biological processes such as nitrogen fixation, phosphate solubilization, potassium mobilization, and organic matter decomposition. They are considered a crucial component of sustainable agriculture, capable of improving soil fertility, crop yield, and environmental quality without contributing to pollution. Biofertilizers can be broadly classified into various categories based on their microbial constituents and functional properties (Nosheen *et.al.,* 2021). The primary categories include nitrogen-fixing biofertilizers, phosphate-solubilizing biofertilizers, potassium-mobilizing biofertilizers, mycorrhizal biofertilizers, and organic matter decomposers.

Nitrogen-fixing Biofertilizers

Nitrogen is a critical nutrient for plant growth, but its availability is often limited due to its inert form in the atmosphere. Nitrogen-fixing biofertilizers include a variety of microorganisms capable of converting atmospheric nitrogen into ammonia, which plants can readily absorb. Among the most extensively studied nitrogen-fixing bacteria are *Rhizobium*, *Azospirillum*, and *Azotobacter*.

Rhizobium

Rhizobium is known for its symbiotic relationship with leguminous plants, where it forms root nodules and enhances nitrogen availability. Studies indicate that inoculation with effective *Rhizobium* strains can increase crop yields by 15–30% compared to uninoculated control groups. *Azospirillum* and *Azotobacter*, on the other hand, are free-living nitrogen-fixing bacteria that contribute to non-leguminous crop productivity. Research has shown that *Azospirillum* inoculation in cereals such as wheat and maize can result in a yield increase of 10–20% due to improved nitrogen availability and phytohormone production (Okon *et.al.,* 1995).

Phosphate-solubilizing Biofertilizers

Phosphorus is another essential nutrient for plant growth, yet its availability is often limited due to its presence in insoluble forms in soil. Phosphate-solubilizing microorganisms (PSMs) such as *Pseudomonas* and *Bacillus* play a crucial role in converting insoluble phosphates into bioavailable forms through the secretion of organic acids, phosphatases, and other chelating agents. Studies have demonstrated that the application of PSMs can enhance phosphorus availability by up to 40%, thereby promoting root development, plant growth, and overall productivity. The use of *Bacillus* strains has been particularly effective in enhancing phosphorus uptake in cereals, legumes, and vegetable crops (Meena *et.al.,* 2016).

Potassium-mobilizing Biofertilizers

Potassium is a vital nutrient involved in photosynthesis, enzyme activation, and osmoregulation. Despite its abundance in soil, a significant portion of potassium exists in inaccessible mineral forms. Potassium-mobilizing biofertilizers contain microorganisms capable of solubilizing insoluble potassium through organic acid production and microbial metabolism. Research indicates that potassium-mobilizing bacteria can increase potassium availability by 20–30%, resulting in enhanced plant growth, improved stress tolerance, and better crop yields (Jha *et.al.,* 2016). Effective strains include species from the genera *Bacillus* and *Frateuria*, which are frequently applied to crops such as rice, wheat, and sugarcane.

Mycorrhizal Biofertilizers

Mycorrhizal fungi, particularly *Arbuscular Mycorrhizal Fungi (AMF)*, form mutualistic associations with plant roots, significantly enhancing nutrient uptake, especially phosphorus while improving soil structure. Mycorrhizal biofertilizers are known to enhance plant tolerance to various environmental stresses, including drought, salinity, and heavy metal contamination. Studies have shown that AMF can improve phosphorus uptake by 30–40% and enhance plant growth by 20–50% depending on soil conditions and crop type. The application of mycorrhizal biofertilizers is particularly beneficial in degraded soils where nutrient availability is limited.

Organic Matter Decomposers

Organic matter decomposers are microorganisms that accelerate the breakdown of organic residues, enhancing soil fertility and structure (Condron *et.al.,* 2010). The most commonly used decomposer is *Trichoderma*, a genus of fungi known for its ability to decompose complex organic materials while promoting plant growth and providing biological control against soil-borne pathogens. The use of *Trichoderma* formulations has been associated with improved soil organic carbon content, enhanced nutrient cycling, and better crop productivity. Additionally, *Trichoderma* exhibits biocontrol properties by producing enzymes and secondary metabolites that suppress pathogenic microorganisms.

Table 1. Classification of Biofertilizers (Source: Nosheen *et.al.,* 2021, Jha et.al., 2016)

Category	Type of Microorganism	Common Genera	Function/Role	Target Crop/Use
Nitrogen Fixing Biofertilizers	Free-living Nitrogen Fixers	*Azotobacter*, *Beijerinckia*	Convert atmospheric nitrogen to ammonium for plant uptake	Non-leguminous crops (e.g., cereals, vegetables)
	Symbiotic Nitrogen Fixers	*Rhizobium*, *Bradyrhizobium*	Form nodules on legumes and fix nitrogen	Leguminous crops (e.g., pulses, beans)
	Associative Symbiotic Fixers	*Azospirillum*, *Acetobacter*	Associate with roots, enhance nitrogen uptake	Grasses, millets, cereals
Phosphate Solubilizing Biofertilizers	Bacteria and Fungi	*Bacillus*, *Pseudomonas*, *Aspergillus*	Solubilize insoluble phosphates in soil for plant absorption	All crops
Potassium Solubilizing Biofertilizers	Bacteria	*Frateuria aurantia*	Release potassium from insoluble minerals	All crops
Sulfur Oxidizing Biofertilizers	Bacteria	*Thiobacillus*	Convert elemental sulfur to sulfate form	Oilseeds, pulses
Zinc Solubilizing Biofertilizers	Bacteria	*Bacillus spp.*, *Pseudomonas spp.*	Make zinc available by solubilizing zinc compounds	Zinc-deficient soils
Mycorrhizal Biofertilizers	Fungi	Arbuscular Mycorrhizal Fungi (AMF)	Improve water and nutrient uptake via root-fungal symbiosis	Horticultural and plantation crops
Plant Growth Promoting Rhizobacteria (PGPR)	Bacteria	*Pseudomonas*, *Bacillus*, *Enterobacter*	Stimulate plant growth through various mechanisms (hormones, enzymes)	Wide range of crops
Cyanobacterial Biofertilizers	Blue-Green Algae (Cyanobacteria)	*Anabaena*, *Nostoc*, *Aulosira*	Fix atmospheric nitrogen and improve soil fertility	Paddy fields, aquatic crops

B. Mechanisms of Action

Nitrogen Fixation

Nitrogen fixation involves the conversion of atmospheric nitrogen into ammonia by diazotrophic bacteria and cyanobacteria (Sun *et.al.,* 2021). This process occurs through the enzyme nitrogenase, which catalyses the reduction of nitrogen (N_2) to ammonia (NH_3). Studies have demonstrated that biofertilizer inoculation can increase nitrogen availability by 30–50%, improving plant growth and soil fertility.

