



Biofertilizer: Effect on soil properties and crop production

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Abstract

The continuous and imbalanced use of chemical fertilizers has led to declining soil health, low fertilizer use efficiency and environmental problems such as nutrient losses and soil degradation, highlighting the need for sustainable nutrient management strategies. Biofertilizers, which contain beneficial microorganisms, have emerged as eco-friendly inputs capable of improving soil fertility and crop productivity. This review summarizes the role of biofertilizers in relation to soil properties, crop production and fertilizer use efficiency, with emphasis on their integration with recommended fertilizer practices. Biofertilizers enhance the availability of essential nutrients such as nitrogen, phosphorus and potassium through biological nitrogen fixation, nutrient solubilization and mobilization processes. Their application improves soil physical properties, including aggregation and water holding capacity, chemical properties such as nutrient availability and pH regulation and biological properties such as microbial biomass and soil enzyme activities. Biofertilizers also stimulate root growth and nutrient uptake through phytohormone production and mycorrhizal associations, resulting in improved nitrogen use efficiency (NUE), phosphorus use efficiency (PUE) and overall fertilizer use efficiency (FUE). Evidence indicates that biofertilizers are most effective when applied in combination with the Recommended Dose of Fertilizers (RDF) or Recommended Dose of Nitrogen (RDN), rather than when used alone, leading to higher crop yields and better nutrient recovery. Overall, integration of biofertilizers with chemical fertilizers under Integrated Nutrient Management (INM) is recommended for sustainable crop production, improved soil health and reduced dependence on chemical fertilizers, while long-term, multi-location field trials are needed to refine recommendations across diverse agro-climatic conditions.

Keywords: Biofertilizer, soil properties, fertilizer use efficiency, sustainable agriculture

Introduction

Biofertilizers are substances containing living microorganisms that colonize the rhizosphere or interior of plants, promoting growth by increasing the supply or availability of primary nutrients. These microorganisms play a significant role in regulating the dynamics of organic matter decomposition and the availability of plant nutrients such as nitrogen, phosphorus, potassium and micronutrients. Biofertilizers contribute to integrated nutrient management, leading to sustainable agriculture and reduced dependency on chemical fertilizers. They also improve soil fertility, soil structure, water retention, pH regulation and biological activity. They enhance microbial diversity and activity in the soil, creating a biologically active ecosystem. Biofertilizers contribute to the long-term sustainability of soil fertility, reduce dependency on chemical fertilizers and prevent soil erosion. They also improve seed germination, early growth, nutrient value and shelf life. They help to improve fertilizer use efficiency.

Objectives of the Review

The present review was undertaken with the following specific objectives:

1. To summarize the major types of biofertilizers and explain their mechanisms of action involved in nutrient fixation, solubilization, mobilization and plant growth promotion.
2. To evaluate the role of biofertilizers in improving soil properties, including physical, chemical and biological attributes and their impact on overall soil health.

3. To assess the contribution of biofertilizers to crop productivity, with emphasis on nutrient availability, root development and yield enhancement.
4. To analyse the effect of biofertilizers on fertilizer use efficiency (FUE), particularly nitrogen, phosphorus and potassium use efficiency under integrated nutrient management systems.
5. To highlight the limitations and prospects of biofertilizers, focusing on technological gaps, field-level constraints and emerging research directions for sustainable agriculture.

What are biofertilizers?

Biofertilizers play an important role in improving the nutrient supplies and their crop availability in the years to come. These are non-bulky, environment-friendly and low-cost inputs in agriculture. A biofertilizer is an organically produced product with a specific type of microorganism, either obtained from plant roots or from the soil in the plant root zone (Swathi, 2010) [20]. Biofertilizers are also called microbial inoculants and can be generally described as containing living microorganisms of efficient strain for nitrogen fixing, solubilization and mobilization of P and K, increasing organic carbon, balanced carbon/nitrogen contents, promotion of plant growth through enhancing absorption of nutrients, antagonistic activity against plant pathogens and plant hormones production useful for agriculture (Borkar, 2015) [5].

