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# Biofertilizer Application for Agricultural Sustainability: Prospects and Challenges

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**ABSTRACT**

The global demand for sustainable agricultural practices has intensified the focus on biofertilizers as eco-friendly alternatives to synthetic fertilizers. This review paper explores the current prospects and challenges associated with biofertilizers, highlighting their role in fostering agricultural sustainability. Biofertilizers are substances which contain living microorganisms which when applied to seeds, plant surfaces and soil, colonize the rhizosphere or the interior of the plant and promote growth by elevating the supply or availability of primary nutrients to the host plant. Biofertilizers derived from living microorganisms such as bacteria, fungi and algae, enhance soil fertility by fixing atmospheric nitrogen, solubilizing phosphates and encouraging plant growth through phytohormone production. Their application offers several benefits, including improved nutrient cycling, reduced greenhouse gas emissions, enhanced soil performance and increased crop yields. In addition, biofertilizers align with environmental sustainability goals by mitigating the ecological impacts of chemical fertilizers, such as soil degradation, water pollution and biodiversity loss. In spite of these merits, the universal adoption of biofertilizers encounters some challenges such as inconsistent field performance, limited shelf life and the specificity of microbial cultures to particular crops or soil types hinder their reliability, effectiveness and acceptability. Also, the lack of standardized production protocols, insufficient awareness among farmers and inadequate regulatory frameworks further impede their commercialization and large scale utilization. Advances in microbial biotechnology, formulation techniques and delivery systems offer promising solutions to these barriers. Research and development efforts are also focusing on the integration of biofertilizers with precision agriculture to optimize their application and efficacy. By addressing existing limitations and leveraging technological innovation, biofertilizers have the potential to revolutionize agriculture, ensuring food security while preserving environmental health as well directly supporting the UN Sustainable Development Goal 2.

**Keywords:** Biofertilizers, Commercialization, Eco-friendly, Phytohormone, Rhizosphere, Sustainable.

## INTRODUCTION

Due to population growth, agriculture production is under pressure to provide enough food to feed rising human population. The "green revolution" has been crucial in advancing high-yielding cultivars and agricultural management practices that promote sustainability. In addition to polluting environmental resources, monoculture practices with extensive field irrigation, the use of chemical fertilizers, pesticides, herbicides, and fungicides during the "Green Revolution" have led to issues with land degradation, soil deterioration, infertility, and high costs associated with farm inputs [1].

As a result, the idea of creating "green technology" has emerged to provide approaches to the ongoing use of natural resources without compromising their stability and integrity. According to Chun-Li et al [2], the use of chemical fertilizers has a negative impact on the ecosystem since it causes eutrophication, soil acidification, infertility, weakens plant roots, reduces genetic diversity, releases gases like nitrous oxide, and leaches chemicals. As a result, there is a great need for technological advancement to replace chemical fertilizers in order to support ecosystem interdependence and environmental sustainability in agriculture [3].

Biofertilizers are a suitable substitute for chemical fertilizers because their microorganisms solubilize soil nutrients, mobilize phosphates, zinc, and potassium, fix nitrogen from the environment, and release growth regulators in the soil. In addition to the methods listed above, biofertilizers aid in plant's ability to withstand stressful conditions. Numerous organisms utilized in biofertilizers possess the capability to reverse the negative effects of metal stress [4]. As a result, they aid in the development of stress resistance in plants [5, 6].

These positive effects of biofertilizers make their use in extended ways. These microbes which benefit agriculture production are in practical use since 1950s and are known as plant growth- promoting bacteria (PGPB). However, their potential has not been commercialized due to some of its limitations including vitality, efficiency, adaptability, and inconsistency. Plant growth-promoting bacteria are microorganisms that have been used in agriculture since the 1950s and are proven to enhance crop productivity, thereby aligning with the UN Sustainable Development Goals 2 (SDG 2). However, because of a few of their drawbacks, such as their lack of vigour,

efficiency, flexibility, and consistency, their promise has not yet been marketed.

There has been a gradual transition from synthetic fertilizer towards various bio-based fertilizer approaches [7]. High moisture content, the upstream processes for biofertilizers are cost-intensive when transported for long distances and therefore necessitates mass production indigenously [3]. These bio-based organic fertilizers either could be from plant or animal sources or can be microbiologically derived [8].

Biofertilizers play a crucial role in sustainable agriculture development, offering a potential approach for enhancing crop production while minimizing the negative environmental impacts of chemical fertilizers. The importance of biofertilizers in agriculture has been recognized by governments and researchers alike. In India, for example, the government has taken steps to ensure the quality and production of biofertilizers, highlighting their significance for agriculture sector [9]. Biofertilizers have gained attention for various applications, including agriculture, bioremediation, and ecology [10]. These microbial-based fertilizers offer a promising alternative to hazardous chemical fertilizers, contributing to achieving sustainable agriculture goals [11, 12]. Additionally, biofertilizers can contribute to the maintenance of organic matter in the soil and reduce the emission of $CO_2$ into the atmosphere, further highlighting their significance in agricultural practices [13].

The commercialization of biofertilizers presents opportunities for sustainable agriculture. Food production can be increased without posing any environmental risks by employing biofertilizers inoculated seeds, crops, or soil [14]. Bioinoculants can also exhibit other beneficial properties, such as biological nitrogen fixation, phytohormone synthesis and stress reduction, which promote plant growth [15]. Biofertilizers have been shown to have potential applications beyond agriculture. They can be used in bioremediation to degrade environmental pollutants, such as malathion pesticides [16].

