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BIOFERTILIZER: PRESENT AND FUTURE PERSPECTIVE IN BANGLADESH

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Abstract

Global food security is seriously threatened by a number of issues facing modern intensive agricultural methods. Chemical fertilizers are rigorously used to boost agricultural output in order to meet the nutritional needs of the world's growing population. The quality, physical characteristics of agricultural soils, their chemical properties and biological health, are extremely deteriorating. Plant-associated microorganisms hold great promise for resolving these issues. Soil microorganisms play a key role for plants and supply nutrients in proper ways, like ions form are very much essential to uptake. In this article, present situation of biofertilizer demand, availability, farmers knowledge, use and future perspective are briefly described. Types of biofertilizer, active inoculum like *Rhizobium,* PSB and VAM fungi, modern microbiome's activity and ecology study procedures though ^{18}O water or ^{13}C use in Stable Isotope Probing (SIP), Quantitative Stable Isotope Probing (qSIP) method and NGS, qPCR techniques are also discussed. This article showed mechanism of biofertilizer, phytohormone regulation and some of advantageous processes of biofertilizer in improved plant growth. The forms of using microbial strains as biofertilizers is rigorously illustrated. The potential of biofertilizers as tools for sustainable agriculture and calls for wider use to increase crop yields and environmental resilience.

Keywords: Biofertilizer, Stable Isotope Probing, Sustainable Agriculture.

Introduction

Agriculture sector contributes towards one third share in global gross domestic products and in Bangladesh about 11.0% (O'Neill, 2025). The increasing trend in human population of Bangladesh, food security and food safety is must. The main obstacles to the production of various crops are abiotic and biotic pressures, urbanization, the scarcity of fertile land, and unfavorable weather occurrences linked to climate change. Furthermore, soil quality, availability of nutrients, environmental conditions as well as the biological health of the soil are other important criteria for improving crop yield per unit area for achieving the targeted goal of food security (Tilman *et al.*, 2011). However, agricultural productivity is declining due to intensive farming, excessive chemical fertilizer use, and unsustainable land management practices (Hoffmann and Stumpf, 2015). The overuse of nitrogen and phosphorus fertilizers has led to soil nutrient depletion, water pollution, and Greenhouse Gas (GHG) emissions. In response to these challenges, biofertilizers have emerged as a sustainable alternative to synthetic fertilizers.

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Biofertilizers are biological products containing beneficial microorganisms that enhance soil fertility, promote plant growth, and support ecosystem health by facilitating natural nutrient cycling (Chen *et al.*, 2019). Unlike chemical fertilizers that supply nutrients directly, biofertilizers stimulate biological processes such as nitrogen fixation, phosphorus solubilization, and organic matter decomposition, making essential nutrients more accessible to plants while improving soil microbial activity (Blin *et al.*, 2013 and Blin *et al.*, 2019). The most widely used biofertilizers include nitrogen-fixing bacteria (*Rhizobium, Azospirillum, Azotobacter*), phosphate-solubilizing bacteria (*Pseudomonas, Bacillus*), and mycorrhizal fungi (*Glomus species*), which form symbiotic or associative relationships with plant roots to enhance nutrient absorption and soil structure. Biofertilizers have emerged as a sustainable solution to soil degradation and increasing agricultural productivity by enhancing soil fertility and nutrient availability through natural biological processes. Biofertilizers active ingredients derived from diverse organisms such as bacteria, algae, fungi, and lower order plants. Biofertilizers facilitate key mechanisms like nitrogen fixation, phosphorus solubilization, and the production of growth-promoting substances. Unlike synthetic fertilizers, they prevent heavy metal accumulation, reduce environmental pollution, and mitigate climate change impacts while promoting long-term soil health (Itamah *et al.*, 2025). Biofertilizers are a type of fertilizer that contains living organisms that help to improve soil fertility. These organisms can fix atmospheric (N_2) nitrogen, increase phosphorus availability and other nutrients in the soil, and also making them available to plants. It is often called as microbial fertilizer. These microbes can break down organic matter, release nutrients, and suppress plant diseases.