Types of Biofertilizers

Nitrogen fixing biofertilizer: Nitrogen-fixing biofertilizers consist of free-living, associative and symbiotic microorganisms capable of converting atmospheric nitrogen (N₂) into plant-available forms through the activity of the nitrogenase enzyme complex.

Mechanism of action: In symbiotic systems, *Rhizobium* forms root nodules in leguminous plants, where atmospheric N₂ is reduced to ammonia (NH₃) under microaerophilic conditions maintained by leghaemoglobin. Free-living bacteria such as *Azotobacter* and associative bacteria like *Azospirillum* fix nitrogen independently in the rhizosphere. Cyanobacteria (blue-green algae) fix nitrogen through specialized cells called heterocysts, particularly in flooded rice ecosystems.

Target crops: Legumes (pulses, soybean, groundnut): *Rhizobium*; Cereals and millets: *Azotobacter*, *Azospirillum*; Rice: Cyanobacteria, *Azolla–Anabaena* system

Soil conditions: Neutral to slightly acidic pH, Adequate organic carbon, Low to moderate available nitrogen, good soil aeration (except flooded rice fields) (Timofeeva *et al.*, 2023) [21].

Phosphate-solubilizing biofertilizer (PSB): Phosphate-solubilizing biofertilizers include bacteria and fungi that convert insoluble inorganic phosphates into soluble forms. Mechanism of action: PSB solubilize phosphorus mainly by secreting organic acids (gluconic, citric, oxalic acids), which lower soil pH and chelate cations such as Ca²⁺, Fe³⁺ and Al³⁺ bound to phosphate. This process releases soluble orthophosphate ions that plants can readily absorb.

Target crops: Cereals (wheat, rice, maize), Oilseeds, Vegetables and fruit crops

Soil conditions: Alkaline and calcareous soils (Ca-P dominance), Soils with high phosphorus fixation, Moderate moisture and temperature (Timofeeva *et al.*, 2022) [22].

Potassium-Mobilizing biofertilizer: Potassium-mobilizing biofertilizers enhance potassium availability by releasing K from insoluble mineral sources.

Mechanism of action: These microorganisms produce organic acids and polysaccharides that weather potassium-bearing minerals such as feldspar and mica. The acids break mineral lattices, releasing K⁺ ions into the soil solution, thereby improving potassium nutrition.

Target crops: Cereals, Sugarcane, Horticultural crops
Soil conditions: K-deficient soils, Soils rich in mica and feldspar, Adequate soil moisture (Kumar *et al.*, 2022) [14].

Phosphate-mobilizing biofertilizer: Mycorrhizal biofertilizers form a symbiotic association between fungal hyphae and plant roots.

Mechanism of action: Arbuscular mycorrhizal fungi (AMF) develop an extensive hyphal network beyond the root depletion zone, increasing the effective root surface area. They enhance phosphorus uptake through hyphal transport mechanisms and improve absorption of micronutrients such as Zn and Cu.

Target crops: Cereals, Pulses, Horticultural and plantation crops

Soil conditions: Low available phosphorus, Well-drained soils, reduced chemical phosphorus application (Chaudhary *et al.*, 2022) [6].

Plant Growth-Promoting Rhizobacteria (PGPR): PGPR are beneficial bacteria that stimulate plant growth directly and indirectly.

Mechanism of action: PGPR enhances plant growth by producing phytohormones (IAA, gibberellins, and cytokinins), solubilizing nutrients, fixing nitrogen and suppressing plant pathogens through antibiotic production, siderophore release and induced systemic resistance (ISR).

Target crops: Cereals, Vegetables, Oilseeds and pulses

Soil conditions: Rhizosphere-rich soils, Moderate organic matter, non-saline to mildly saline soils (Chaudhary *et al.*, 2022) [6].