However, the journey from laboratory research to the commercial application of such microorganisms is filled with challenges and opportunities. One of the key challenges is the effective selection of microbial strains [16]. Additionally, the performance of biofertilizers under *in situ* conditions is not always reliable and needs improvement [17]. Given these challenges and opportunities, there is a pressing need for multidisciplinary research to bridge the gap between laboratory findings and field applications, thereby unlocking the full potential of biofertilizers in

sustainable agriculture and environmental management.

As global agricultural systems face the challenge of feeding a growing population while conserving natural resources, the adoption of biofertilizers offers promising potentials to improve crop yields, restore soil fertility and support sustainable agricultural practices [18].

Biofertilizers as natural preparations containing living microorganisms that promote plant growth work through various mechanisms, including nitrogen fixation, phosphate solubilization, and the production of growth-promoting substances such as phytohormones. Some of the most commonly used biofertilizers include *Rhizobium*, *Azotobacter*, and mycorrhizal fungi. These microorganisms not only help plants access essential nutrients but also contribute to the improvement of soil structure and water retention capacity as well as enhance soil performance [19].

The concept of biofertilizers originated from the discovery of the symbiotic relationship between leguminous plants and nitrogen-fixing *Rhizobium* bacteria. Today, biofertilizers are used to improve the nutrient availability for various crops beyond legumes. Some common types include nitrogen-fixing bacteria (e.g., *Rhizobium, Azotobacter*), phosphate-solubilizing bacteria (e.g. *Bacillus*, *Pseudomonas*), and mycorrhizal fungi, which help plants in nutrient uptake and enhance root growth [20].

However, the widespread adoption of biofertilizers is not without its challenges. Issues such as inconsistent performance in different environmental conditions, limited shelf life and lack of awareness among farmers hinder the potential impact of biofertilizers in mainstream agriculture. Additionally, regulatory and quality control issues pose barriers to the commercialization of biofertilizers, as the efficacy of these products varies depending on the strains of microorganisms and the soil conditions [21]. Overcoming these challenges is crucial for the widespread adoption and successful commercialization of biofertilizers.

This review explores the prospects and challenges of different types of bioferilizers in achieving agricultural sustainability, considering their environmental benefits, economic feasibility, and practical limitations in modern farming systems.

## TYPES OF BIOFERTILIZERS

**Nitrogen biofertilizers:** This group fixes nitrogen symbiotically. Nitrogen is a limiting factor for plant growth because plants need a certain amount of nitrogen in the soil to thrive. Different bioferilizers have an optimum effect for different soils, so the choice of nitrogen biofertilizer to be used depends on the cultivated crop. *Rhizobia* are used for legume crops, *Azotobacter* or *Azospirillum* for non-legume crops, *Acetobacter* for sugarcane and blue-green algae and *Azolla* for lowland rice paddies [22].

a. *Rhizobium*: A symbiotic bacterium that associates with leguminous plants, forming nodules in their roots and fixing nitrogen. *Rhizobium* is widely used in legume cultivation [7].
b. *Azotobacter*: A free-living nitrogen-fixing bacterium found in non-legume soils. It is effective in enhancing nitrogen availability for cereals and vegetables [20].
c. Cyanobacteria (Blue-green algae): These photosynthetic microorganisms, including genera like *Anabaena* and *Nostoc*, fix nitrogen in paddy fields and aquatic ecosystems [18].

**Phosphorus biofertilizers:** Just like nitrogen, phosphorus is also a limiting factor for plant growth. Phosphorus biofertilizers help the soil to reach its optimum level of phosphorus and correct the phosphorus levels in the soil. Unlike nitrogen biofertilizers, the usage of phosphorus bioferiizers is not dependent on the crops cultivated on the soil. *Phosphatika* is used for all crops with *Rhizobium, Azospiillum* and *Acetobacter* [18].

a. *Bacillus* and *Pseudomonas*: These bacteria produce organic acids that help in dissolving insoluble phosphate [14].
b. Arbuscular Mycorrhizal (AM) Fungi: These fungi establish symbiotic relationships with plant roots, enhancing the uptake of phosphorus and other nutrients while improving soil structure [21].

**Compost biofertilizers:** Biofertilizers are also used for enrichment of compost and for enhancement of the bacterial processes that break down the compost waste. Suitable biofertilizers for compost use are cellulolytic fungal cultures and *Phosphotika* and *Azotobacter* cultures. A 100% pure eco-friendly organic fertilizer is Vermi Compost: this organic fertilizer has nitrogen, phosphorus, potassium, organic carbon, sulphur, hormones, vitamins, enzymes and antibiotics, which help to improve the quality and quantity of yield [22]. Obviously, continuous misuse of

chemical fertilizers makes the soil lose its fertility and becomes saline day by day. To overcome such problems, natural farming is the only remedy and Vermi compost is the best solution [23].

**Mycorrhizal biofertilizers:** Mycorrhizal are fungi that form symbiotic associations with plant roots, particularly arbuscular mycorrhizal fungi (AMF). These fungi improve the absorption of water and nutrients, such as phosphorus and enhance plant tolerance to stress [20].

**Plant Growth-Promoting Rhizobacteria (PGPR):** These bacteria inhabit plant roots and stimulate growth by producing phytohormones like auxins, cyokinins and gibberellins. PGPR strains such as *Pseudomonas fluorescens* and *Bacillus subtilis* also act as biocontrol agents by inhibiting pathogenic microorganisms [22].

## KEY MECHANISMS OF BIOFERTILIZERS

The success of biofertilizers in agriculture is largely based on several mechanisms through which they interact with soil and plants to improve nutrient availability and plant health as shown in Figure 1.

