

Biofertilizers: A Sustainable Path to Soil Health

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Abstract

Soil health determines the efficacy of sustainable agriculture, since decades of intensive farming and excessive chemical fertilizer use have deteriorated soil fertility, biodiversity, and natural nutrient cycles. Biofertilizers present a promising and eco-friendly solution to restore this balance. Derived from beneficial microorganisms, biofertilizers enhance nutrient availability by fixing nitrogen present in atmosphere, solubilizing phosphorus, mobilizing potassium, and stimulating root growth through natural biological processes. Unlike synthetic fertilizers, they work by strengthening plant-microbe interactions and improving soil microbial and biological activity rather than directly supplying nutrients. This article explores the different types of biofertilizers, including nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, mycorrhizae, cyanobacteria, and plant growth-promoting rhizobacteria, along with their mechanisms of action and practical application methods. It highlights their role in optimising soil structure, increasing crop productivity, reducing environmental pollution, and lowering input costs for farmers. While challenges such as storage stability and field variability exist, advancements in microbial research are expanding their potential. By improving soil life and promoting long-term fertility, biofertilizers offer a sustainable pathway toward resilient farming systems and future food security.

Keywords: Biofertilizers, Microorganisms, Cyanobacteria, Rhizobacteria and Food Security

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Introduction

As the world's population grows, producing enough food for the future has become a major challenge. Healthy soil is the foundation of agriculture, yet decades of intensive farming and heavy use of inorganic fertilizers and chemical pesticides have damaged soils worldwide. This has reduced soil fertility, lowered biodiversity, weakened water retention and disrupted natural nutrient cycles (Kumar *et al.*, 2017). Soil fertility status and crop productivity depend greatly on the interaction between plants and the microorganisms residing in the soil. These microbes play an important role in supporting plant growth by maintaining soil balance and making nutrients available. When this natural partnership is disturbed, crop performance and soil quality decline.

Biofertilizers offer a sustainable solution to restore soil health. They are made from beneficial microorganisms, they increase microbial activity in the soil, improve nutrient availability and enhance the breakdown of organic matter. By supporting diverse and active microbial communities, biofertilizers helps in improving soil health and crop growth in an environmentally friendly way. Plants need essential nutrients to grow, most of which must be absorbed from the soil. Biofertilizers help by converting nutrients into forms that plants can easily use, such as fixing nitrogen and improving the availability of phosphorus and micronutrients (Sharma *et al.*, 2024). They can be applied to seeds, soil, roots, or leaves, where they multiply and support nutrient uptake. By improving soil health naturally, biofertilizers promote healthier crops, better yields and long-

term agricultural sustainability making them an important tool for the future of farming.

What Are Biofertilizers?

Biofertilizers are products made from beneficial microorganisms, either living or dormant, that support plant growth by improving nutrient availability in the soil. Rather than supplying nutrients directly, they enhance natural soil processes by fixing atmospheric nitrogen, mobilizing nutrients already present in the soil, and releasing compounds that promote plant development (Kumar *et al.*, 2017).

How biofertilizers work?

Biofertilizers are formulations containing beneficial microorganisms that may exist in active or dormant forms. These microorganisms assist plant growth by increasing the availability of nutrients in the soil. Instead of directly supplying nutrients, biofertilizers stimulate natural soil processes such as atmospheric nitrogen fixation, mobilization of existing nutrients, and the production of substances that encourage plant development (Kumar *et al.*, 2017).

How Biofertilizers Work

Biofertilizers improve plant growth by strengthening the natural biological processes that regulate nutrient cycling and soil fertility. Rather than adding nutrients to the soil, they help plants utilize the nutrients that are already available more efficiently.