Role of biofertilizers in crop production

1. Regulation of Nutrient Availability and Organic Matter Dynamics: Soil microorganisms introduced through biofertilizers play a crucial role in decomposition of organic matter and nutrient cycling, thereby increasing the availability of essential plant nutrients such as nitrogen (N), phosphorus (P) and potassium (K). Nitrogen-fixing bacteria convert atmospheric nitrogen into plant-available forms, while phosphate-solubilizing and potassium-mobilizing microorganisms transform insoluble nutrient forms into soluble forms, enhancing nutrient uptake and crop growth (Vessey, 2003; Bhattacharyya & Jha, 2012) [4, 23].

Table 1: Types of biofertilizers, microorganisms, major functions and target crops

| Biofertilizer type | Microorganisms | Major function (mechanism-based) | Target crops |
|--|--|--|-------------------------------------|
| Nitrogen-fixing biofertilizers (Symbiotic) | <i>Rhizobium</i> spp. | Fix atmospheric N ₂ into ammonia via the nitrogenase enzyme in root nodules under microaerophilic conditions. | Pulses, soybean, groundnut, legumes |
| Nitrogen-fixing biofertilizers (Free-living) | <i>Azotobacter</i> spp. | Free-living nitrogen fixation produces growth-promoting substances (IAA, GA) | Cereals, vegetables, cotton |
| Nitrogen-fixing biofertilizers (Associative) | <i>Azospirillum</i> spp. | Associative N ₂ fixation in the rhizosphere enhances root growth and nutrient uptake. | Rice, wheat, maize, millets |
| Cyanobacterial biofertilizers | <i>Anabaena</i> , <i>Nostoc</i> , <i>Scytonema</i> | Nitrogen fixation through heterocyst improves soil fertility in flooded systems. | Rice (paddy fields) |
| Azolla biofertilizer | <i>Azolla–Anabaena</i> symbiosis | Biological nitrogen fixation and organic matter addition | Rice |

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| Phosphate-solubilizing biofertilizers (PSB) | <i>Pseudomonas</i> spp., <i>Bacillus</i> spp. | Solubilize insoluble P by secretion of organic acids and phosphatases | Cereals, oilseeds and vegetables |
| Phosphate-mobilizing biofertilizers | Arbuscular mycorrhizal fungi (AMF), Ectomycorrhiza | Mobilize P through an extensive hyphal network beyond the root depletion zone | Cereals, pulses, horticultural crops |
| Potassium-mobilizing biofertilizers | <i>Frateruria aurantia</i> , <i>Bacillus</i> spp. | Release K ⁺ from mineral sources by organic acid production and mineral weathering. | Sugarcane, cereals, horticultural crops |
| Plant Growth-Promoting Rhizobacteria (PGPR) | <i>Pseudomonas fluorescens</i> , <i>Bacillus subtilis</i> , <i>Azospirillum</i> | Produce phytohormones, enhance nutrient uptake, suppress pathogens (ISR) | Cereals, vegetables, pulses, oilseeds |