Phosphate Solubilization and Mobilization

Phosphate-solubilizing microorganisms enhance phosphorus availability by producing organic acids, phosphatases, and other chelating agents that release phosphorus from insoluble compounds. This process has been found to increase phosphorus uptake by 40–50%, resulting in improved root development and higher yields.

Production of Growth-Promoting Substances

Biofertilizers often produce growth-promoting substances such as auxins, gibberellins, and cytokinins. These phytohormones stimulate root growth, enhance nutrient uptake, and improve plant resistance to stress conditions. Reports suggest a yield improvement of 15–20% in crops treated with biofertilizers producing phytohormones.

Enhanced Nutrient Uptake and Soil Structure Improvement

The application of biofertilizers contributes to enhanced nutrient uptake by increasing root surface area, improving soil structure, and promoting beneficial microbial activity. Studies indicate that biofertilizer-treated soils exhibit higher organic carbon content, better water retention, and improved soil porosity (Sivaram *et.al.,* 2023).

C. Commercial Production and Formulation

The commercial production of biofertilizers involves two main types: liquid formulations and carrier-based formulations. Liquid biofertilizers provide higher microbial viability, longer shelf-life, and ease of application compared to carrier-based products. Carrier-based biofertilizers remain popular due to their cost-effectiveness and suitability for various crops. Ensuring quality control is essential for effective biofertilizer production (Agarwal *et.al.,* 2021). Standards are set to maintain microbial viability, purity, and efficiency, with guidelines established by agencies such as the Food and Agriculture Organization (FAO) and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

3. ROLE OF BIOFERTILIZERS IN SUSTAINABLE AGRICULTURE

A. Enhancement of Crop Yield and Quality

The application of biofertilizers has gained significant attention due to their ability to enhance crop yield and quality by promoting nutrient availability and uptake (Table 2). Biofertilizers contribute to improved plant growth through various mechanisms, including nitrogen fixation, phosphate solubilization, potassium mobilization, and the production of growth-promoting substances such as phytohormones.

Increased Nutrient Availability and Uptake

The use of biofertilizers facilitates nutrient availability by converting inaccessible forms of nutrients into bioavailable ones (Itelima *et.al.,* 2018). Nitrogen-fixing bacteria such as *Rhizobium*, *Azospirillum*, and *Azotobacter* enhance nitrogen availability in the soil through biological nitrogen fixation. Studies have reported that inoculation with *Rhizobium* can increase nitrogen uptake by approximately 20–30%, leading to improved legume productivity. Phosphate-solubilizing microorganisms (PSMs), including *Pseudomonas* and *Bacillus* species, contribute to the solubilization of insoluble phosphate compounds, increasing phosphorus availability by up to 50%. Enhanced phosphorus availability promotes root growth, seed development, and overall crop performance. Similarly, potassium-mobilizing bacteria improve potassium availability through mineral solubilization, enhancing crop yields by approximately 15–25%.

Improved Plant Growth and Productivity

Biofertilizers play a critical role in promoting plant growth by enhancing nutrient absorption, improving root architecture, and stimulating the production of phytohormones such as auxins, gibberellins, and cytokinins (Singh *et.al.,* 2023). Research has demonstrated that *Azospirillum* inoculation in cereals such as wheat and maize increases yield by 10–20% compared to uninoculated control groups. Mycorrhizal biofertilizers, particularly *Arbuscular Mycorrhizal Fungi (AMF)*, have been shown to enhance phosphorus uptake and improve drought resistance. Studies have indicated that AMF inoculation can increase crop yields by 20–50% in phosphorus-deficient soils. The beneficial effects of biofertilizers on crop productivity are evident across various crop systems, including cereals, legumes, vegetables, and fruit crops.

Case Studies and Experimental Findings

Numerous field experiments and case studies have demonstrated the positive impact of biofertilizers on crop productivity (Latkovic *et.al.,* 2020). In a study conducted on soybean crops, the combined use of *Rhizobium* and phosphate-solubilizing bacteria resulted in a 40% increase in yield compared to chemical fertilizers alone. Similarly, an experiment on wheat crops inoculated with *Azospirillum* and potassium-mobilizing bacteria showed a 25% improvement in grain yield, attributed to enhanced nitrogen and potassium availability. Such findings highlight the potential of biofertilizers to improve agricultural productivity through natural mechanisms that enhance nutrient availability and uptake.

B. Reduction in Chemical Fertilizer Usage

The excessive use of chemical fertilizers has led to severe environmental issues, including soil degradation, water pollution, and greenhouse gas emissions (Kumar *et.al.,* 2019). The integration of biofertilizers into agricultural practices offers a sustainable alternative that can reduce the dependency on chemical fertilizers while maintaining or enhancing crop productivity.

Synergistic Use with Chemical Fertilizers

Biofertilizers are often used in combination with chemical fertilizers to enhance nutrient use efficiency. Studies have shown that integrating biofertilizers with reduced chemical fertilizer doses can achieve comparable or even higher yields than conventional practices. For instance, applying *Azospirillum* along with 50% of the recommended nitrogen fertilizer resulted in a 15–20% yield increase in maize crops. Such synergistic use improves nutrient uptake efficiency, reduces fertilizer wastage, and promotes balanced plant growth.

Potential for Complete or Partial Substitution

Several studies have highlighted the potential of biofertilizers to partially or completely replace chemical fertilizers under specific conditions (Mahanty *et.al.,* 2017). Experiments on legumes using *Rhizobium* inoculation have demonstrated that nitrogen requirements can be met entirely through biological nitrogen fixation without compromising yield. Similarly, phosphate-solubilizing bacteria have shown promising results in enhancing phosphorus availability, potentially reducing the need for chemical phosphate fertilizers by up to 50%.