- **Nutrient Mobilization and Availability:** Microorganisms present in biofertilizers transform nutrients in the soil into forms that plants can easily absorb. Processes like biological nitrogen fixation and phosphorus solubilization help maintain a continuous supply of important nutrients required for healthy plant growth (Kumar *et al.*, 2017).
- **Improved Root Growth and Nutrient Uptake:** Biofertilizers also promote better root development by producing natural growth-stimulating substances. Strong and well-developed roots enable plants to absorb water and nutrients more effectively, which ultimately leads to better crop growth and productivity (Sharma *et al.*, 2024).
- **Enhanced Microbial Activity in Soil:** Applying biofertilizers increases the population of beneficial microorganisms in the soil. These microbes break down organic materials, release nutrients, and improve soil

structure, creating a more balanced and fertile environment for crop growth (Sharma *et al.*, 2024).

Types of Biofertilizers

Biofertilizers are broadly classified based on the microorganisms they contain or the specific nutrients they help plants absorb. Each type plays a unique role in supporting soil health and plant growth (Vessey, 2003). Below are the important categories farmers and agronomists use in sustainable crop management.

1. Nitrogen-Fixing Biofertilizers

Nitrogen is one among the most essential nutrients for plants, yet most crops can't use atmospheric nitrogen directly. Nitrogen-fixing biofertilizers contain microorganisms which convert atmospheric nitrogen into plant-usable forms like ammonia and nitrates (Vessey, 2003). These biofertilizers improve soil nitrogen naturally which reduces the need for synthetic nitrogen fertilizers.

Common examples:

- Rhizobium – Works symbiotically with legume crops such as peas, beans, chickpeas, and soybeans by forming nodules on roots.
- Azotobacter – A free-living bacterium ideal for cereals, vegetables and non-leguminous crops.
- Azospirillum – Associates with plant roots and stimulates root growth in crops like maize, wheat and sugarcane.



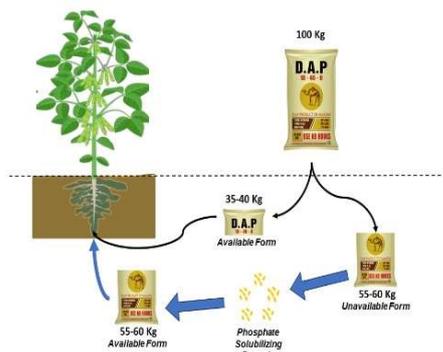
Fig 1(a). Rhizobium root nodules on cowpea

Fig. 1(b). Nitrogen fixation in root of legumes

2. Phosphate-Solubilizing Biofertilizers (PSB)

Phosphorus, present in the soil mainly as phosphate compounds, plays an important role in root development, flowering, and fruit formation in plants. However, a large portion of soil phosphorus remains in insoluble forms that plants cannot readily utilize. Phosphate-solubilizing microorganisms (PSMs) such as *Bacillus*, *Pseudomonas*, *Aspergillus*, and *Penicillium* help convert these unavailable forms into soluble phosphate that plants can absorb easily. The application of phosphate-solubilizing biofertilizers therefore promotes better root

development, improves nutrient uptake, and



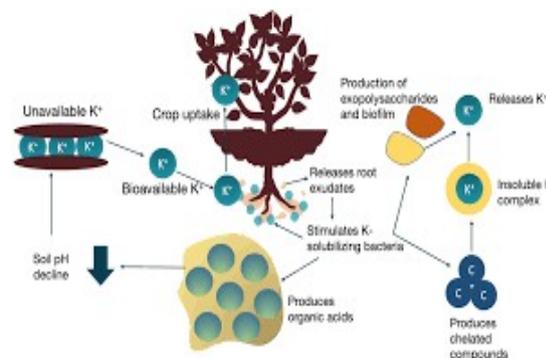
enhances overall plant growth, particularly in soils where phosphorus availability is limited.

Fig. 2. Mobilization of phosphate by PSB

3. Potassium-Mobilizing Biofertilizers

Potassium is often called the “quality nutrient” because it enhances crop resilience, water regulation and fruit quality. Potassium-mobilizing biofertilizers contain bacteria such as *Bacillus mucilaginosus* and *Frateria aurantia* that release potassium from mineral-bound forms. They not only reduce the requirement for chemical potash fertilizers but also improve drought tolerance and disease resistance in crops.