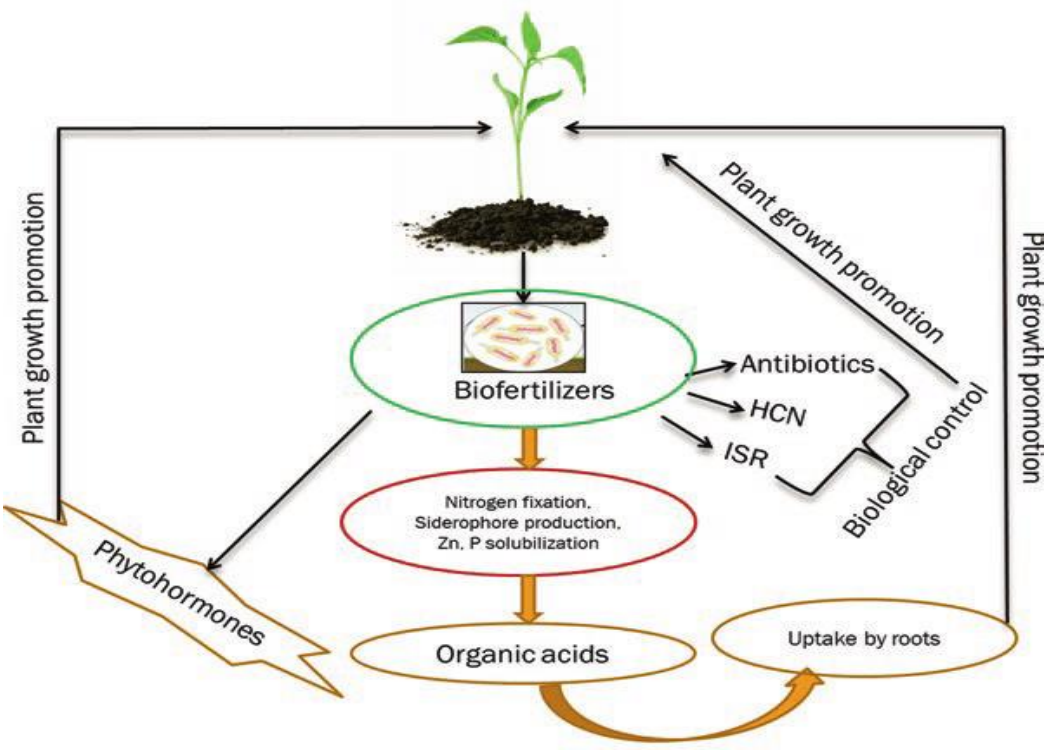



Figure 1: Plant growth promoting hormones and biocontrol properties [24].

**Nitrogen fixation:** Symbiotic nitrogen-fixing bacteria like *Rhizobium* form nodules on the roots of leguminous plants, converting atmospheric nitrogen ($N_2$) into ammonia ($NH_3$), a form that plants can absorb. Free-living bacteria like *Azotobacter* contribute to nitrogen fixation in non-legume crops, though on a smaller scale [22].

**Phosphate solubilization:** Phosphorus is a critical nutrient often locked in soil minerals in an insoluble form. Phosphate solubilizing microorganisms (PSMs) release organic acids and enzymes that convert these forms into soluble phosphates, improving phosphorus availability to plants [14].

**Production of Growth-Promoting Substances:** Biofertilizers, particularly PGPR, produce growth-promoting hormones like indole-3- acetic acid (IAA) and gibberellins. These substances enhance root growth, increase nutrient uptake and improve plant resilience to stress conditions [20].

**Disease suppression:** Many biofertilizers have biocontrol properties, where they suppress plant pathogens through the production of antibiotics, competition for resources, or inducing plant defense mechanisms. For example, *Pseudomonas* species produce secondary metabolites that inhibit the growth of harmful fungi and bacteria [22].

**Improvement of soil structure:** Mycorrhizal fungi and other microorganisms in biofertilizers enhance soil structure by stabilizing soil aggregates. They also improve soil porosity and water retention, thus creating a favourable environment for root growth and nutrient absorption [21]. Some biofertilizers and the species of organism implicated as well as their mode of action are summarized in Table 1.

Table 1: Classification of biofertilizers and their mechanism of action.

| Biofertilizers | Mechanism | Groups | Examples | References |
|---|---|---|---|---|
| **Nitrogen-fixing** | **Increase the amount of $N_2$ in the soil by fixing atmospheric nitrogen and making it available to plants.** | **Free-living, symbiotic, and associative symbiotic** | ***Aulosira bejerinkia, Nostoc, Klebsiella, Stigonema, Desulfovibrio, Azotobacter, Anabaena, Clostridium, Rhodospirillum*, and *Rhodopseudomonas* Rhizobium, Frankia, *Anabaena azollae*, and *Trichodesmium Azospirillum* spp., *Herbaspirillum* spp., *Alcaligenes, Enterobacter, Azoarcus* spp., and *Acetobacter diazotrophicus*** | [23]. |
| **Phosphorus-Mobilizing** | **Phosphorus is transferred from the soil to the root cortex. These are bio-fertilizers with a wide range of applications.** | **Mycorrhiza** | ***Arbuscular mycorrhiza, Acaulospora* spp., *Scutellospora* spp., *Glomus* spp., *Gigaspora* spp., and *Sclerocystis* spp.** | [23]. |
| **Potassium Solubilizing** | **Produce organic acids that degrade silicates and aid in the removal of metals to solubilize potassium (silicates) ions and make it available to plants.** | **Bacteria** | ***B. edaphicus, Arthrobacter* spp., *Bacillus, Mucilaginosus*, and *B. circulanscan*** | [24]. |
| **Potassium Mobilizing** | **They transfer potassium from the soil's inaccessible forms.** | **Bacteria** | ***Bacillus* spp.** | [25]. |
| | | **Fungi** | ***Aspergillus niger*** | |
| **Phosphorus Solubilizing** | **To dissolve bound phosphates, they secrete organic acids and lower soil pH by converting insoluble forms of P in the soil into soluble forms.** | **Bacteria, fungi** | ***Pseudomonas striata, Bacillus circulans, Bacillus subtilis, Penicilium spp., B. polymyxa, Agrobacterium, Micrococcus, Flavobacterium, Aereobacterium. Aspergillus awamori, Penicillum* spp., and *Trichoderma* spp.** | [23] |
| | **Sulfur is oxidized to sulfate, which is the usable form for plants.** | **Sulfur-oxidizing** | ***Thiobacillus* spp.** | [26]. |
| **Micronutrient** | **Protons, chelated ligands, acidification, and oxidoreductive systems can all be used to dissolve zinc.** | **Zinc-solubilizing** | ***Pseudomonas* spp., *Mycorhiza*, and *Bacillus* spp.** | [27]. |