Economic and Environmental Benefits

Reducing the reliance on chemical fertilizers provides both economic and environmental benefits. The use of biofertilizers can lower input costs for farmers, reduce soil and water contamination, and decrease greenhouse gas emissions associated with fertilizer production and application. Estimates suggest that replacing 30% of chemical fertilizers with biofertilizers can reduce nitrogen-based emissions by approximately 20%.

C. Contribution to Soil Fertility

Biofertilizers play a significant role in enhancing soil fertility by promoting the accumulation of organic matter, improving soil structure, and increasing microbial diversity and activity. Their application contributes to the sustainability of agricultural systems by enhancing soil health and ensuring long-term productivity.

Soil Organic Matter Enhancement

The decomposition of organic residues by microorganisms such as *Trichoderma* contributes to the formation of humus, which improves soil organic carbon content and nutrient availability (Khatoon *et.al.,* 2017). Increased organic matter enhances soil fertility, water retention, and nutrient-holding capacity, promoting sustainable agricultural practices.

Improved Soil Structure and Aeration

Biofertilizers improve soil structure by promoting the formation of soil aggregates, enhancing porosity, and increasing aeration. Enhanced soil structure facilitates root growth and improves water infiltration, ultimately contributing to better crop productivity.

Soil Microbial Diversity and Activity

The application of biofertilizers increases microbial diversity and activity, promoting nutrient cycling and improving soil health (Yadav *et.al.,* 2021). Enhanced microbial populations contribute to the suppression of soil-borne pathogens, promoting plant growth and resilience against environmental stresses.

D. Environmental Benefits

The use of biofertilizers contributes to environmental sustainability by reducing greenhouse gas emissions, minimizing soil and water pollution, and enhancing biodiversity.

Reduction of Greenhouse Gas Emissions

Biofertilizers contribute to the reduction of greenhouse gas emissions by decreasing the need for synthetic fertilizers, which are associated with high carbon emissions during production and application. Studies estimate that the use of biofertilizers can reduce nitrogen-based emissions by up to 20–30%.

Decreased Soil and Water Pollution

Chemical fertilizers are often responsible for soil and water pollution through nutrient leaching and runoff. Biofertilizers provide a safer alternative by promoting nutrient cycling without causing harmful environmental effects (Sahoo *et.al.,* 2012).

Enhanced Biodiversity

Biofertilizers enhance soil biodiversity by promoting beneficial microorganisms and improving overall soil health. Increased microbial diversity contributes to ecosystem resilience and sustainability.

Table 2. Role of Biofertilizers in Sustainable Agriculture (Source: Itelima et.al., 2018, Yadav et.al., 2021)

S. No.	Sustainability Domain	Specific Role	Microbial Agents Involved	Impact on Agriculture
1	Nutrient Management	Biological nitrogen fixation	*Rhizobium*, *Azotobacter*, *Azospirillum*	Reduces need for synthetic nitrogen fertilizers
2	Phosphorus Solubilization	Conversion of insoluble phosphates to plant-available forms	*Bacillus*, *Pseudomonas*, *Aspergillus*	Enhances phosphorus uptake, improving root and shoot growth
3	Potassium and Zinc Mobilization	Mobilization of K and Zn from soil minerals	*Frateuria aurantia*, *Bacillus*, *Pseudomonas*	Improves overall nutrient balance in crops
4	Soil Health Improvement	Enhancement of soil microbial biomass and enzymatic activity	Mycorrhizae, PGPR (Plant Growth-Promoting Rhizobacteria)	Increases soil organic carbon, water retention, and structure
5	Plant Growth Promotion	Production of phytohormones and enzymes that stimulate growth	*Pseudomonas fluorescens*, *Bacillus subtilis*	Accelerates germination, root elongation, and crop vigor
6	Biocontrol of Pathogens	Suppression of harmful soil pathogens through competitive exclusion and antibiosis	*Trichoderma*, *Bacillus*, *Streptomyces*	Reduces disease incidence and chemical pesticide usage
7	Environmental Sustainability	Reduction in greenhouse gas emissions and prevention of chemical runoff	All major biofertilizer groups	Supports climate-smart agriculture and reduces ecological footprint
8	Yield and Productivity	Enhanced nutrient uptake and stress resilience leading to higher yield stability	*Azospirillum*, *Mycorrhizae*, PGPR	Promotes sustainable yield under various agro-climatic conditions

4. IMPACT OF BIOFERTILIZERS ON SOIL HEALTH IMPROVEMENT

A. Soil Microbial Diversity and Activity

The application of biofertilizers plays a significant role in enhancing soil microbial diversity and activity, which are critical components of healthy soil ecosystems. Beneficial microorganisms present in biofertilizers contribute to various processes that improve nutrient availability, organic matter decomposition, and plant growth promotion. Increased microbial diversity promotes ecosystem stability and resilience, thereby enhancing soil health and agricultural productivity (Bertola *et.al.,* 2021).

Role in Promoting Beneficial Microbial Populations

The introduction of biofertilizers into soil systems enhances the proliferation of beneficial microorganisms, including nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, potassium-mobilizing bacteria, and mycorrhizal fungi. Studies have demonstrated that inoculation with *Rhizobium* and *Azospirillum* can increase microbial biomass by approximately 30–40%, contributing to improved nitrogen cycling and availability. Research indicates that phosphate-solubilizing bacteria such as *Bacillus* and *Pseudomonas* enhance microbial activity by producing organic acids and other metabolites that solubilize insoluble phosphate compounds, thereby promoting plant growth. Enhanced microbial diversity also contributes to nutrient mineralization and organic matter decomposition, which are essential for maintaining soil fertility (Biswas *et.al.,* 2017).

Inhibition of Pathogenic Microorganisms

The application of biofertilizers promotes the establishment of beneficial microbial populations that can outcompete and inhibit the growth of harmful pathogens. Biofertilizers containing antagonistic fungi such as *Trichoderma* exhibit biocontrol properties by producing enzymes, antibiotics, and secondary metabolites that suppress soil-borne pathogens. Studies have reported that the application of *Trichoderma* can reduce the incidence of root diseases by 40–60%, thereby improving crop health and productivity. The competitive exclusion of pathogens by beneficial microorganisms contributes to enhanced soil health and improved plant resilience against diseases.

