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ROLE OF BIOFERTILIZERS IN PROMOTING SOIL HEALTH FOR SUSTAINABLE AGRICULTURE: A REVIEW

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ABSTRACT

The increasing worldwide population, especially in emerging nations has made it extremely difficult to supply enough food, feed and agricultural products. In order to supply the need for food, synthetic fertilizers help plants to grow quickly and efficiently. The harmful effects of applying more of chemical fertilizers include environmental pollution, long-term variations in the physiochemical compositions and soil ecology, reduced agricultural production, and other harmful health effects. Biofertilizers are the best alternative solution for chemical fertilizers used in agriculture since they contain living microorganisms that help in improving the nutrient availability through natural processes. It helps in supporting sustainable agriculture by enhancing crop output, avoiding environmental degradation, and improving or managing the soil health. By means of natural processes including nitrogen fixation, organic matter breakdown, hormone production, hydrolytic enzymes, zinc, potassium and phosphorus solubilization and defense against various plant diseases and stresses, they provide nutrients. Enhancing soil structure, boosting soil microbial diversity, raising soil organic matter, and assisting in carbon sequestration all depend on biofertilizers. Many barriers, including a lack of understanding, inconsistent field performance and inadequate regulatory frameworks, hinder their widespread adoption despite their many advantages. The development of multifunctional biofertilizers, microbial consortia, and genetic engineering are examples of recent advancements in biofertilizer technology that have shown promising results in terms of boosting their efficacy. Precision farming and other modern agricultural methods can be combined with biofertilizers to increase their effectiveness and promote their broad use. Encouragement of farmers to utilize biofertilizers requires appropriate policy support, training initiatives and public awareness campaigns.

Key words : Biofertilizers, Chemical fertilizer, Soil health, Sustainable agriculture, Environment.

Introduction

In the past few years, excessive use of chemical fertilizers has led to serious ecological and agronomic issues, including nutrient imbalance, soil acidification, and a decrease in soil microbial fertility and diversity, all of which contribute to the soil's eventual nutritional deficiencies (Nosheen *et al.*, 2021). Growing awareness of the detrimental effects of traditional farming practices has led researchers and policymakers to look for alternatives that are both economically viable and environmentally beneficial (Sekhar *et al.*, 2024). By using biological agents instead of chemical fertilizers, a number

of agricultural parameters have improved dramatically (Singh *et al.*, 2025). Complex interactions between microbes, plants, and soil have a significant impact on soil health and plant output (Harman and colleagues, 2021). Incorporating biofertilizers is a viable way to significantly increase productivity in agriculture permanently (Albahri *et al.*, 2023). Biofertilizers are micro inoculants that use biological processes to transform the soil's vital nutrients from ineffective to crop-useful (Rajendra *et al.*, 2024). Biofertilizers are natural substances that contain living microorganisms, such as algae, fungi, and bacteria, or their byproducts. Agricultural practices use these substances to the soil, seeds, or plant

surfaces in order to increase soil fertility and encourage plant growth (Alnaass *et al.*, 2023). Due to their ability to grow crops in a range of geographic locations with less dependence on chemical fertilizers, biofertilizers are crucial for environmental protection. Biofertilizers are helpful tools in the agricultural ecosystem because they enhance soil quality and reduce the negative impacts of chemical fertilizers by adding essential elements like nitrogen, vitamins, proteins, and increased water retention capabilities (Maria and Sripriya, 2023). They can increase the accessibility and bioavailability of nutrients to help plants absorb them more easily (Mahapatra *et al.*, 2022). Jaroszuć-Scisiel *et al.* (2024) claim that the release of phytohormones by biofertilizers, including cytokinin, ACC deaminase, and IAA (auxin), enhances the overall performance of plants. They enable the plants to access complicated nutrients by converting them into simple ones. *Azotobacter* is a free-living bacterium that can fix 0.026 to 20 kg N ha⁻¹ in various crops, while *Rhizobium* is a symbiotic soil bacterium that can fix 50 to 300 kg N ha⁻¹ in mung beans. Also, enhancing phosphorus solubility with microorganisms as bioinoculants is a risk-free and efficient method (Iftikhar *et al.*, 2023). According to Chaudhary *et al.* (2022) and Priyanka *et al.* (2025), biofertilizers can enhance crop development, yield, and overall performance by reducing biotic and abiotic stresses for plants, such as drought and soil pathogens. By improving soil fertility and plant development, biofertilizers offer long-term benefits like reduced input costs, greater agro-ecosystem resilience and less environmental pollution (Han *et al.*, 2025).