| | | | | |
|---|---|---|---|---|
| **Plant growth-promoting** | **Produce hormones that encourage root growth, increase nutrient availability, and boost crop yields.** | **Plant growth-promoting rhizobacteria** | ***Agrobacterium, Pseudomonas fluorescens, Arthrobacter, Erwinia, Bacillus, Rhizobium, Pseudomonas* spp. *Enterobacter, Streptomyces,* and *Xanthomonas*** | [23]. |

Furthermore, different biofertilizers play different roles in the soil using various mechanisms which can be categorized into direct or indirect methods as shown in Figure 2.

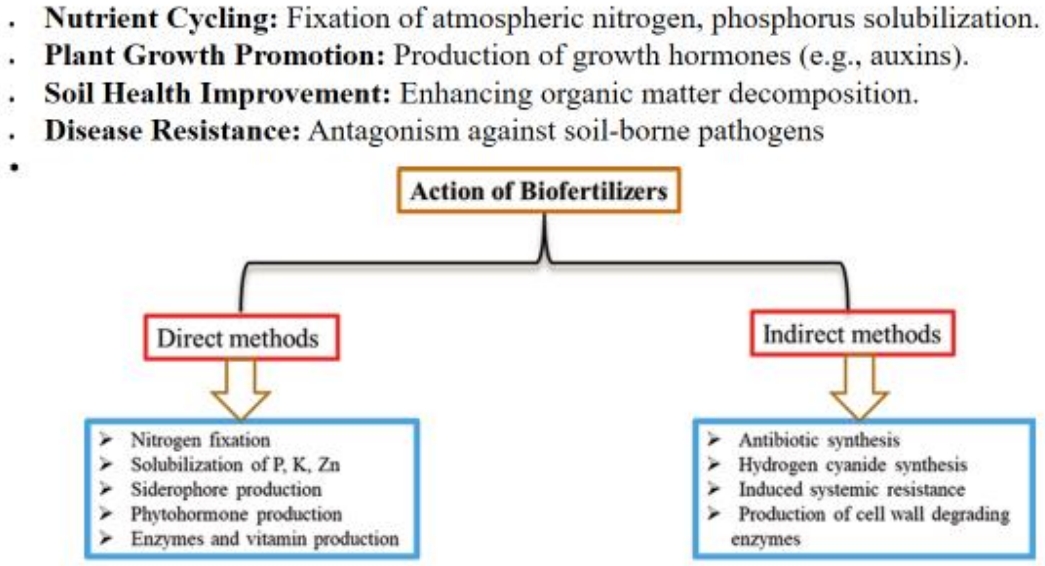



Figure 2: Different roles of Biofertilizers in the soil [25, 26]

## BENEFITS OF BIOFERTILIZERS

Biofertilizers offer numerous environmental and economic benefits that make them a sustainable alternative to synthetic fertilizers. As global agricultural practices seek to minimize their environmental impact, biofertilizers stand out for their ability to offer the following benefits;

- Mitigation of water pollution: Chemical fertilizers often cause eutrophication in water bodies leading to aquatic life degradation and water quality deterioration. However, biofertilizers, such as phosphate-solubilizing bacteria (PSB) and mycorrhizal fungi, improve the efficiency of nutrient uptake by plants, reducing the need for excessive chemical fertilizer application, thus preventing nutrient runoff into water bodies [20, 27].

- Reduction in Greenhouse Gas Emissions: The application of synthetic nitrogen fertilizers contribute to the release of nitrous oxide ($N_2O$), a potent greenhouse gas. Nitrogen-fixing biofertilizers, such as *Rhizobium*, *Azospirllum*, and *Azotobacter*, provide a sustainable source of nitrogen to plants through biological nitrogen fixation, reducing the demand for nitrogen fertilizers and subsequently lowering $N_2O$ emissions from agricultural fields [28].
- Enhanced Nutrient Cycling: Biofertilizers such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi enhance the natural nutrient cycles in the soil. Nitrogen-fixing biofertilizers convert atmospheric nitrogen into ammonia, which plants can directly use. Phosphate-solubilizing microorganisms convert insoluble phosphorus into soluble forms, making it available to plants [14, 29].
- Soil Structure and Organic Matter: Mycorrhizal fungi, mostly arbuscular mycorrhizal (AM) fungi, are known to improve soil structure and texture. The hyphae of these fungi form extensive networks that bind soil particles together, enhancing soil aggregation and porosity [21, 30].
- Increase in Soil Microbial Diversity: The application of biofertilizers helps boost the population and diversity of beneficial microorganisms in the soil unlike chemical fertilizers, which can harm soil biota by disrupting microbial balance. [8, 31].
- Reduction in Soil Degradation and Desertification: Biofertillizers help prevent soil erosion by improving soil structure and water retention. Mycorrhizal fungi, in particular, increase the stability of soil aggregates, which reduce the likelihood of erosion by wind and water. As soil erosion is a key contributor to desertification, biofertilizers can contribute to the reclamation of degraded lands [29, 32].
- Conservation of Biodiversity: The use of biofertilizers can support agricultural biodiversity by promoting crop diversity and reducing reliance on monoculture practices that degrade ecosystems. By improving soil performance and nutrient availability, farmers can grow a wider variety of crops sustainably, to enhance agro biodiversity. This is crucial for food security, ecosystem resilience and the conservation of traditional crop varieties [18, 33].
- Resilience to Environmental Stress: Biofertilizers, especially mycorrhizal fungi and PGPR, enhance plant resilience to environmental stressors such as drought, salinity, and extreme temperatures. Mycorrhizae improve water uptake in plants, helping them cope with drought