B. Improvement of Soil Physical and Chemical Properties

Biofertilizers contribute significantly to the enhancement of soil physical and chemical properties, which are essential for promoting plant growth and maintaining soil health. Improved soil structure, aggregation, porosity, pH modification, and nutrient availability are some of the notable benefits associated with biofertilizer application.

Soil Aggregation and Porosity

The use of biofertilizers promotes soil aggregation through the production of extracellular polysaccharides and organic compounds by beneficial microorganisms (Yilmaz *et.al.,* 2017). Improved soil aggregation enhances porosity, water infiltration, and root penetration, thereby supporting plant growth. Studies have shown that the application of mycorrhizal biofertilizers increases soil aggregation by approximately 30%, resulting in better soil structure and reduced erosion. Research also indicates that microbial activity stimulated by biofertilizer application contributes to the stabilization of soil particles, enhancing soil porosity and improving water retention capacity. Increased porosity facilitates gas exchange and nutrient availability, promoting overall soil health.

pH Modification and Nutrient Availability

Biofertilizers influence soil pH through the release of organic acids and other metabolites produced during microbial metabolism (Zhu *et.al.,* 2022). Phosphate-solubilizing bacteria such as *Pseudomonas* and *Bacillus* produce organic acids that lower soil pH, increasing phosphorus solubility and availability for plant uptake. Studies have demonstrated that the application of phosphate-solubilizing biofertilizers can reduce soil pH by approximately 0.5–1.0 units, enhancing phosphorus availability by up to 50%. Additionally, potassium-mobilizing bacteria enhance potassium availability by releasing organic acids and chelating agents that solubilize insoluble potassium compounds.

C. Enhancement of Soil Organic Matter

The presence of soil organic matter is a crucial determinant of soil fertility, influencing nutrient availability, water retention, and microbial activity. Biofertilizers contribute to the enhancement of soil organic matter through the decomposition of organic residues and the promotion of carbon sequestration.

Role in Organic Matter Decomposition

Biofertilizers containing organic matter decomposers such as *Trichoderma* play a vital role in breaking down complex organic materials into simpler, bioavailable compounds (Vurukonda *et.al.,* 2024). This process enhances soil fertility by increasing organic carbon content and improving nutrient cycling. Research has shown that *Trichoderma* application increases organic matter decomposition rates by approximately 30–40%, contributing to higher nutrient availability and better crop productivity.

Contribution to Carbon Sequestration

The application of biofertilizers contributes to carbon sequestration by promoting the accumulation of organic matter in the soil. Mycorrhizal fungi, particularly *Arbuscular Mycorrhizal Fungi (AMF)*, enhance carbon storage by facilitating the formation of soil aggregates and stabilizing organic matter. Studies have reported that AMF inoculation can increase soil carbon content by approximately 20–30%, contributing to improved soil structure and fertility. Research suggests that enhancing soil organic matter through biofertilizer application is an effective strategy for mitigating climate change by sequestering carbon dioxide from the atmosphere.

D. Biofertilizer-Plant-Microbe Interactions

The effectiveness of biofertilizers depends significantly on the interactions between beneficial microorganisms, plants, and the soil environment (Sahoo *et.al.,* 2012). These interactions are fundamental to promoting plant growth, enhancing nutrient availability, and improving overall soil health.

Rhizosphere Dynamics

The rhizosphere, the narrow region of soil surrounding plant roots, serves as a dynamic environment where plant-microbe interactions occur. Biofertilizers enhance rhizosphere dynamics by promoting beneficial microbial populations that contribute to nutrient solubilization, nitrogen fixation, and disease suppression. Research indicates that biofertilizer application increases microbial biomass in the rhizosphere by approximately 25–35%, resulting in improved nutrient availability and plant growth.

Symbiotic and Non-Symbiotic Associations

Biofertilizers establish both symbiotic and non-symbiotic associations with plants, contributing to nutrient acquisition and improved soil health. Symbiotic associations, such as those formed by *Rhizobium* with leguminous plants and *Arbuscular Mycorrhizal Fungi* with various crops, enhance nutrient uptake and promote plant growth. Non-symbiotic associations involving free-living nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and potassium-mobilizing microorganisms also play a crucial role in nutrient cycling and soil fertility enhancement.

5. CHALLENGES AND LIMITATIONS

A. Limited Adoption and Awareness

The large-scale adoption of biofertilizers has been hindered by various social, economic, and technical challenges (Yadav *et.al.,* 2024). Among these, limited awareness and misconceptions about their efficacy remain significant barriers. Despite extensive research demonstrating the potential of biofertilizers to enhance crop productivity and soil health, their adoption remains low compared to conventional chemical fertilizers.

Farmer Perceptions and Misconceptions

A significant portion of the farming community remains skeptical about the effectiveness of biofertilizers. The belief that biofertilizers are inferior to chemical fertilizers in terms of crop yield enhancement persists, especially among small-scale and resource-poor farmers. Studies have indicated that approximately 40–50% of farmers are unwilling to adopt biofertilizers due to concerns about inconsistent performance, delayed results, and lack of immediate visual impact on crops. The preference for synthetic fertilizers, which provide rapid nutrient availability and noticeable improvements in crop growth, further contributes to the limited adoption of biofertilizers (Sharma *et.al.,* 2023). Moreover, the absence of proper information regarding the benefits of biofertilizers and their application methods exacerbates the issue. Nearly 35% of farmers reported inadequate knowledge of biofertilizer application techniques, which directly impacts their effectiveness.

Lack of Proper Training and Knowledge

The lack of effective extension services and training programs targeting biofertilizer use is another critical barrier to widespread adoption. Many farmers are unaware of the potential benefits of biofertilizers, particularly their long-term impact on soil fertility and environmental sustainability. A survey conducted by the Agricultural Extension Research Institute (AERI) revealed that more than 60% of farmers had never received training or guidance on biofertilizer application. Effective dissemination of knowledge regarding the correct use of biofertilizers, including suitable crops, application methods, and dosage recommendations, remains a key challenge (Atieno *et.al.,* 2020). Additionally, the absence of standardized training modules further complicates the promotion of biofertilizer technology among farming communities.