Fig. 3. Pottasium Mobilization



4. Mycorrhizal Biofertilizers (Fungal)

Mycorrhizae are symbiotic fungi which are known to form associations with plant roots, creating a vast network of filaments that act as extensions of the root system and also establish an underground plant-to-plant communication system called the wood wide web. Arbuscular Mycorrhizal Fungi (AMF), such as *Glomus* and *Rhizophagus* species are the most common in biofertilizer formulations. They significantly increase the uptake of phosphorus, zinc, and water, especially in horticultural, forestry and plantation crops. Mycorrhizae also enhance plant tolerance to drought and soil-borne diseases which makes them ideal for long-term soil productivity and health.

5. Cyanobacterial Biofertilizers

Commonly referred to as Blue-Green Algae (BGA), these photosynthetic microorganisms have the ability to fix atmospheric nitrogen under waterlogged conditions. Because of this property, they are widely used in paddy fields. BGA can naturally contribute around 20–30 kg of nitrogen per hectare during a cropping season. Genera such as *Anabaena* and *Nostoc* help enrich soil fertility while also increasing organic matter and promoting microbial diversity, making them valuable for sustainable rice cultivation (Havlin *et al.*, 2016).

6. Plant Growth-Promoting Rhizobacteria (PGPR)

PGPRs are the beneficial bacteria which are known to colonize plant roots and stimulate growth through multiple mechanisms. They:

1. Produce plant hormones such as auxins and cytokinins that enhance root development.
2. Suppress soil pathogens through natural antibiotic production.
3. Improve nutrient uptake and stress tolerance.

Pseudomonas fluorescens, *Bacillus subtilis* and *Enterobacter* species are common PGPR strains used in integrated nutrient management programs.

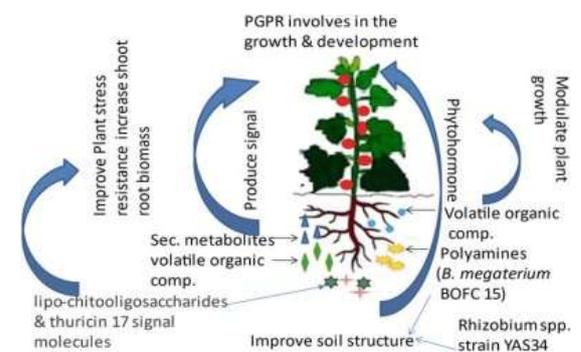


Fig. 4. Role of PGPR in enhancing the plants growth and productivity

7. Bio-Organic or Composite Fertilizers

Bio-organic fertilizers are produced by combining organic materials such as compost or vermicompost with a mixture of beneficial microorganisms. This combination provides a dual advantage by supplying nutrients from organic matter while also stimulating microbial activity in the soil. Such formulations are becoming increasingly popular because they help improve soil fertility in a holistic manner by enhancing the physical, chemical, and biological properties of the soil. In addition, bio-organic

fertilizers are well suited for use in most organic farming systems.

Benefits of Biofertilizers

1. Biofertilizers contribute to sustainable agriculture by promoting healthier soils and balanced crop production. Through the activity of beneficial microorganisms, they strengthen natural biological processes that support plant growth, maintain soil fertility, and help preserve environmental balance.
2. Improvement of soil fertility is one of the major advantages of biofertilizers. These microorganisms help fix atmospheric nitrogen, solubilize phosphorus, and mobilize micronutrients that already exist in the soil, making them more available to plants (Mahanty *et al.*, 2017). This process enhances nutrient availability while maintaining soil biodiversity and long-term productivity.
3. Enhanced plant growth and yield is another important benefit. Many biofertilizers contain microorganisms that produce natural plant growth-promoting substances, which stimulate stronger root development and improve nutrient absorption. Healthy root systems ultimately lead to better plant growth and more stable yields.
4. Environmental sustainability is a key advantage of biofertilizers. Their use reduces dependence on synthetic fertilizers, minimizes pollution, lowers greenhouse gas emissions, and helps prevent long-term soil degradation, making them an important component of sustainable agriculture (Mahanty *et al.*, 2017).
5. Cost-effectiveness for farmers is another benefit. After application, beneficial microbes multiply in the soil and continue improving soil health, which reduces the need for repeated chemical fertilizer inputs. This can lower production costs while maintaining crop productivity.
6. Biofertilizers also improve soil structure and water retention capacity, which helps crops tolerate drought and other environmental stresses. Because they are naturally derived, they can be easily integrated into organic and natural farming systems.