conditions, while PGPR produce stress-alleviating compounds that protect plants from oxidative damage under stressful conditions. This is mostly in regions vulnerable to climate change impacts, hence contributing to Climate-Smart Agriculture [28, 34].

- Biocontrol of Pests and Pathogens: Many biofertilizers have biocontrol properties that help manage pests and diseases in crops [35]. For example, *Bacillus subtilis* and *Pseudomonas fluorescens* produce antimicrobial compounds that suppress the growth of pathogenic bacteria and fungi, reducing the need for chemical pesticides. These biofertilizers can be used as part of an integrated pest management (IPM) strategy, reducing the environmental impact of synthetic pesticides [7, 36].

Bioferilizers have emerged as an environmentally sustainable alternative to chemical fertilizers in agriculture and their economic feasibility is a key consideration for their widespread adoption. The economic benefits of biofertilizers are outlined below.

- **Cost-effectiveness of Biofertilizers;** Biofertilizers are generally cheaper to produce and apply than chemical fertilizers, particularly nitrogen and phosphate-based fertilizers, which require significant energy inputs for production [37]. They are eco- friendly and cost effective.
- **Return on Investment (ROI);** ROI in biofertilizer use is a function of reduced costs and increased yields over time. Research indicates that biofertilizers offer positive ROI when integrated into sustainable agricultural systems [38].
- **Long-Term Benefits of Biofertilizers;** Biofertiiizers offer multiple long-term economic advantages, including sustainability, resilience to climate change, and improved soil fertility [39], thus may prevent the growth and multiplication of soil pathogens.
- **Challenges to Economic Feasibility;** While the economic benefits of biofertilizers are well-documented, several challenges affect their feasibility on a large scale. These challenges include issues related to production, market acceptance, and regulatory frameworks [40].

## CHALLENGES IN THE ADOPTION OF BIOFERTILIZERS

In spite of the environmental and economic benefits of biofertilizers, their widespread adoption faces several challenges (Figure 3) such as:




Figure 3: Opportunities and challenges in rhizosphere engineering [34, 41].

- Quality Control and Standardization: Ensuring the quality and efficacy of biofertilizers is a significant challenge. Biofertilizers must contain viable and effective strains of microorganisms to be effective. Variability in production processes and lack of standardization can lead to inconsistent product quality, which undermines farmer confidence and adoption [17, 42].
- Shelf Life and Storage: Biofertilizers often have a limited shelf life due to the sensitivity of microbial strains to environmental conditions such as temperature and humidity. Maintaining the viability of these microorganisms during storage and transport can be challenging and may require special packaging and storage conditions. This increases production and distribution costs, which can be a barrier to widespread use, especially in low-resource settings [18, 43].
- Scalability and Infrastructure: Scaling up the production of biofertilizers to meet growing demand requires significant infrastructure investment. Small-scale production facilities may lack the capacity to produce biofertilizers in large quantities or may not have the necessary technology for large-scale production. Additionally, establishing a robust distribution network

to ensure that biofertilizers reach farmers in remote areas is a logistical challenge [29,].

- Application Techniques; the methods for applying biofertilizers can be complex and require specific knowledge and equipment. Different types of biofertilizers may require different application techniques, such as seed coating, soil incorporation, or foliar spraying. Farmers may lack the expertise or resources to apply biofertilizers correctly, resulting to suboptimal results and reduced efficacy [28, 44].
- Compatibility with Conventional Input; Biofertilizers may not always be compatible with conventional chemical fertilizers or pesticides. In some cases, chemical fertilizers can inhibit the activity of beneficial microorganisms or disrupt their effectiveness. Farmers who are accustomed to using synthetic inputs may face challenges in integrating biofertilizers into their existing farming methods without compromising overall crop management [30, 45].
- Farmers Education and Training; Many farmers are not familiar with biofertilizers, their application and benefits. Lack of these information can hinder the adoption/integration of biofertilizer into agricultural practices in the society. Educating farmers on the advantages, proper application methods and expected results is vital for increasing adoption rates [21].
- Perceived Efficacy and Reliability: Some farmers may perceive biofertilizers as less effective or reliable compared to traditional chemical fertilizers. Negative experiences with poorly performing products or inconsistent results can lead to skepticism about the benefits of biofertilizers. Building trust through successful case studies, demonstrations, and endorsements from agricultural experts can help overcome these perceptions [18, 46].
- Cost and Affordability: The initial cost of biofertilizers can be a barrier to adoption, particularly for smallholder farmers in developing regions. While biofertilizers can reduce overall input costs in the long term, the upfront cost may be a challenge for farmers with limited financial resources. Providing subsidies, financial incentives, or low-cost options can help improve affordability and encourage adoption [20].
- Lack of Standardization and Regulation: In many regions, biofertilizers are not well-regulated, leading to issues with product quality and efficacy. The absence of standardized guidelines for production, labeling and testing can result in variability in product performance and consumer trust. Establishing clear regulations and certification processes is essential for ensuring the quality and safety of biofertilizers [29, 47].