B. Variability in Performance

Biofertilizers are biological products whose performance can be significantly influenced by various environmental and agronomic factors. Variability in their effectiveness is one of the most critical challenges limiting their adoption and widespread application.

Influence of Environmental Factors (Soil Type, pH, Moisture)

The efficacy of biofertilizers is highly dependent on environmental conditions such as soil type, pH, moisture content, temperature, and nutrient availability. Studies have shown that nitrogen-fixing bacteria like *Azospirillum* and *Azotobacter* are more effective in neutral to slightly acidic soils, whereas their efficiency declines in highly acidic or alkaline soils. Soil moisture also plays a crucial role in determining the survival and colonization of microbial inoculants (Sivaram *et.al.,* 2023). Research indicates that drought conditions can reduce the efficiency of phosphate-solubilizing bacteria by approximately 30–40%. Similarly, potassium-mobilizing bacteria exhibit reduced performance under extreme temperature fluctuations, limiting their efficacy in specific agroecological regions.

Inconsistent Results Under Field Conditions

The inconsistent performance of biofertilizers under field conditions remains a significant concern. While controlled experimental studies often report positive results, field trials have shown mixed outcomes. The inconsistency in results can be attributed to variations in environmental factors, soil microbial diversity, and the presence of native microbial populations that may outcompete or inhibit introduced biofertilizers. Field trials revealed that the effectiveness of biofertilizers varied by 20–50% depending on soil type, climate, and crop species. This variability has contributed to the perception that biofertilizers are unreliable, discouraging farmers from adopting them on a large scale.

C. Production, Formulation, and Shelf-life Issues

The production and formulation of biofertilizers present significant challenges that can affect their viability, effectiveness, and commercialization (Yadav *et.al.,* 2024). Ensuring the survival and functionality of microbial inoculants during storage and application is essential for achieving the desired results.

Carrier Material Selection

Carrier materials are critical components of biofertilizer formulations as they provide a suitable environment for microbial survival and growth. Commonly used carriers include peat, lignite, vermiculite, and charcoal. The choice of carrier material influences the shelf-life, viability, and efficiency of biofertilizers. Studies have shown that peat-based formulations generally provide higher microbial viability compared to other carriers, with shelf-lives extending up to six months. Despite their advantages, peat-based carriers are not universally available and may be associated with high production costs. Alternative carriers such as vermiculite and charcoal are less expensive but may provide reduced microbial viability. Research indicates that vermiculite-based formulations exhibit microbial viability loss of approximately 30–35% after three months of storage.

Preservation of Viability During Storage

Maintaining the viability of microbial inoculants during storage remains a significant challenge. Factors such as temperature, humidity, and exposure to sunlight can adversely affect microbial survival (Handley *et.al.,* 1995). Liquid biofertilizers have been developed to address this issue, offering enhanced viability and longer shelf-lives compared to conventional carrier-based formulations. Studies have reported that liquid formulations exhibit microbial viability retention of approximately 80–90% after six months of storage, compared to 50–60% for carrier-based products. Despite these improvements, the high cost of production and limited availability of advanced formulations continue to impede the widespread adoption of biofertilizers.

D. Regulatory and Standardization Challenges

The absence of harmonized guidelines and quality control standards for biofertilizer production and application presents a significant barrier to their effective utilization. Inconsistent regulations and inadequate monitoring mechanisms have contributed to the proliferation of substandard products in the market.

Need for Quality Control Standards

Quality control is essential for ensuring the efficacy and safety of biofertilizers. Inconsistent product quality, low microbial counts, and contamination with harmful organisms are common issues reported by farmers and researchers alike. Studies have shown that nearly 25% of commercially available biofertilizers fail to meet the minimum microbial viability standards required for effective application. The establishment of stringent quality control protocols is necessary to maintain product reliability and promote farmer confidence (Martinez *et.al.,* 2004). Standardized procedures for production, packaging, labelling, and testing are essential for ensuring the quality and consistency of biofertilizers.

Lack of Harmonized Guidelines

The absence of unified guidelines for the registration, approval, and commercialization of biofertilizers presents a significant regulatory challenge. Inconsistencies in regulations between different regions hinder the commercialization of innovative biofertilizer products. Developing a comprehensive regulatory framework that addresses these issues is essential for promoting the widespread adoption of biofertilizers.

6. FUTURE AND RESEARCH NEEDS

A. Innovations in Biofertilizer Technology

The demand for efficient and sustainable agricultural practices has led to significant advancements in biofertilizer technology. Innovations aimed at improving the effectiveness, stability, and adaptability of biofertilizers continue to emerge, with a focus on enhancing their potential to meet the growing needs of global agriculture.

Development of Multi-Functional Biofertilizers

Recent research has increasingly focused on the development of multi-functional biofertilizers that combine various beneficial microorganisms to achieve a broader range of plant growth-promoting effects (Wang *et.al.,* 2024). Multi-functional biofertilizers often include nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, potassium-mobilizing bacteria, and plant growth-promoting rhizobacteria (PGPR). The concept of microbial consortia has gained prominence as it allows the formulation of biofertilizers containing multiple microbial strains capable of performing complementary functions. Studies have shown that inoculation with consortia of *Rhizobium*, *Azospirillum*, *Pseudomonas*, and *Bacillus* can enhance crop yields by approximately 30–40% compared to single-strain applications. Research has also demonstrated that the use of multi-functional biofertilizers improves nutrient uptake efficiency, promotes disease resistance, and enhances stress tolerance in various crops. For instance, field trials involving rice crops treated with a consortium of nitrogen-fixing and phosphate-solubilizing bacteria reported yield improvements of up to 35% under nutrient-deficient conditions.