- 2. Role in Integrated Nutrient Management (INM):** Microbial inoculants are recognized as a vital component of integrated nutrient management systems, where they complement chemical fertilizers and organic inputs. Biofertilizers improve nutrient use efficiency, reduce nutrient losses and maintain soil biological activity, resulting in sustainable crop production over the long term (Malusa *et al.*, 2012; Shabbir *et al.*, 2019) [15, 18].
- 3. Enhancement of Crop Productivity and Economic Benefits:** Biofertilizers contribute to higher crop yields by improving root growth, nutrient uptake and physiological efficiency of plants through phytohormone production and enhanced rhizosphere activity. Their use allows a reduction in chemical fertilizer doses, lowering input costs and increasing net returns to farmers, making them an economically viable option in crop production systems (Kumar *et al.*, 2017; Chaudhary *et al.*, 2022) [6, 13].
- 4. Reduction in Dependency on Chemical Fertilizers:** Regular application of biofertilizers reduces dependency on synthetic fertilizers by partially meeting crop nutrient requirements through biological processes. This not only lowers production costs but also minimizes environmental problems associated with excessive chemical fertilizer use, such as soil degradation and nutrient leaching (Bhattacharyya & Jha, 2012; ICAR, 2021) [4].
- 3. Regulation of Soil pH:** Certain biofertilizers, especially phosphate-solubilizing microorganisms, influence soil pH by producing organic acids such as gluconic, citric and oxalic acids. These acids lower soil pH in alkaline soils and solubilize calcium-bound phosphates, thereby improving nutrient availability. This pH regulation enhances nutrient uptake efficiency and soil chemical balance (Kumar *et al.*, 2017; Timofeeva *et al.*, 2022) [13, 22].
- 4. Enhancement of Beneficial Microbial Activity:** Biofertilizers stimulate soil biological activity by increasing microbial population density, microbial biomass carbon and enzyme activities. They promote beneficial interactions such as symbiosis, nutrient mobilization and antagonism against soil-borne pathogens, leading to improved nutrient cycling and biological fertility of soil (Bhattacharyya & Jha, 2012; Backer *et al.*, 2018) [2, 4].
- 5. Role in Sustainable Soil Management:** Regular use of biofertilizers helps maintain soil health by improving biological diversity, nutrient cycling and organic matter dynamics. These effects enhance soil resilience and long-term productivity without degrading soil physical, chemical or biological properties, making biofertilizers an essential component of sustainable soil management systems (Malusa *et al.*, 2012; ICAR, 2021) [15].
- 6. Reduction of Soil Degradation:** By minimizing excessive use of chemical fertilizers and pesticides, biofertilizers reduce soil degradation, nutrient leaching and environmental contamination. They help maintain the natural balance of soil ecosystems and prevent long-term deterioration of soil quality, thereby contributing to environmentally sustainable agriculture (Shabbir *et al.*, 2019; Chaudhary *et al.*, 2022) [6, 18].

Role of biofertilizers in soil properties

- 1. Improvement in Soil Fertility:** Biofertilizers improve soil fertility by enhancing the availability of essential nutrients such as nitrogen (N), phosphorus (P) and potassium (K). Nitrogen-fixing microorganisms convert atmospheric nitrogen into plant-available forms, while phosphate-solubilizing and potassium-mobilizing microorganisms transform insoluble nutrient compounds into soluble forms. Continuous application increases nutrient availability and reduces dependence on synthetic fertilizers over time (Vessey, 2003; Bhattacharyya & Jha, 2012) [4, 23].
- 2. Improvement in Soil Structure and Water Retention:** Beneficial microorganisms introduced through biofertilizers produce extracellular polysaccharides and organic binding agents that enhance soil aggregation. Improved aggregation increases pore space, reduces bulk density and enhances water holding capacity of soil. These changes improve soil aeration, root penetration and moisture retention, particularly in degraded and light-textured soils (Malusa *et al.*, 2012; Chaudhary *et al.*, 2022) [6, 15].

Influence of biofertilizers on Fertilizer Use Efficiency

- 1. Nutrient Availability and Uptake:** Biofertilizers significantly enhance fertilizer use efficiency (FUE) by improving the bioavailability of nutrients that are otherwise present in unavailable or fixed forms in soil. Phosphate-solubilizing microorganisms (PSM) release organic acids such as gluconic, citric and oxalic acids, which dissolve insoluble phosphates and convert them into plant-available forms, thereby improving phosphorus use efficiency (PUE). Similarly, nitrogen-fixing microorganisms such as *Rhizobium*, *Azotobacter* and *Azospirillum* convert atmospheric nitrogen into ammonia through biological nitrogen fixation, reducing dependence on synthetic nitrogen fertilizers and enhancing nitrogen use efficiency (NUE) (Vessey, 2003; Bhattacharyya & Jha, 2012) [4, 23].