- Market Access and incentives; Farmers may face difficulties accessing biofertilizers due to limited availability or high costs. Government policies and incentives, such as subsidies for biofertilizer purchases or support for local production facilities, can improve market access and encourage adoption. Policymakers need to create an enabling environment that supports the development and dissemination of biofertilizers [21].
- Compatibility with Agroecosystems; Biofertilizers must be compatible with the broader agroecosystem to be effective. Integrating biofertilizers into diverse cropping systems, including rotations and intercropping, requires careful consideration of their interactions with other components of the ecosystem. Research on the synergistic effects of biofertilizers in different farming systems can help optimize their use [28].

## ADVANCES IN BIOFERTILIZER TECHNOLOGY

- Isolation of Novel Strains: Researchers have isolated and characterized new strains of beneficial microorganisms, such as bacteria and fungi that exhibit superior growth-promoting and nutrient-enhancing capabilities. For example, recent studies have identified novel strains of *Rhizobium* and *Azotobacter* with improved nitrogen-fixing abilities and stress tolerance [22]. Additionally, new strains of phosphate-solubilizing bacteria have been discovered that can effectively mobilize phosphorus in diverse soil conditions [8, 48].
- Genetic Engineering; Advances in genetic engineering have enabled the development of genetically modified microbial strains with enhanced properties. For instance, genetically engineered *Rhizobium* strains with increased nitrogen-fixing efficiency and resistance to environmental stresses have been developed. These modifications improve the performance of biofertilizers in challenging agricultural environments [18].
- Synthetic Biology; Synthetic biology techniques are being employed to create novel microbial consortia with tailored functionalities. By combining different microorganisms with complementary traits, researchers are developing biofertilizer formulations that can simultaneously address multiple soil and plant needs, such as nitrogen fixation, phosphorus solubilization, and pathogen suppression [21].
- Cryopreservation and Stabilization: Advances in cryopreservation techniques have extended the shelf life of biofertilizers by preserving microbial viability during storage and transport.

Techniques such as freeze-drying and encapsulation are used to stabilize microorganisms and maintain their activity over extended periods [31, 49].

- Encapsulation Technologies: Encapsulation technologies protect microorganisms from environmental stresses and enhance their stability during storage and application. Methods such as alginate bead encapsulation, polymer coating, and nanoencapsulation are being used to improve the release and effectiveness of biofertilizers [20]. Nanoencapsulation can provides targeted delivery of microorganisms and nutrients, enhancing their availability to plants.
- Biofertilizer Delivery Systems: New delivery systems, such as seed coatings and soil inoculants, have been developed to enhance the application of biofertilizers. Seed coating technologies ensure that beneficial microorganisms are directly applied to seeds, improving germination and early plant growth. Soil inoculants are designed to deliver high concentrations of beneficial microorganisms directly to the root zone [32].
- Integrated Pest Management (IPM): Advances in biofertilizer technology are being integrated with IPM strategies to provide holistic solutions for pest and disease management. Biofertilizers that also act as biocontrol agents can reduce the need for synthetic pesticides and improve crop health. Research on the synergistic effects of biofertilizers and biocontrol agents is ongoing [33].

## PROSPECTS FOR BIOFERTILIZER USE IN GLOBAL AGRICULTURE

Biofertilizers, with their potentials, offer promising prospects for global agriculture. Their use is increasingly seen as a critical component of sustainable farming practices in modem agriculture as shown in Figure 3.

**Sustainability and Environmental Benefits:** The ability of biofertilizers to promote nitrogen fixation, phosphorus solubilization, and organic matter decomposition supports ecological balance and reduces greenhouse gas emissions [18, 50], hence, biofertilizers contribute significantly to sustainable agricultural practices

**Economic Advantages:** From an economic perspective, biofertilizers offer cost-effective alternatives to synthetic fertilizer by reducing input costs and improving crop yields through enhanced nutrient uptake. Furthermore, the use of biofertilizers can lower the costs associated with soil amendments and pest control. The economic feasibility of biofertilizer is supported by recent

advancements in production and formulation technologies that aim to make them more affordable and accessible [22].

**Technological Advancements:** Recent technological advances/innovations in microbial strain development, formulation techniques and application methods have enhanced biofertilizer effectiveness and versatility. Innovations such as nanoencapsulation, precision application technologies, and integrated pest management strategies have made biofertilizers more adaptable to diverse agricultural conditions and crop types [20, 51].

**Global Adoption Trends:** Globally, there is a growing trend towards the adoption of biofertilizers as part of integrated nutrient management strategies. Governments and organizations are increasingly recognizing the role of biofertilizers in achieving sustainable development goals and promoting environmentally friendly agricultural practices. The integration of biofertilizers into mainstream farming practices is supported by policies that encourage their use and by market-driven innovations that enhance their availability and effectiveness [29, 30].

## CONCLUSION

Biofertilizers represent a promising advancement in sustainable agriculture, offering significant benefits for enhancing soil fertility, improving crop yields and reducing environmental impacts associated with synthetic fertilizers. Their ability to improve nutrient availability, support plant growth and contribute to ecological balance underscores their potential as a key component of integrated nutrient management strategies. The advancements in microbial technology, formulation techniques and application methods have enhanced the effectiveness and versatility of biofertilizers, making them more adaptable to diverse agricultural contexts.

Despite their promising prospects, the adoption of biofertilizers faces several challenges. Issues related to product quality, shelf life and variability in effectiveness can hinder widespread use. Additionally, the need for greater farmer education, standardized regulations and cost-effective production methods remain critical. Addressing these challenges through continued research, technological innovation and supportive policies will be essential for realizing the full potentials of biofertilizers in promoting agricultural sustainability. While biofertilizers offer substantial opportunities for advancing sustainable agricultural practices, overcoming existing challenges will require collaborative efforts from research, policymakers and industry stakeholders. With

continued investment in research and development and the implementation of supportive policies and practices, biofertilizers have the potential to play a transformative role in achieving global agricultural sustainability goals as well directly supporting the UN Sustainable Development Goal 2; to achieve zero hunger.