Genetic Engineering and Microbial Consortia

Advances in genetic engineering and microbial biotechnology have opened new possibilities for enhancing the efficiency of biofertilizers (Ali *et.al.,* 2020). Genetic modification of beneficial microorganisms can improve their nutrient solubilization capacity, stress tolerance, and ability to colonize plant roots effectively. Studies have demonstrated that genetically engineered *Azotobacter* strains with enhanced nitrogen fixation capabilities can increase nitrogen availability by approximately 50% compared to wild-type strains. Moreover, engineered phosphate-solubilizing bacteria exhibiting improved organic acid production have shown promising results in enhancing phosphorus availability in various crops. The development of synthetic microbial consortia, where different microorganisms are deliberately assembled to achieve specific functions, is also gaining attention. These consortia can be tailored to address particular soil deficiencies and improve crop productivity under varying environmental conditions. Research on microbial consortia for wheat and maize cultivation has demonstrated yield improvements of approximately 25–30%.

B. Integration with Modern Agricultural Practices

The integration of biofertilizers with modern agricultural practices is essential for maximizing their potential benefits (Atieno *et.al.,* 2020). The compatibility of biofertilizers with precision agriculture techniques and strategies for promoting large-scale adoption remains a critical area of research and development.

Compatibility with Precision Agriculture

Precision agriculture involves the use of advanced technologies such as remote sensing, soil mapping, and data analytics to optimize crop management. The compatibility of biofertilizers with precision agriculture techniques can enhance nutrient use efficiency, reduce environmental impacts, and improve crop productivity. Studies have demonstrated that site-specific application of biofertilizers based on soil nutrient mapping can improve nutrient availability by approximately 30–40% compared to conventional broadcast application methods. The use of biofertilizers in conjunction with precision irrigation systems has also shown promising results in improving water use efficiency and enhancing nutrient uptake in crops such as wheat, rice, and maize.

Strategies for Large-Scale Adoption

Promoting large-scale adoption of biofertilizers requires the development of effective strategies that address economic, technical, and social barriers (Mawar *et.al.,* 2021). Establishing demonstration plots, providing farmer training, and promoting public-private partnerships are essential for increasing awareness and acceptance of biofertilizers. Research indicates that collaborative efforts between research institutions, government agencies, and private companies can significantly enhance the adoption of biofertilizers. A study conducted that farmers participating in training programs exhibited a 60% increase in biofertilizer usage compared to those with no access to educational resources. Efforts to integrate biofertilizers into existing agricultural frameworks must consider factors such as product availability, ease of application, and economic viability. Developing cost-effective production methods and improving distribution networks are critical for ensuring widespread adoption.

C. Policy and Institutional Support

Effective policy frameworks and institutional support are essential for promoting the adoption of biofertilizers and enhancing their contribution to sustainable agriculture (Masso *et.al.,* 2015). Government initiatives, subsidies, and public awareness programs play a crucial role in encouraging farmers to adopt biofertilizer technology.

Government Initiatives and Subsidies

Governments across various regions have introduced initiatives aimed at promoting the use of biofertilizers as part of sustainable agricultural practices. Policies that provide subsidies, tax incentives, and financial support for biofertilizer production and distribution can significantly enhance their adoption. Research indicates that providing financial incentives to small-scale farmers can increase biofertilizer usage by approximately 50%. Additionally, establishing regulatory frameworks that ensure product quality and efficacy is essential for maintaining farmer confidence and promoting the widespread use of biofertilizers.

Public Awareness Programs

Public awareness programs focused on educating farmers about the benefits of biofertilizers are essential for overcoming barriers to adoption (Kassem *et.al.,* 2021). Extension services, workshops, and media campaigns can effectively disseminate information regarding biofertilizer technology. Studies have shown that farmers exposed to awareness programs are more likely to adopt biofertilizers and report higher satisfaction levels with their performance.

D. Areas for Further Research

Although biofertilizers have shown significant potential, several areas require further research to enhance their effectiveness and ensure their successful integration into modern agricultural systems.

Long-Term Impact Studies on Soil Health

The long-term effects of biofertilizer application on soil health, including microbial diversity, nutrient cycling, and carbon sequestration, require further investigation. Long-term studies can provide valuable insights into the sustainability of biofertilizers and their role in promoting resilient agricultural systems.

Improvement of Formulation Techniques

Improving the formulation techniques of biofertilizers is essential for enhancing their shelf-life, viability, and effectiveness under varying environmental conditions (Sahu *et.al.,* 2016). Research aimed at developing advanced carrier materials, optimizing microbial consortia, and improving liquid formulations is critical for ensuring consistent performance. Studies have shown that enhanced formulation techniques can improve microbial viability by approximately 30–40% during storage.

7. CONCLUSION

The application of biofertilizers plays a crucial role in promoting sustainable agriculture by enhancing soil health, improving crop productivity, and reducing dependency on chemical fertilizers. Their ability to increase nutrient availability, enhance soil microbial diversity, improve soil structure, and contribute to carbon sequestration demonstrates their potential as eco-friendly alternatives to synthetic fertilizers. Despite their numerous benefits, challenges related to inconsistent performance, limited awareness, and inadequate regulatory frameworks hinder their widespread adoption. Innovations in biofertilizer technology, such as multi-functional formulations, genetic engineering, and precision agriculture integration, offer promising solutions to these challenges. Effective policy support, farmer training programs, and improved production techniques are essential for promoting large-scale adoption. Continued research focused on enhancing biofertilizer efficacy, developing advanced formulations, and conducting long-term impact studies is vital for ensuring agricultural sustainability and environmental protection.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Agarwal, S., Kumari, S., & Khan, S. (2021). Quality control of biofertilizers. *Biofertilizers: Study and Impact*, 413-428.

Ali, R., Zulaykha, K. D., & Sajjad, N. (2020). Genetically modified microbes as biofertilizers. *Bioremediation and Biotechnology, Vol 4: Techniques for Noxious Substances Remediation*, 275-293.

Atieno, M., Herrmann, L., Nguyen, H. T., Phan, H. T., Nguyen, N. K., Srean, P., ... & Lesueur, D. (2020). Assessment of biofertilizer use for sustainable agriculture in the Great Mekong Region. *Journal of environmental management*, *275*, 111300.

Atieno, M., Herrmann, L., Nguyen, H. T., Phan, H. T., Nguyen, N. K., Srean, P., ... & Lesueur, D. (2020). Assessment of biofertilizer use for sustainable agriculture in the Great Mekong Region. *Journal of environmental management*, *275*, 111300.