Categories of Biofertilizers

According to Bargaz *et al.* (2018), microbial-based fertilizers, also known as biofertilizers, are a crucial component of sustainable farming and greatly improve soil fertility over the long run. The term “biofertilizer” refers to a broad category of substances that includes mycorrhizae, phosphorus and potassium solubilizers, nitrogen-fixing bacteria, and various microbial consortia. These organisms are commonly referred to by a variety of names, such as soil injections, microbial fertilizers, bioenhancers, phytostimulators, microbial injections, bioinoculants and Plant Growth Promoting Rhizobacteria, among others (Mitter *et al.*, 2021). The three most important types of microorganisms used in the producing biofertilizer are bacteria, fungi, and cyanobacteria; most of these species coexist symbiotically with plants. A biofertilizer of a particular effective living microbial culture can colonize the rhizosphere, or the interior of the host plant, when applied to seeds, soils, or plant surfaces. This increases the host’s availability, supply, or absorption of

primary nutrients, which in turn promotes plant growth. Various biofertilizer types may stand out due to their unique functions and ways of action. Rhizobacteria that sell plant boom, nitrogen-solving shops (N-fixers), potassium-solubilizing microorganisms (K-solubilizers), phosphorus-solubilizing creatures (P-solubilizers) and PGPR are the most widely employed Biofertilizers (Singh *et al.*, 2025).

Nitrogen-fixing Biofertilizers

One of the three nutrients that are necessary for plant growth is nitrogen (Quiong *et al.*, 2025). The group of microorganisms known as “diazotrophs” are able to fix nitrogen dioxide (N₂) biologically by associating themselves to plant roots (Aasfar *et al.*, 2021). *Rhizobium*, *Azospirillum*, *Azotobacter*, and cyanobacteria like *Anabaena* and *Nostoc* are examples of nitrogen-fixing biofertilizers. The soil-aggregating slime produced by a common bacterium *i.e.* *Azotobacter chroococcum*, in arable soils, can fix 2–15 mg N g⁻¹ of carbon source in culture media. In Indian soils, the population of *A. chroococcum* rarely approaches 105/g soil, despite the dominance of hostile microorganisms and the absence of organic matter (Barla and Bharteey, 2022). The ability of some cyanobacteria, including *Trichodesmium*, *Nostoc* and *Anabaena*, to use atmospheric nitrogen (N₂) as a source of nitrogen is referred to as nitrogen fixation. In cyanobacteria, as in many other biological systems, nitrogen fixation is carried out by an enzyme called nitrogenase.

Phosphate Solubilizing and Mobilizing biofertilizers

Phosphorus is an essential ingredient for the growth and development of plants and is normally present in plants at a dry weight of 0.2%. Phosphorus is often the least mobile macronutrient that plants can access in the majority of soil conditions. Micro organisms help to convert insoluble phosphate forms into soluble forms (Kalayu, 2019). Phosphate-solubilizing microbes (PSBs) plays role in changing insoluble phosphate compounds into soluble forms through a number of mechanisms which include organic acid release, ion-to-ion exchange interactions, and chelation reactions. As per Sharma *et al.* (2022), PSBs make up roughly 1–50% of the entire microbial population involved in phosphate solubilization within microbial communities.

PSMs can increase the activity of defense enzymes linked to plant disease resistance, which in turn can increase plant resistance to pests and diseases (Palmieri *et al.*, 2022; Feng *et al.*, 2024). The microbes that help mobilize phosphate can convert less accessible forms of phosphorus into more accessible forms. Phosphorus-