Despite their numerous benefits, the large-scale adoption of biofertilizers remains limited due to several challenges. Their effectiveness varies under different environmental conditions, they have a relatively short shelf life (around six months), and many farmers and foresters lack awareness of their advantages. Moreover, the complex interactions between biofertilizers and native soil microbial communities necessitate site-specific application strategies tailored to different agroecological zones. Addressing these challenges requires advancements in formulation technology, improved regulatory frameworks, and widespread education on their benefits (Turkina and Vikström, 2019). This review provides a comprehensive analysis of the science and practical applications of biofertilizers. It explores the different types of biofertilizers, their mechanisms of action, and their impact on soil health and plant productivity. Furthermore, it examines their role in both traditional and modern agricultural systems, their importance in sustainable agriculture, and the challenges associated with their application. By synthesizing recent scientific advancements and field studies, this review highlights the current state of biofertilizer technology, identifies future research directions, and underscores their potential in promoting food security while preserving environmental integrity. Chemical fertilizers (which include N, P, and K) are overused in high input farming systems and technologies nowadays to meet plant nutrient needs and boost agricultural output of Bangladesh. However, only a limited amount (30–40%) of these nutrients is absorbed by the plants due to low fertilizer-use efficiency and rest is lost to soil causing environmental pollution. In addition, heavy metals and radionuclides are present in chemical fertilizers, which are difficult to degrade, thus making them persistent pollutants in nature. Another major issue related to application of excessive chemical fertilizers is eutrophication of water sources. These pollution problems leading to public health hazards necessitated the development of technologies that are sustainable and eco-friendly, which could reduce the application of synthetic fertilizers (Zhang *et al.,* 2021). Therefore, application of beneficial microbiomes as biofertilizers in sustainable agriculture practices has emerged as innovative and environment-friendly technology for improving soil fertility and plant growth (Murgese *et al.,* 2020; Fasusi *et al.*, 2021).

Present status of Biofertilizers

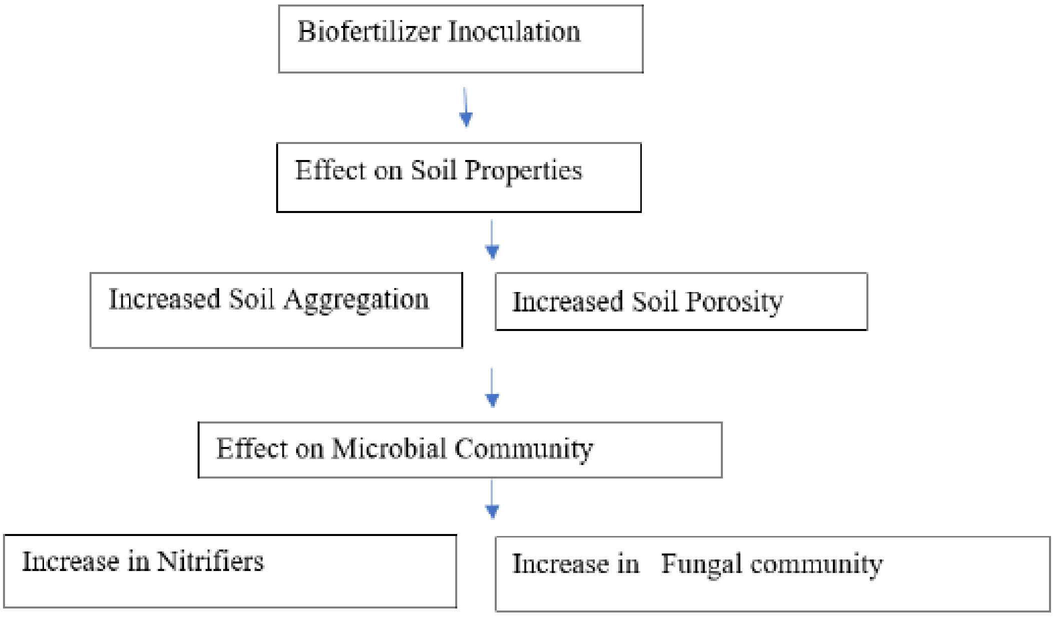
Biofertilizers are living or dormant cells like nitrogen fixers, phosphate-solubilizing bacteria (PSB), mycorrhizal fungi, biocontrol agents, bioremediation agents, plant growth promoting rhizobacteria (PGPR) make up active ingredient of biofertilizers, which are given to soil, seeds, or seedlings to increase the availability and uptake of nutrients from the soil.