Bertola, M., Ferrarini, A., & Visioli, G. (2021). Improvement of soil microbial diversity through sustainable agricultural practices and its evaluation by-omics approaches: A perspective for the environment, food quality and human safety. *Microorganisms*, *9*(7), 1400.

Bhardwaj, D., Ansari, M. W., Sahoo, R. K., & Tuteja, N. (2014). Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. *Microbial cell factories*, *13*, 1-10.

Billah, M., Khan, M., Bano, A., Hassan, T. U., Munir, A., & Gurmani, A. R. (2019). Phosphorus and phosphate solubilizing bacteria: Keys for sustainable agriculture. *Geomicrobiology Journal*, *36*(10), 904-916.

Biswas, T., & Kole, S. C. (2017). Soil organic matter and microbial role in plant productivity and soil fertility. *Advances in Soil Microbiology: Recent Trends and Future Prospects: Volume 2: Soil-Microbe-Plant Interaction*, 219-238.

Condron, L., Stark, C., O'Callaghan, M., Clinton, P., & Huang, Z. (2010). The role of microbial communities in the formation and decomposition of soil organic matter. *Soil*

microbiology and sustainable crop production, 81-118.
Crews, T. E., Carton, W., & Olsson, L. (2018). Is the future of agriculture perennial? Imperatives and opportunities to reinvent agriculture by shifting from annual monocultures to perennial polycultures. *Global Sustainability*, *1*, e11.
Dönmez, D., Isak, M. A., İzgü, T., & Şimşek, Ö. (2024). Green Horizons: Navigating the future of agriculture through sustainable practices. Sustainability, 16(8), 3505.
Dzvene, A. R., & Chiduza, C. (2024). Application of Biofertilizers for Enhancing Beneficial Microbiomes in Push–Pull Cropping Systems: A Review. Bacteria, 3(4), 271-286.
Han, Z., Zheng, T., Yan, W., Rensing, C., Wu, H., Wu, W., & Wu, H. (2025). Substitution of chemical fertilizer by biogas slurry maintain wheat yields by regulating soil properties and microbiomes. Environmental Technology & Innovation, 104161.
Handley, B. A., & Webster, A. J. F. (1995). Some factors affecting the airborne survival of bacteria outdoors. *Journal of Applied bacteriology*, *79*(4), 368-378.
Itelima, J. U., Bang, W. J., Onyimba, I. A., Sila, M. D., & Egbere, O. J. (2018). Bio-fertilizers as key player in enhancing soil fertility and crop productivity: A review.
Jha, Y., & Subramanian, R. B. (2016). Regulation of plant physiology and antioxidant enzymes for alleviating salinity stress by potassium-mobilizing bacteria. *Potassium solubilizing microorganisms for sustainable agriculture*, 149-162.
Kassem, H. S., Alotaibi, B. A., Aldosri, F. O., & Muddassir, M. (2021). Exploring the relationship between information-seeking behavior and adoption of biofertilizers among onion farmers. *Agronomy*, *11*(6), 1258.
Khaliq, A., Perveen, S., Alamer, K. H., Zia Ul Haq, M., Rafique, Z., Alsudays, I. M., ... & Attia, H. (2022). Arbuscular mycorrhizal fungi symbiosis to enhance plant–soil interaction. Sustainability, 14(13), 7840.
Khatoon, H., Solanki, P., Narayan, M., Tewari, L., Rai, J. P. N., & Hina Khatoon, C. (2017). Role of microbes in organic carbon decomposition and maintenance of soil ecosystem. *International Journal of Chemical Studies*, *5*(6), 1648-1656.
Koushal, Sanjay, Annupama Devi, Jaydeep Panda, Samreen, Johnson Lakra, Chandan Kumar Panigrahi, Nagarjuna S, R. Wongamthing, and Bhim Singh. 2024. “The Role and Future Potential of Bio-Fertilizers in Indian Agriculture”. Journal of Advances in Biology & Biotechnology 27 (11):386-99. https://doi.org/10.9734/jabb/2024/v27i111624.
Kumar, R., Kumar, R., & Prakash, O. (2019). Chapter-5 the impact of chemical fertilizers on our environment and ecosystem. *Chief Ed*, *35*(69), 1173-1189.
Latkovic, D., Maksimovic, J., Dinic, Z., Pivic, R., Stanojkovic, A., & Stanojkovic-Sebic, A. (2020). Case study upon foliar application of biofertilizers affecting microbial biomass and enzyme activity in soil and yield related properties of maize and wheat grains. *Biology*, *9*(12), 452.
Mahanty, T., Bhattacharjee, S., Goswami, M., Bhattacharyya, P., Das, B., Ghosh, A., & Tribedi, P. (2017). Biofertilizers: a potential approach for sustainable agriculture development. *Environmental Science and Pollution Research*, *24*, 3315-3335.
Martinez, M. G., & Poole, N. (2004). The development of private fresh produce safety standards: implications for developing Mediterranean exporting countries. *Food Policy*, *29*(3), 229-255.
Masso, C., Ochieng, J. A., & Vanlauwe, B. (2015). Worldwide contrast in application of bio-fertilizers for sustainable agriculture: lessons for sub-Saharan Africa. *Journal of Biology, Agriculture and Healthcare*, *5*(12), 34-50.
Masso, C., Ochieng, J. A., & Vanlauwe, B. (2015). Worldwide contrast in application of bio-fertilizers for sustainable agriculture: lessons for sub-Saharan Africa. *Journal of Biology, Agriculture and Healthcare*, *5*(12), 34-50.
Mawar, R., Manjunatha, B. L., & Kumar, S. (2021). Commercialization, diffusion and adoption of bioformulations for sustainable disease management in Indian arid agriculture: prospects and challenges. *Circular Economy and Sustainability*, *1*(4), 1367-1385.
Meena, V. S., Maurya, B. R., Meena, S. K., Meena, R. K., Kumar, A., Verma, J. P., & Singh, N. P. (2016). Can Bacillus species enhance nutrient availability in agricultural soils?. *Bacilli and agrobiotechnology*, 367-395.
Negi, R., Sharma, B., Jan, T., Kaur, T., Chowdhury, S., Kapoor, M., ... & Yadav, A.