**REFERENCES**

1. Karanja, A. W., Njeru, E. M. & Maingi, J. M. (2019) Assessment of physicochemical changes during composting rice straw with chicken and donkey manure. International *Journal of Recycling of Organic Waste in Agriculture* 8 (Suppl. I) S65-S72.
2. Chun-Li, W., Shiuan-Yuh, C. & Chiu-Chung, Y. (2014). Present situation and future perspective of bio-fertilizer for environmentally friendly agriculture, *Annual Reports*, 1-5,
3. Chittora, D., Meena, M., Barupal, T., Swapnil, P. & Sharma, K. (2020) Cyanobacteria as a source of biofertilizers for sustainable agriculture. *Biochemistry and Biophysics Report*s. 22, 100737
4. Pal, A. K., Chakraborty, A. & Sengupta, C. (2018). Differential effects ol plant growth promoting rhizobacteria on chilli (*Capsicum annuum* L.) seedling under cadmium and lend stress. *Plant Sci. Today* 5 (4): 182—90.
5. Li, Y., Shi, H., Zhang, H. & Chen, S. (2019). Amelioration of drought effects in wheat and cucumber by the combined application of super absorbent polymer and potential biofertilizer, *Peer* J7: e6073,
6. Ojuederie, O. B., Olanrewaju, O. S. & Babalola, O. O. (2019). Plant Growth Promoting Rhiziobacterial Mitigation of Drought Stress in Crop Plants: Implications for Sustainable Agriculture, *Agronomy*, 9, 712,
7. Kumar, A., Duhey, A. & Verma, A. (2020). Advances in biofertilizer production, formulation, and application technology: Current status and future prospects. *Agriculture*, I0 (9), 123- 145 *Sciences and Medicine Research*, 21, 1-30.
8. Nosheen, S., Ajmal, I. & Song, Y. (2021). Microbes as biofertilizers, a potential approach for sustainable crop production. *Sustainability* 13, 1868.
9. Bahadir, P. S., LI Aqat, F. & Eltem, R. (2018). Plant growth promoting properties of phosphate solubilizing Bacillus species isolated from the Aegean Region of Turkey. *Turkish Journal of Botany*. 42(2), 183-196.

11. Oliveira Filho, J. D. S., Viana, T. V. D. A., Azevedo, B. M. D., Sousa, G. G. D. & Pereira, M. G. (2019). Phosphorus forms and lability of organic matter during anaerobic digestion of swine manure. Semina: *Ciencias Agrarias*, 40(5Supll), 2107-2119.
12. Malboobi, M. A. Owlia, P. & Behbahani, M. (2009). Solubilization of organic and inorganic phosphates by three highly efficient soil bacterial isolates. *World Journal of Microbiology and Biotechnology*. 25(8), 1471-1477
13. Tjahjoleksono, A., Mubarik, N. R. & Fitriyanti, D. (2017). Characterization of phosphate solubilizing bacteria and nitrogen-fixing bacteria from limestone mining region. Malaysian *Journal of Microbiology*. 13(3), 147-155.
14. Alori, E- T., Glick, B. R. & Babalola, O. O. (2017). Microbial phosphorus solubilization and its potential for use in sustainable agriculture. *Frontiers in Microbiology*, 8, 971.
15. Patel, G., Singh, S., Saxena, D. S. K. & Kaur, D. K. J. (2016). Isolation, biochemical characteri/ati and production of biofertilizer from *Bacillus megaterium*. *The International Journal Life-Sciences Scientific Research*. 2(6), 749-752.
16. Chakma, P. Chowdhury, S. Bari, L. & Hoque, S. A. (2019) Feasible Way of Degrading Malathion Pesticide under Laboratory Condition Using Phosphate Solubilizing Bacteria. *Journal of Geoscience and Environment Protection*. 07(01), 1-12.
17. Sharma, S. B., Sayyed, R. Z., Trivedi, M. H. & Gobi, T. A. (2013). Phosphate solubilizing microbes: Sustainable approach for managing phosphorus deficiency in agricultural soil *Springerplus*. 2, 587.
18. Gouda, S., Kerry, R. G., Das, G., Paramithiotis, S., Shin, H. S. & Patra, J. K. (2018). Revitalization of plant growth-promoting rhizobacteria for sustainable development in agriculture. *Microbiological Research*, 206, 131-140.
19. Rao, N. S. & Reddy, M. S. (2020). Role of biofertilizers in agriculture: A brief overview. *Agricultural Sciences*, 11 (2), 109-119.
20. Sharma, A., Johri, B. N. Sharma, A. K. & Glick, B. K. (2019). Plant growth-promoting bacteria: Diversity, mechanisms of action, and perspectives for sustainable agriculture. *Critical Reviews in Biotechnology*, 39(2), 1-19.
21. Lugtenberg, B. & Kamilova, l. (2019), Plant-growth-promoting rhizobacteria. *Annual Review of Microbiology*, 63, 541-556.