2. **Enhanced Root Growth and Nutrient Absorption:** Biofertilizers improve FUE by stimulating root growth and development, which enhances nutrient absorption capacity. Plant growth-promoting rhizobacteria (PGPR) produce phytohormones such as indole-3-acetic acid (IAA), gibberellins and cytokinins, leading to increased root length, root surface area and lateral root formation. Mycorrhizal fungi further enhance nutrient uptake by extending the effective root system through extensive hyphal networks, enabling plants to access nutrients and water from a larger soil volume. This improved root–soil interaction results in more efficient utilization of applied fertilizers (Backer *et al.*, 2018; Chaudhary *et al.*, 2022)^[2, 6].
3. **Synergistic Effects with Synthetic Fertilizers:** Biofertilizers exhibit strong synergistic interactions with chemical fertilizers when used in integrated nutrient management systems. Application of biofertilizers along with reduced doses of inorganic fertilizers improves nutrient solubilization, minimizes nutrient losses through leaching or fixation and enhances nutrient uptake by crops. This synergy ensures that a greater proportion of applied nutrients is utilized by plants, leading to improved FUE and reduced environmental pollution. Several studies have reported that combined application of biofertilizers with recommended or reduced fertilizer doses results in higher yields and better nutrient recovery compared to sole application of chemical fertilizers (Malusa *et al.*, 2012; Shabbir *et al.*, 2019)^[15, 18].
4. **Environmental and Economic Implications of Improved FUE:** Improved fertilizer use efficiency through biofertilizer application reduces nutrient losses, lowers fertilizer input costs and minimizes environmental risks such as nitrate leaching and phosphorus runoff. This contributes to sustainable crop production and long-term soil health while maintaining high productivity levels (Kumar *et al.*, 2017; ICAR, 2021)^[13].

Limitations of Biofertilizers

Despite their significant role in sustainable agriculture, biofertilizers have certain limitations that restrict their widespread and consistent adoption. A critical evaluation of these constraints is essential for balanced interpretation and better field-level implementation.

1. **Short Shelf Life:** Biofertilizers contain living microorganisms, whose viability declines rapidly during storage. Shelf life is generally 3–6 months, depending on formulation and storage conditions. Exposure to high temperature, direct sunlight or improper packaging reduces microbial population below effective levels, resulting in poor field performance. (Borkar, 2015)^[5]
2. **Sensitivity to Temperature and Moisture:** The effectiveness of biofertilizers is highly influenced by environmental conditions. High soil temperature, drought, waterlogging or salinity can reduce microbial survival and activity. Improper soil moisture during or

after application may prevent microbial establishment in the rhizosphere. (Borkar, 2015)^[5]

3. **Crop- and Soil-Specific Effectiveness:** Biofertilizers are often crop-specific and soil-specific, limiting their universal applicability. For example, *Rhizobium* strains are highly specific to particular legume hosts. Soil factors such as pH, organic carbon content, native microbial population and nutrient status significantly affect biofertilizer efficiency. (Vessey, 2003)^[23]
4. **Inconsistent Field Performance:** Although biofertilizers perform well under controlled or experimental conditions, their performance in farmers' fields is often variable and inconsistent. Variability arises due to differences in soil properties, climate, crop management practices and quality of biofertilizer formulations. This inconsistency reduces farmer confidence compared to chemical fertilizers, which provide immediate and predictable responses. (Malusa and Ciesielska, 2012)^[15]
5. **Poor Farmer Awareness and Adoption:** Lack of awareness and technical knowledge among farmers remains a major constraint. Many farmers are unfamiliar with correct application methods, timing and compatibility with chemical fertilizers. Inadequate extension services and limited demonstrations further restrict adoption at the field level. (Kumar *et al.*, 2017)^[13]
6. **Quality Control and Standardization Issues:** Variations in microbial strain purity, carrier material and contamination during production affect product quality. Absence of strict quality control and regulatory enforcement leads to marketing of substandard biofertilizer products. (Bhattacharyya & Jha, 2012)^[4]
7. **Slower Response Compared to Chemical Fertilizers:** Biofertilizers generally show gradual and long-term benefits, rather than immediate nutrient supply. This slow response makes them less attractive for farmers seeking quick yield improvements, especially in high-input cropping systems. (Shabbir *et al.*, 2019)^[18]

These limitations highlight the need for improved formulation technologies, quality regulation and location-specific recommendations.