N. (2024). Microbial consortia: promising tool as plant bioinoculants for agricultural sustainability. Current Microbiology, 81(8), 222.

Nosheen, S., Ajmal, I., & Song, Y. (2021). Microbes as biofertilizers, a potential approach for sustainable crop production. *Sustainability*, *13*(4), 1868.

Okon, Y., & Itzigsohn, R. (1995). The development of Azospirillum as a commercial inoculant for improving crop yields. *Biotechnology advances*, *13*(3), 415-424.

Rashid, M. H. O., Krehenbrink, M., & Akhtar, M. S. (2015). Nitrogen-fixing plant-microbe symbioses. *Sustainable Agriculture Reviews: Volume 15*, 193-234.

Sahoo, R. K., Bhardwaj, D., & Tuteja, N. (2012). Biofertilizers: a sustainable eco-friendly agricultural approach to crop improvement. In *Plant acclimation to environmental stress* (pp. 403-432). New York, NY: Springer New York.

Sahoo, R. K., Bhardwaj, D., & Tuteja, N. (2012). Biofertilizers: a sustainable eco-friendly agricultural approach to crop improvement. In *Plant acclimation to environmental stress* (pp. 403-432). New York, NY: Springer New York.

Sahu, P. K., & Brahmaprakash, G. P. (2016). Formulations of biofertilizers–approaches and advances. *Microbial inoculants in sustainable agricultural productivity: Vol. 2: Functional Applications*, 179-198.

Sahu, P. K., & Brahmaprakash, G. P. (2016). Formulations of biofertilizers–approaches and advances. *Microbial inoculants in sustainable agricultural productivity: Vol. 2: Functional Applications*, 179-198.

Sekhar, M., Rastogi, M., Rajesh, C. M., Saikanth, D. R. K., Rout, S., Kumar, S., & Patel, A. K. (2024). Exploring traditional agricultural techniques integrated with modern farming for a sustainable future: A review. *Journal of Scientific Research and Reports*, *30*(3), 185-198.

Sharma, B., Tiwari, S., Kumawat, K. C., & Cardinale, M. (2023). Nano-biofertilizers as bio-emerging strategies for sustainable agriculture development: Potentiality and their limitations. *Science of The Total Environment*, *860*, 160476.

Sharma, B., Tiwari, S., Kumawat, K. C., & Cardinale, M. (2023). Nano-biofertilizers as bio-emerging strategies for sustainable agriculture development: Potentiality and their limitations. *Science of The Total Environment*, *860*, 160476.

Singh, K., Guleria, V., & Kaushal, S. (2023). Utilization of Biofertilizers and plant growth promoters in hydroponic production system. *Curr. J. Appl. Sci. Technol*, *42*, 13-23.

Sivaram, A. K., Abinandan, S., Chen, C., Venkateswartlu, K., & Megharaj, M. (2023). Microbial inoculant carriers: Soil health improvement and moisture retention in sustainable agriculture. *Advances in Agronomy*, *180*, 35-91.

Sivaram, A. K., Abinandan, S., Chen, C., Venkateswartlu, K., & Megharaj, M. (2023). Microbial inoculant carriers: Soil health improvement and moisture retention in sustainable agriculture. *Advances in Agronomy*, *180*, 35-91.

Suhag, M. (2016). Potential of biofertilizers to replace chemical fertilizers. Int. Adv. Res. J. Sci. Eng. Technol, 3(5), 163-167.

Sun, W. E. N. L. I., Shahrajabian, M. H., & Cheng, Q. I. (2021). Nitrogen fixation and diazotrophs–a review. *Rom Biotechnol Lett*, *26*(4), 2834-2845.

Vurukonda, S. S. K. P., Fotopoulos, V., & Saeid, A. (2024). Production of a rich fertilizer base for plants from waste organic residues by microbial formulation technology. *Microorganisms*, *12*(3), 541.

Wang, J., Yang, X., Huang, S., Wu, L., Cai, Z., & Xu, M. (2025). Long-term combined application of organic and inorganic fertilizers increases crop yield sustainability by improving soil fertility in maize–wheat cropping systems. Journal of Integrative Agriculture, 24(1), 290-305.

Wang, T., Xu, J., Chen, J., Liu, P., Hou, X., Yang, L., & Zhang, L. (2024). Progress in microbial fertilizer regulation of crop growth and soil remediation research. *Plants*, *13*(3), 346.

Wei, X., Xie, B., Wan, C., Song, R., Zhong, W., Xin, S., & Song, K. (2024). Enhancing soil health and plant growth through microbial fertilizers: Mechanisms, benefits, and sustainable agricultural practices. Agronomy, 14(3), 609.

Yadav, A. N., Kour, D., Kaur, T., Devi, R., Yadav, A., Dikilitas, M., ... & Saxena, A. K. (2021). Biodiversity, and biotechnological contribution of beneficial soil microbiomes for nutrient cycling, plant growth improvement and nutrient uptake. *Biocatalysis and Agricultural Biotechnology*, *33*, 102009.

Yadav, A., & Yadav, K. (2024). Challenges and opportunities in biofertilizer commercialization. *SVOA Microbiol*, *5*(1), 1-14.

Yadav, A., & Yadav, K. (2024). Challenges and opportunities in biofertilizer commercialization. *SVOA Microbiol*, *5*(1), 1-14.

Yilmaz, E., & Sönmez, M. (2017). The role of organic/bio–fertilizer amendment on aggregate stability and organic carbon content in different aggregate scales. *Soil and Tillage Research*, *168*, 118-124.

Zhao, G., Zhu, X., Zheng, G., Meng, G., Dong, Z., Baek, J. H., ... & Jia, B. (2024). Development of biofertilizers for sustainable agriculture over four decades (1980–2022). Geography and Sustainability, 5(1), 19-28.

Zhu, Y., Zhong, M., Li, W., Qiu, Y., Wang, H., & Lv, X. (2022). Cotton straw biochar and Bacillus compound biofertilizer decreased Cd migration in alkaline soil: Insights from relationship between soil key metabolites and key bacteria. *Ecotoxicology and Environmental Safety*, *232*, 113293.

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