Common microorganisms used in biofertilizers

Several key microbial groups are used in biofertilizer formulations, each playing a distinct role in enhancing soil fertility:

a. *Rhizobium*- A symbiotic nitrogen-fixing bacterium that forms nodules on the roots of leguminous plants. It converts atmospheric nitrogen into a plant-usable form, reducing the need for synthetic nitrogen fertilizers.
b. *Azospirillum*- A free-living nitrogen-fixing bacterium that associates with the roots of cereals and grasses, promoting root elongation and nutrient uptake (Bauman *et al.,* 2021).
c. *Azotobacter*- A non-symbiotic nitrogen-fixing bacterium that thrives in the rhizosphere, enhancing soil fertility and producing plant growth-promoting substances.
d. *Mycorrhizae*- A type of beneficial fungus that forms mutualistic associations with plant roots, increasing water and nutrient absorption, particularly phosphorus (Atencio *et al.,* 2020).
e. Phosphate- Solubilizing Bacteria (PSB)- Microorganisms such as *Pseudomonas* and *Bacillus* that break down insoluble phosphate compounds in the soil, making phosphorus available for plant uptake.
f. Potassium- Solubilizing Bacteria (KSB)- Microbes that help release potassium from soil minerals, improving plant growth and stress resistance (Adeleke *et al.,* 2021).

The benefits of biofertilizers over chemical fertilizers are manyfold. It is environmentally friendly, less expensive, increases soil organic matter, and believed to have growth promoting substances. Schematic mechanism of biofertilizer presented in Figure 1.



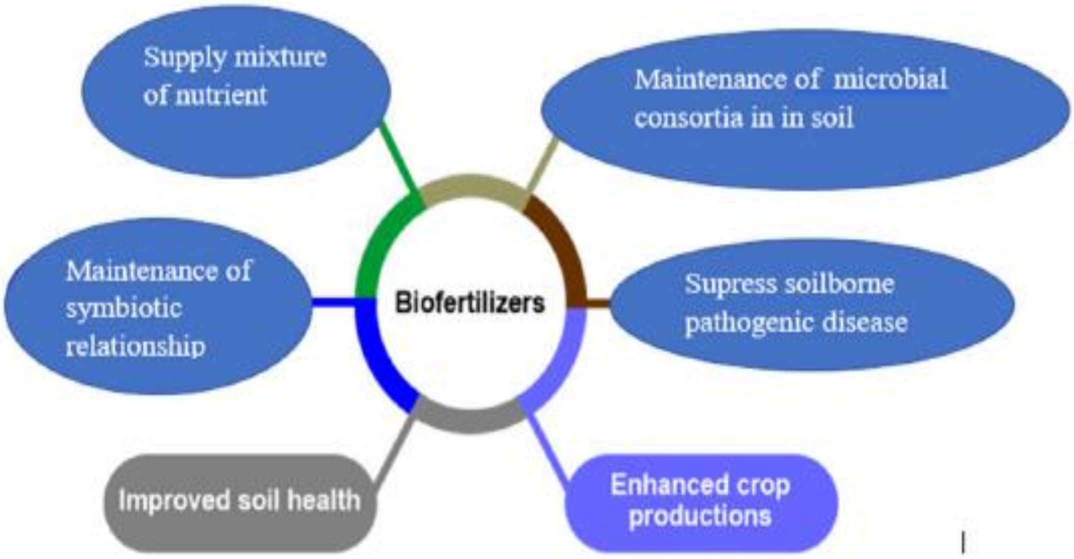
(Source: Itamah *et al.*, 2025)

Figure 1. Schematic mechanism of biofertilizer

Nowadays, using biofertilizers has become a more economical and environmentally responsible option than using fertilizers based on chemicals. Recently, significant advancements have been made in the creation of efficient biofertilizers for many crops. Recent technological advancements that investigate the taxonomic and functional elements of various microbiomes have led to the selection and modification of a specific rhizosphere microbial population for sustainable crop production. The prosperity of biofertilizers and microbial fertilizers in Bangladesh is evident in the increasing demand for these products. In 2020, the market for biofertilizers in Bangladesh was valued at $100 million, and it is expected to grow at a compounded annual growth rate (CAGR) of 10% over the next five years. This growth is being driven by a number of factors, including: The increasing awareness of the environmental and health risks associated with chemical fertilizers, the government's support for the use of biofertilizers and the increasing demand for organic food (Hossain, 2023). Soil Microbiology and soil microbiome can be a time demanding sustainable tools for overcoming this situation.

The following informations demonstrates the success of microbiological and biofertilizers in Bangladesh:

The Bangladeshi government started a campaign to encourage the use of biofertilizers in 2020. Farmers who employ biofertilizers are eligible for payments under the program. Some free-living or symbiotic bacteria and blue-green algae (Cyanobacteria) fix gaseous nitrogen as ammonia and release it, increasing the fertility of soil and water. Rhizobium or *Bradyrhizobium* producing root nodules in legumes and *Anabaena azollae* living in leaf cavities of *Azolla* (aquatic fern) are very efficient nitrogen fixers, and contribute about 500 kg N/ha/year.