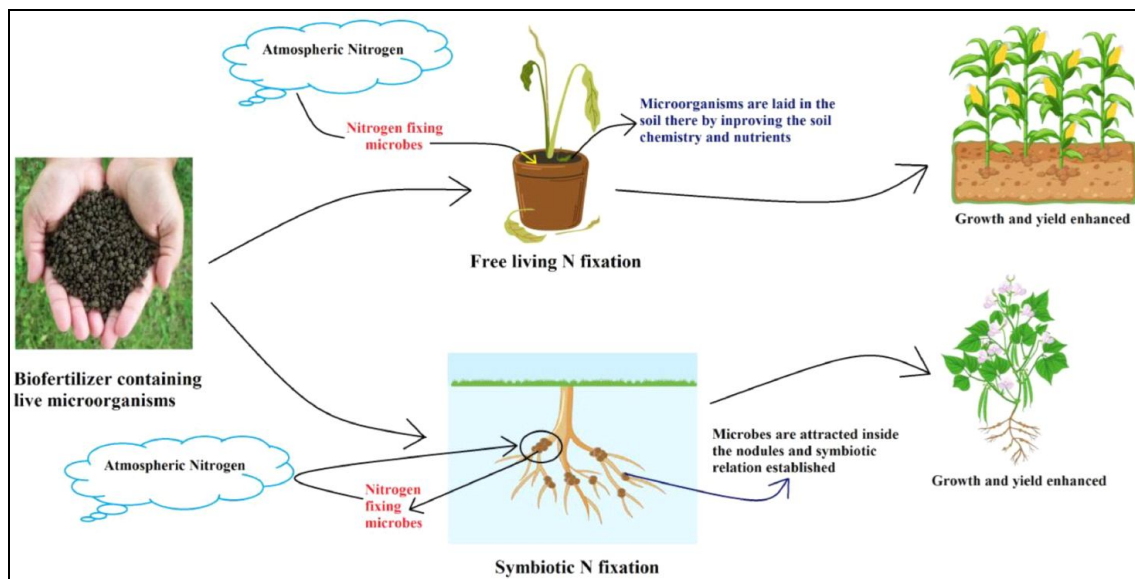


Fig. 1 : Types of nitrogen fixation and their beneficial mode of action to the plant (Samantaray *et al.*, 2024).

mobilizing bacteria (PMB) include *Pseudomonas*, *Rhizobium*, and *Bacillus* (Kirui *et al.*, 2022). PSMs release phosphorus for plant absorption through processes like chelation, mineralization, and lowering the pH of the soil (Girmay, 2019). Functional mutualistic symbioses with mycorrhizal fungi are found in over 80% of all land plants. According to Thakur and Singh (2018), these symbioses involve the fungus relying on the host for energy and photosynthates while offering the host a number of advantages in return.

Potassium-Solubilizing biofertilizers

Potassium solubilizing microorganisms (KSM), which include bacteria and fungi, can convert the insoluble form of potassium (K) into a soluble form to enhance plant uptake. They can also act as bio-control agents by producing antibiotics (Olanian *et al.*, 2022). Potassium-soluble microbes mobilize K from soil minerals, making them accessible to plants, and they also solubilize potassium minerals that are inaccessible to plants (Pandey *et al.*, 2020). Some of the key solubilizers of potassium from insoluble matrixes to accessible form for plant use are soil microbes like actinomycetes, fungi (*Aspergillus niger*, *Aspergillus fumigatus* and *Aspergillus terreus*), and bacteria (*Bacillus mucilaginosus*, *Bacillus edaphicus* and *Bacillus circulans*) (Hamid and Bashir, 2019). Microorganisms in the rhizosphere, particularly bacteria, can dissolve potassium from minerals so that plants can absorb them more easily (Hamid and Bashir, 2019; Sun *et al.*, 2020). In order to help liberate potassium from minerals, these potassium solubilizing microorganisms (KSMs) create metal-complexing ligands, exopolysaccharides and a variety of organic acids (Sharma *et al.*, 2024).

Sulfur-Oxidizing Biofertilizers

Legumes need a lot of sulfur, and adding rhizobium and Sulfur-Oxidizing Biofertilizers (SOBs) encourages nodule formation while meeting the plants' sulfur requirements. In order to satisfy the plants' need for sulfur, it is therefore beneficial to feed SOB and sulfur to the rhizosphere of legume plants (Patel *et al.*, 2024). *Wollinella succinogenes*, aerobic bacteria like *Bacillus* and *Thiobacillus*, and archaea like *Sulfolobales* are examples of microorganisms that oxidize sulfur (Kusale *et al.*, 2021). Many researchers have noticed that the predominant genus *Thiobacillus* has the ability to oxidize substances that are rich in sulfur (Suparjo, 2019). While *Halothiobacillus* increases production in saline soils, biofertilizers like *Thiobacillus thiooxidans* increase crop yields (Subedi, 2025). According to certain research, using sulfur biofertilizer in addition to sulfur chemical fertilizer has improved the plants' development and biochemical markers and improved the nutrients' solubility (Manzoor *et al.*, 2021; Booali *et al.*, 2024).