Future Prospects: To enhance the consistency, credibility and large-scale adoption of biofertilizers, future research must move beyond single-strain products and short-term trials. Key priority areas are summarized below.

1. **Molecular and Genomic Approaches:** Modern molecular and genomic tools such as genomics, transcriptomics and metabolomics help in identifying functional genes responsible for nutrient solubilization, nitrogen fixation and stress tolerance, enabling strain improvement and quality control of biofertilizers (Bhattacharyya & Jha, 2012; Berg *et al.*, 2020)^[3, 4].
2. **Consortium-Based Biofertilizers:** Microbial consortia provide synergistic effects through combined nutrient

mobilization, hormone production and biocontrol activity, resulting in better stability and field performance than single-strain inoculants (Malusa *et al.*, 2012; Chaudhary *et al.*, 2022)^[6, 15].

3. **Nano-Biofertilizers and Advanced Delivery Systems:** Nano-biofertilizers improve nutrient use efficiency, microbial survival and controlled release of nutrients; however, their long-term environmental safety and field validation remain important research gaps (Raliya *et al.*, 2017; Dimkpa & Bindraban, 2017)^[7, 17].
4. **Region- and Crop-Specific Strain Development:** Biofertilizer effectiveness depends on crop genotype, soil type and agro-climatic conditions, highlighting the need for development of region-specific microbial strains and multilocation field validation (Vessey, 2003; ICAR, 2021)^[23].
5. **Climate-Resilient Bioinoculants:** Climate-resilient bioinoculants possessing ACC-deaminase activity, osmolyte production and antioxidant enhancement can improve plant tolerance to drought, salinity and heat stress, but require long-term field evaluation under climate extremes (Nadeem *et al.*, 2014; Backer *et al.*, 2018)^[2, 16].
6. **Standardization, Quality Control and Regulation:** Lack of strain authentication, contamination and poor carrier materials result in inconsistent biofertilizer performance; molecular tools and strict regulatory frameworks are needed for standardization and quality assurance (Malusa *et al.*, 2012; Bhattacharyya & Jha, 2012)^[4, 15].
7. **Farmer Awareness and Technology Transfer** Limited farmer awareness, inadequate extension services and lack of on-farm demonstrations reduce biofertilizer adoption, emphasizing the need for participatory research and effective extension strategies (Kumar *et al.*, 2017)^[13].

Conclusion

Biofertilizers play a vital role in improving soil health, enhancing nutrient availability, increasing fertilizer use efficiency and sustaining crop productivity. Their integration with chemical fertilizers and organic inputs under Integrated Nutrient Management (INM) offers a practical approach to reduce chemical fertilizer dependency while maintaining yields and environmental quality. From a policy perspective, promotion of quality-assured biofertilizers, region-specific strain development and farmer training should be prioritized to support sustainable agriculture and climate resilience.

However, the benefits of biofertilizers are often site- and crop-specific, highlighting the need for long-term, multi-location field trials to standardize recommendations across agro-climatic zones. Such trials will help quantify yield stability, nutrient recovery and soil health improvements over time. Overall, biofertilizers should be adopted as a complementary component of INM, supported by research, regulation and extension to realize their full agronomic and environmental potential. Thus, biofertilizers represent a

biologically driven pathway to enhance productivity while restoring soil ecological balance under intensive agriculture.

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