7. By improving soil health and nutrient cycling today, biofertilizers help sustain agricultural productivity for future generations.

How to Use Biofertilizers: Application Methods

Selecting an appropriate biofertilizer is important, but its correct application is equally essential for obtaining good results. Since biofertilizers contain living microorganisms, they must be handled carefully so that the microbes remain viable and active when applied to the soil or plant roots. When used properly, these beneficial organisms can improve nutrient availability, stimulate root growth, and enhance overall crop performance.

Biofertilizers are available in different formulations designed to suit various crops and agricultural practices. Solid or carrier-based formulations, often prepared using materials such as peat or compost, are widely used for



seed treatment and soil application. Liquid biofertilizers contain a high concentration of active microbial cultures and generally have a longer shelf life. They can be conveniently applied through drip irrigation systems, foliar sprays, or root dipping methods. Granular or pelletized formulations can be applied directly to the soil during planting or mixed with compost to ensure even distribution in the field (Dubey, 2022). Regardless of the formulation used, the success of biofertilizers largely depends on creating conditions that allow the microorganisms to establish and multiply in the root zone, where they can effectively interact with plant roots.

One of the most effective application methods is seed treatment. In this method, biofertilizer is mixed with water or a natural adhesive to form a slurry, which is then used to coat seeds evenly. Treated seeds should be dried in the shade and sown within 24 hours. This early contact allows microbes to colonize young roots quickly, improving nutrient uptake and protecting

seedlings from soil-borne diseases (Shahzad *et al.*, 2025).

- Soil application is ideal for carrier-based and granular biofertilizers. The product is mixed with compost or well-decomposed farmyard manure and spread evenly across the field before sowing or during the final ploughing (Shahzad *et al.*, 2025). Applying biofertilizers in moist soil and avoiding direct sunlight helps maintain microbial viability.
- For transplanted crops such as rice, vegetables and fruit saplings, root dipping is highly effective. Seedling roots are dipped in a biofertilizer solution before transplanting, ensuring direct microbial contact with root surfaces (Shahzad *et al.*, 2025). This promotes faster establishment and healthier early growth.
- Foliar spraying is another convenient option, particularly for liquid biofertilizers. When sprayed on leaves during early growth stages or periods of stress, certain beneficial microbes can enter through leaf pores and support nutrient absorption and plant health (Shahzad *et al.*, 2025).

Role of Biofertilizers in soil fertility and Sustainable Agriculture

1. Biofertilizers complement chemical fertilizers by helping crops meet their nutrient requirements through biological processes.
2. Nitrogen-fixing microorganisms can contribute significant amounts of nitrogen to the soil. For example, *Rhizobium* may supply about 50–100 kg N/ha/year, while *Azospirillum* and *Azotobacter* contribute 20–40 kg N/ha/year. Similarly, *Azolla* can add 40–80 kg N/ha, and Blue-Green Algae (BGA) about 20–30 kg N/ha under favourable soil conditions. These contributions may increase crop yield by 15–25% (Havlin *et al.*, 2016).
3. By improving nutrient availability, biofertilizers can reduce the dependence on chemical fertilizers, sometimes lowering nitrogen fertilizer requirements by 40–50 kg N/ha under ideal agronomic conditions.
4. Application of biofertilizers enhances root development, vegetative growth, nutrient uptake, and biological nitrogen fixation, ultimately improving crop productivity (Vessey, 2003).
5. Certain microorganisms such as *Rhizobium*, *Azotobacter*, and BGA

produce growth-promoting substances including vitamin B-complex, indole acetic acid (IAA), and gibberellic acid, which stimulate plant growth.