Other Mineral Solubilizing Biofertilizers

Unavailable/insoluble Zinc-solubilizing bacteria (ZSB) can regulate mechanisms which convert zinc compounds in the soil to soluble or readily available forms (Aloo *et al.*, 2022; Yadav *et al.*, 2022). ZSB is a sustainable, economical, and ecologically friendly method of Zn biofortification in cereal grain crops. Many ZSB strains have the ability to solubilize inaccessible forms of zinc, improving plant growth, yield and grain quality (Yadav *et al.*, 2020). Bacteria like *Frateruia aurantia* and *Bacillus mucilaginosus* are essential for solubilizing potassium and zinc, increasing their availability to plants, especially in nutrient-deficient soils (Nath *et al.*, 2017).

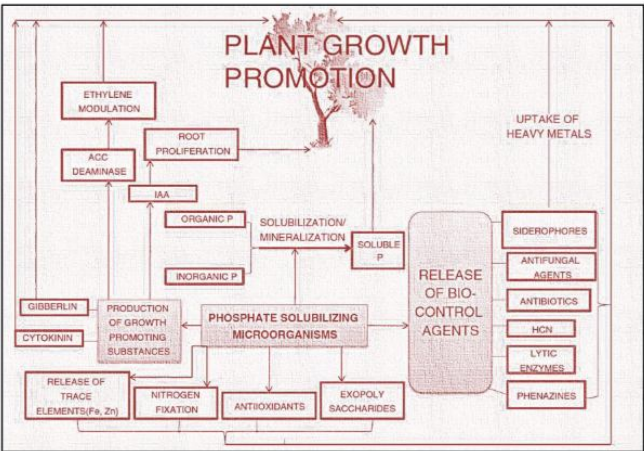


Fig. 2 : Plant growth promotion by Phosphorus solubilizing micro-organism (Lokesh *et al.*, 2024).

metabolites produced during microbial metabolism. Biofertilizers contain organic matter decomposers which break down complex organic components into smaller and accessible compounds. Biofertilizers helps in carbon sequestration by promoting the growth of organic matter in the soil. The application of bioinoculants lowers the adverse effects of soil salinity by enhancing the physicochemical characteristics of the soil, which eventually enhance the agricultural output (Jiménez-Mejía *et al.*, 2022).

Biofertilizers play an important role in improving food security, encouraging environmental preservation, establishing sustainable agriculture, and strengthening the resilience of farming communities globally with sustained

Table 1 : Types of Biofertilizers (Bhartey *et al.*, 2022).

Sl. No.	Types	Sub-group	Examples
1.	Nitrogen-fixing	Free-living	<i>Anabaena</i> , <i>Nostoc</i> , <i>Azotobacter</i> , <i>Clostridium</i> , <i>Klebsiella</i> , <i>Rhodospirillum</i> , and <i>Bacillus polymyxa</i> , <i>Beijerinckia</i>
		Symbiotic	<i>Frankia</i> , <i>Rhizobia</i> , <i>Anabaena azollae</i>
		Associative	<i>Acetobacter diazotrophicus</i> , <i>Azospirillum spp.</i>
2.	Phosphorus	Phosphate solubilizing	<i>Aspergillus awamori</i> , <i>Penicillium spp.</i> , <i>Bacillus subtilis</i> , <i>B. polymyxa</i> , <i>Pseudomonas striata</i>
		Phosphate mobilizing	<i>Arbuscular mycorrhiza (Sclerocystis spp., Glomus spp., Acaulospora spp. Gigaspora spp.)</i> , <i>ectomycorrhiza (Pisolithus spp., Boletus spp., Laccaria spp., Amanita spp.)</i>
3.	Micronutrients	Potassium solubilizing	<i>Bacillus edaphicus</i> , and <i>Paenibacillus glucanolyticus</i> , <i>B. mucilaginosus</i>
		Silicate and zinc solubilizing	<i>Saccharomyces spp.</i> , <i>Bacillus subtilis</i>
4.	Growth promoting	Plant growth promoting rhizobacteria	<i>Pseudomonas fluorescens</i> , <i>Bacillus</i>