22. Kumaar, S., Babu, R. P., Vivek, P. & Saravanan, D. (2020). Role of Nitrogen fixers as Biofertilizers in Future Perspective: A Review. *Res. J. Pharm. Technol*. 13, 2459-2467.
23. Nosheen, S, Ajmal, I, & Song, Y. (2022B). Microbes as bio fertilizers, a potential approach for sustainable crop production. Sustainability. 13(4), 1868.
24. Etesami, H., Emami, S. & Alikhani, H. A. (2017). Potassium solubilizing bacteria (KSB): Mechanisms, promotion of plant growth, and future prospects: A review. *J. Soil Sci. Plant Nutr*. 17, 897-911
25. Jha, Y. (2017). Potassium mobilizing bacteria: Enhance potassium intake in paddy to regulate membrane permeability and accumulate carbohydrates under salinity stress. *Braz. J. Biol. Sci.* 4, 333-344.
26. Itelima, J., Bang, W., Onyimba, I., Sila, M. & Egbere, O. (2018). Biofertilizers as key player in enhancing soil fertility and crop productivity: A review. *Direct Res. J. Agric. Food Sci*. 6, 73-83.
27. Kamran, S., Shahid, I., Baig, D. N., Rizwan, M., Malik, K. A. & Mehnaz, S. (2017). Contribution of zinc solubilizing bacteria in growth promotion and zinc content of wheat. *Front. Microbiol*. 8, 2593.
28. Adesemoye, A. O. & Kloepper, J. W. (2009). Plant-microbes interactions in enhanced fertilizer- use efficiency. *Applied Microbiology and Biotechnology*, 85(1), 1-12.
29. Hussain, A., Hasnain, S. & Robinson, Z. P. (2016). Biological nitrogen fixation and biofertiiizer technology for sustainable agriculture. Agricultural Research and Technology: *Open Access Journal*, 1(2), 1-9.
30. Meena, V. S., Maurya, B. R. & Verma, J. P. (2016). Potassium-solubilizing microorganisms for sustainable agriculture: Current trends, mechanism, and future aspects. *Ecological Engineering*, 51, 35-45.
31. Singh, B., Kumar, A. & Sharma, P. (2017). Effectiveness of *Rhizobium* and *Azotohacter* biofertilizers in improving the growth and yield of chickpeas. *Journal of Agronomy and Crop Science*, 203(5), 358-367.
32. Bardi, A. & Malusa, E. (2018). Drought and nutritional stresses in plant; Alleviating role of rhizospheric microorganisms. In *Abiotic Stress*: *New Research*; Nova Science Publishers, Inc.; Hauppauge, NY, USA. PP. 1-57.

33. Garcia, A. C., Mendez, G. & Gonzalez, F. (2019). Application of biofertilizers in sustainable coffee production: A case study from Colombia. *Sustainable Agriculture Research*, 8(3), 12-25.

34. Unurag, Y. & Kusum, Y. (2024). Challenges and Opportunities in Biofertilizer Commercialization. Department of Microbiology, C.R College of Agriculture, Sardarkrushinagar Dantiwada Agricultural University.

35. Bargaz, A. (2018). Soil microbial resources for improving fertilizers efficiency in an integrated plant nutrient management system. *Frontiers in Microbiology* 9, 1906.

36. Mahanty, T. (2017). Biofertilizers; a potential approach for sustainable agricultural development. *Environmental Science and Pollution Research*, 24, 3315 – 3335.

37. Bhattarcharyya, P. N. & Jha, D. K. (2012). Plant growth promoting rhizobacteria (PGPR): emergence in agriculture. *World journal of Microbiology Biotechnology* 28, 1327-1350.

38. Koud, D. (2020). Microbial biofertilizers: bioresources and eco-friendly technologies for sustainability. *Biocatalysis and Agricultural Biotechnology,* 23, 101487.

39 Aloo B. N. (2022). Plant growth promoting rhizobacterial biofertilizers for crop production: the past, present and future. *Frontiers in Plant Science* 13, 100448.

40. Herridge, D. F.; Peoples, M. B. & Boddy, R. M. (2008). Global inputs of biological nitrogen fixation in agricultural systems. *Plant and Soil*, 311, 1-18.

41. Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil*, 255, 571-586.

42. Pretty, J. (2018). Intensification for redesigned and sustainable agricultural systems. *Science*, 362.

43. Fukami, J. Cerezini, P. & Hungric, M. (2018). Azospirillum benefit that go far beyond biological nitrogen fixation. *AMB Express*, 8, 73.

44. Berruti, A. (2016). Arbuscular mycorrhizal fungi as natural biofertilizers; let's benefit from past successes. *Frontiers in Microbiology*, 6, 1559.

45. Backer, R. (2018). Plant growth promoting rhizobacteria: Context, Mechanisms of action and roadmap to commercialization of biostimulants for sustainable agriculture. *Frontiers in Plant Science*, 9, 1473.

46. Owen, D. (2015). Use of commercial bio-inoculants to increase agricultural production through improved phosphorus acquisition. *Applied Soil Ecology*, 86, 41-54.

47. Santos, M. S., Nogueria, M. A. & Hungria M. (2019). Microbial inoculant: reviewing the past, discussing the challenges and outlining future visions. *AMB Express*; 9, 205.

48. Sammauria, R. (2020). Microbial inoculant: Potential tool for sustainability of agricultural production systems. *Archives of Microbiology*, 202, 677-693.

49. Fadiji, A. E. (2024), Formulation challenges associated with microbial biofertilizers in sustainable agriculture and paths forward. *Journal of Sustainable Agriculture and Environment*. 10, 1002/sae2.70006.

50. Ibanez, A., Garrido-Chamorro, S., Vasco-Cardenas, M. F. & Barreiro, C. (2023). From lab. to field: Biofesrtilizers in the 21st century. Horticulturae, 9(12), 1306.

51. Goenadi, D. H., Mustafa, A. B. & Santi, L. P. (2018). Bio-organo-chemical fertilizers: A new prospecting technology for improving fertilizer use efficiency (FUE). IOP Conference Series: *Earth and Environmental Science*, 183, 012011.