6. Phosphate-solubilizing microorganisms including bacteria, fungi, and mycorrhiza convert insoluble phosphorus compounds in soil into plant-available forms by secreting organic acids. Under favourable conditions, they may solubilize 30–50 kg P₂O₅ per hectare, which can increase crop yield by 10–20% (Havlin *et al.*, 2016).
7. Mycorrhizal fungi (VAM) improve the uptake of nutrients such as phosphorus, zinc, and sulphur as well as water. They also enhance plant resistance to root diseases, improve transplant survival, and contribute to better crop growth and yield (Sharma *et al.*, 2024).
8. Some biofertilizer microorganisms act as biocontrol agents, suppressing soil-borne plant pathogens and reducing the incidence of certain diseases.
9. Nitrogen-fixing, phosphate-mobilizing, and cellulolytic microorganisms present in biofertilizers increase the availability of plant nutrients in the soil and support sustainable agricultural production systems (Sharma *et al.*, 2024).
10. Biofertilizers are environment-friendly, renewable, and cost-effective, making them an attractive alternative to excessive chemical fertilizer use.
11. They help improve soil structure, soil tilth, and overall soil health.
12. By enhancing microbial activity and nutrient cycling, biofertilizers contribute to improved soil fertility and long-term productivity.
13. Certain blue-green algae such as *Nostoc*, *Anabaena*, and *Scytonema* are also useful in the reclamation of alkaline soils.
14. Bio-inoculants containing cellulolytic and lignolytic microorganisms accelerate the decomposition of organic matter in soil and compost, thereby improving nutrient recycling.
15. In tropical rice ecosystems, BGA plays a significant role in the nitrogen economy of paddy fields. Likewise, *Azotobacter* inoculation in non-leguminous crops can promote seed germination and early plant vigor through the production of growth-promoting substances (Sharma *et al.*, 2024).

16. *Azolla* associated with *Anabaena* grows abundantly as a floating plant in flooded rice fields. It can produce large amounts of biomass and fix 100–150 kg N/ha/year, playing an important role in nutrient recycling in rice-based systems (Sharma *et al.*, 2024; Havlin *et al.*, 2016).

Challenges and Limitations

1. Although biofertilizers provide several advantages, their widespread adoption still faces certain limitations. One of the major challenges is related to storage and shelf life. Since these products contain living microorganisms, unfavourable conditions such as high temperatures, exposure to direct sunlight, or loss of moisture during storage can reduce the viability and effectiveness of the microbes.
2. The field performance of biofertilizers may also vary depending on several factors, including soil characteristics, climatic conditions, crop type, and farm management practices. In many cases, the positive effects of biofertilizers appear gradually rather than immediately, which may discourage farmers who are accustomed to the quick results often associated with chemical fertilizers.
3. Another important limitation is the lack of awareness and technical knowledge among farmers. Successful use of biofertilizers requires proper storage, correct application techniques, and appropriate timing. Therefore, strengthening farmer training programs, extension services, and practical field demonstrations is essential to promote their effective adoption.

Future Prospects

1. The future of biofertilizers appears encouraging with ongoing advancements in microbial research and formulation technologies. Efforts are being made to develop more stable products with longer shelf life and strains that can perform consistently under diverse soil and climate conditions.

2. Increasing attention is being given to microbial consortia that combine multiple beneficial organisms. These formulations offer wider benefits by improving nutrient availability, enhancing plant resilience to stress and reducing disease incidence.
3. With the growing emphasis on sustainable farming, biofertilizers are expected to become an integral part of agricultural systems that focus on soil health, environmental safety and long-term productivity.

Conclusion

Biofertilizers provide an effective and environmentally responsible alternative to conventional inputs in modern agriculture. By naturally improving soil fertility and strengthening plant-microbe interactions, they support stable crop production while minimizing ecological harm. As agriculture seeks to balance productivity with environmental protection, biofertilizers offer a viable solution. Their adoption can help build resilient farming systems that meet present food demands while safeguarding soil resources for future generations.

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