Role of biofertilizers in improvement of Soil Health and sustainable Agriculture

Biofertilizers are capable to improve nutrient cycling, organic matter breakdown, and enzyme activity by enhancing the biological activity and variety of soil (Bertola *et al.*, 2021). Increase in microbial diversity promotes ecosystem stability and resilience, improves soil health and agricultural productivity (Bertola *et al.*, 2021). The microbial inoculants gradually enhance soil health and resilience by enhancing the microbial biomass and carbon sequestration (Singh *et al.*, 2018). Also, the use of biofertilizers promotes soil aggregation by enabling beneficial bacteria to create organic molecules and extracellular polysaccharides (Yilmaz and Sönmez, 2017). According to Zhu *et al.* (2022), biofertilizers influence the pH of the soil by releasing organic acids and other

innovation, collaboration, and investment (Kumar *et al.*, 2024). The use of biofertilizers results into less environmental pollution than synthetic fertilizers. Biofertilizers are more environmentally friendly than chemical fertilizers and don't affect the quality of the soil or water. Biofertilizers reduce the need for chemical inputs, which helps to reduce greenhouse gas emissions, water contamination, and soil acidity. Biofertilizers enhance soil microbial activity, boost organic matter content, and improve soil structure, due to which over a period of time, sustainable crop production results from this contribution to long-term soil fertility (Monisha *et al.*, 2023).

Biofertilizers are essential to accomplish food security as they increase nutrient availability, promote healthy root systems, and increase plant resistance to diseases, which

Table 2 : Role of Biofertilizers in Sustainable Agriculture (Itelima *et al.*, 2018, Yadav *et al.*, 2021; Keerthanan *et al.*, 2025).

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

in result increases the crop yields and improve the nutritional quality of the foods. It has been shown that using biofertilizers in combination with compost or vermicompost has synergistic effects on soil fertility and crop productivity (Nath *et al.*, 2017). Biofertilizers improve soil nutrient availability and microbial balance, which helps to sustain steady crop production even under environmental stress. Furthermore, they contribute to climate-resilient agriculture by lowering emissions of nitrous oxide linked to synthetic nitrogen fertilizers (Singh *et al.*, 2018).

Challenges and Future prospects

Some crops, soil types and climates respond well to the majority of the biofertilizers produced. Several biotic and abiotic stressors in the soil environment have influence on plant growth and development (Allouzi *et al.*, 2022). As per Santos *et al.* (2019), it is necessary to find microbial strains that can tolerate stressful conditions and to develop biofertilizers that can withstand stresses caused by drought and other environmental challenges brought on by changes in the seasons. This will make such biofertilizer beneficial to farmers in developing nations or hard locations. Since some industries struggle to treat their wastes and wastewater or must pay to dispose of them, waste by-products that are rich in valuable sources like nutrients, chemical oxygen demand, sulfates, chlorine, ammonia, and other non-toxic, environmentally friendly substances can be used as an alternative source for biofertilizers carriers (Arumugam *et al.*, 2021; Namfon Rai *et al.*, 2022). Compared to chemical fertilizers, a significantly lesser quantity of biofertilizers are required to provide plants with the same amount of nutrients. Additionally, this inexpensive way of adding nutrients to

the soil appeals to small-holder farmers (Raimi *et al.*, 2017). Thus, additional research is needed to perform cost-benefit analyses of biofertilizers based on plant yields.

Existing strains of bacteria aid in the improvement of one plant characteristic, but scientists may need to create more effective genetically modified strains while making sure that these strains pose no risks or hazards (Mahanty *et al.*, 2017; Mitter *et al.*, 2021). Furthermore, it is necessary to promote education on biofertilizers and their long-term benefits over chemical fertilizers, as well as to challenge the myth that bacteria cause disease. Also, more research is needed to generate biofertilizers that are both environmentally beneficial and commercially viable (Allouzi *et al.*, 2022). Government incentives and training programs may also promote their use in conventional and organic farming systems (Singh *et al.*, 2018).

Conclusion

A key element of sustainable agriculture is the use of biofertilizers, which increase crop yield, improve soil health, and reduce dependency on chemical fertilizers. They reduce the demand for artificial fertilizers by improving soil structure, nutrient accessibility and microbial diversity. As biofertilizers have been demonstrated to speed up food production and are a safer agricultural product for consumers, they remain the best option for growing healthier crops and increasing global food security. They are not being extensively adopted despite their many benefits due to issues with lack of knowledge, inappropriate regulatory frameworks and inconsistent performance. Advancements in biofertilizers technology, such as precision agriculture integration, genetic engineering and multifunctional formulations,

etc. provide promising answers to these issues. Research, policy support and extension services must all work together to boost their adoption on a global scale.

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