(Source: Itamah *et al.*, 2025)

Figure 2. Functions of biofertilizer in soil

Nostoc, *Calothrix, Gloeotrichia, Stigonema*, etc are free-living aerobically nitrogen fixing Cyanobacteria. In addition, Vesicular Arbuscular Mycorrhizae (VAM fungi) are free-living soil forms that increase nutrient uptake (specially by converting organic phosphorus into inorganic phosphorus), plant growth, nodulation and nitrogen fixation in legumes. The nitrogen fixers release nitrogen during their life time and also add other elements after their decay, essential for the growth of crops. *Azolla* contains well balanced amino acids and high amount of anthocyanine, a -carotene. These compounds also have positive effects on growth and yield of crops. Large-scale production (2.5m tons/year) or *Rhizobium* or *Bradyrhizobium* inoculants has been successful at Bangladesh Institute of Nuclear Agriculture (BINA), Mymensingh. About 1.5 to 2.0 kg inoculant/ha used with seeds may result to increase production of pulses by 20 to 40%. Average *Azolla* production in a pond could be up to 1.0 m ton/ha/day. It could also be grown along with irrigated rice crop. One cover of *Azolla* is about 10 m tons/ha and incorporation of two such covers could reduce urea-N fertilizer by about 50%. *Azolla* could also be made into compost and addition of about 10 m tons could supplement all fertilizers by about 50% (Aziz, 2021).

Crop-specific applications

Different crops benefit from specific biofertilizers based on their nutrient requirements and growth conditions.

Some key applications includes

i. Cereals (Rice, Wheat, Maize, etc.)- *Azospirillum* and *Azotobacter* are commonly used to enhance nitrogen fixation and promote root growth. Phosphate-solubilizing bacteria improve phosphorus uptake, leading to higher yields (Cisse *et al.*, 2019).

ii. Legumes (Soybean, Peas, Lentils, etc.)- *Rhizobium* is essential for nitrogen fixation in leguminous plants, improving their growth and reducing the need for nitrogen fertilizers.

iii. Vegetables (Tomatoes, Carrots, Spinach, etc.)- Mycorrhizal fungi and potassium-solubilizing bacteria enhance nutrient absorption, leading to improved quality and productivity (Walters *et al.*, 2013).

The targeted use of biofertilizers in different cropping systems ensures maximum efficiency, leading to sustainable and profitable agricultural production. Bangladesh Institute of Nuclear Agriculture (BINA), has developed 13 (thirteen) crop specific biofertilizers. BINA developed biofertilizers for legumes (pulses) and oil seed (soybean) primarily are symbiotic Nitrogen fixing *Rhizobium sp. Trichoderma* as biological control agents have been widely used against many plant pathogens, such as viruses, bacteria, fungi, nematodes, and higher parasitic plants. *Trichoderma* significantly suppresses the growth of plant pathogenic microorganisms and regulates the rate of plant growth. Recent works have shown that common plant diseases such as root rot disease, damping off, wilt, fruit rot and other plant diseases can be controlled by *Trichoderma* spp. It is well-documented that the application of beneficial fungi, such as *Trichoderma* spp., improves crop productivity and reduces the use of agrochemicals and their negative effects on human health and the environment. Trichoderma grows on the surface of roots, where it provides disease control and enhances root growth. *Trichoderma* kills several major root rot fungi: *Pythium*, *Rhizoctonia*, and *Fusarium*. The process is called mycoparasitism. *Trichoderma* secretes an enzyme that dissolves the cell wall of the other fungi. BINA has developed biofertilizers containing microbes that are effective in stress-prone areas, such as saline-tolerant *Rhizobium* for soybean and saline-tolerant *Rhizobium* for groundnut, running for coastal regions. BINA has been working with free living bacteria for non-legumes and also *Azotobacter*. Phosphorus is an essential nutrient for all life on earth and has a major impact on plant growth and crop yield. BINA also working with Phosphate-solubilizing bacteria (PSB) from different agro-ecological zones for developing crop specific biofertilizer. The forms of phosphorus that can be directly absorbed and utilized by plants are mainly HPO_4^{2-} and $H_2PO_4^{-}$, which are known as usable phosphorus. At present, the total phosphorus content of soils worldwide is 400-1000 mg/kg, of which only 1.00-2.50% is plant-available, which seriously affects the growth of plants and the development of agriculture, resulting in a high level of total phosphorus in soils and a scarcity of available phosphorus. Phosphorus-solubilizing bacteria (PSB) can convert insoluble phosphorus in the soil into usable phosphorus that can be directly absorbed by plants, thus improving the uptake and utilization of phosphorus by plants.

Mechanism action of PSB

Phosphorus-solubilizing bacteria (PSB) convert insoluble soil phosphates into plant-available forms primarily through organic acid production, which lowers soil pH and chelates metal ions, and enzyme mineralization, which breaks down organic phosphorus compounds. Other mechanisms include the production of siderophores to chelate metal-bound phosphorus and the secretion of growth-promoting phytohormones to enhance overall plant growth.

Mechanisms of Phosphorus Solubilization

1. Organic Acid Production

Acidolysis: PSB secrete low-molecular-weight organic acids
(e.g., malic, succinic, oxalic, citric acid).

Lowering Soil pH: These acids reduce the soil pH, which helps to dissolve inorganic phosphate minerals bound to metal ions like calcium, iron, and aluminum.

Chelation: The carboxyl and hydroxyl groups on these organic acids chelate (bind to) these metal ions, preventing them from binding to phosphorus and making the phosphorus more available.

2. Enzyme Production

Phosphatases: PSB secrete acid phosphatases that hydrolyze (break down) organophosphorus compounds like phytate and sugar phosphates, releasing inorganic phosphate (Pi).

Phytases: These enzymes are crucial for degrading phytate, the primary storage form of phosphorus in many plants and soil organic matter, further increasing available phosphorus.

C-P Lyases: Some bacteria can also break down phosphonates, a type of organophosphorus compound, using C-P lyase enzymes.

3. Siderophore Production

PSB produce siderophores, which are iron-chelating compounds. These siderophores bind to metal ions in the soil, including those bound to insoluble phosphorus, forming soluble complexes and releasing the phosphorus.

4. Phytohormone Production

The production of plant-growth-promoting hormones such as Indole acetic acid (IAA), gibberellins, and cytokinins by PSB also contributes to plant growth and the overall availability and uptake of phosphorus. PSB interact with microorganisms in soil processes of acidolysis, enzymolysis, chelation siderophore production, and phytohormone production with complexation reactions The effects of PSB on the structure and abundance of microbial communities in soil are well described the mechanism of how PSB interact with microorganisms in soil and indirectly increase the amount of available phosphorus in soil.

(Source: Pan and Cai, 2023)

Clybio Biofertilizer: Clybio is a mixture of yeast fungi, *Bacillus natto*, and *Lactobacillus*, which can improve the yield and quality of vegetables. Clybio can prevent different fungal diseases, reducing the requirement for pesticides during the growing season for vegetables (Akter *et al.*, 2021). Additionally, various studies on horticultural crops have shown that the use of beneficial microorganisms improves vegetative growth and boosts crop yield (Uddin *et al.*, 2020, Rakibuzzaman *et al.*, 2021). The components of Clybio also have significant functionality of their own which protects plants against biotic and abiotic stresses. Clybio improves soil health and plant growth by harnessing the power of enzymes and the synergy of *Lactobacilli*, Yeast Fungi, and *Bacillus Natto*. It has antibacterial qualities, deters pathogens, promotes leaf microbes, increases resiliency, elevates the presence of natural microbes, improves mineral uptake, and aids in nitrogen digestion. Also, it lessens the need for pesticides and fertilizers (Ahmed *et al.*, 2023).

Types of biofertilizers, their mechanisms, and examples

Biofertilizer Type	Crops Benefited	Mode of Action	Microbial Group	Examples
Nitrogen-Fixing	Chickpea, White Spruce	Enhances soil nitrogen content by capturing atmospheric nitrogen and converting it into a plant-available form	Free-living	*Azotobacter, Anabaena, Clostridium, Aulosira, Beijerinckia, Nostoc, Klebsiella, Stigonema, Desulfovibrio, Rhodospirillu, Rhodopseudomonas*
	Pea	Establishes a symbiotic relationship with plants to fix nitrogen	Symbiotic	*Rhizobium, Frankia, Anabaena azollae, Trichodesmium*
	Lavender	Forms an associative symbiotic relationship, aiding nitrogen fixation	Associative Symbiotic	*Azospirillum spp., Herbaspirillum spp., Alcaligenes, Enterobacter, Azoarcus spp., Acetobacter diazotrophicus*

Table Continued

Biofertilizer Type	Crops Benefited	Mode of Action	Microbial Group	Examples
Phosphorus-Solubilizing	Chickpea, Wheat, Mangrove	Converts insoluble phosphorus into a soluble form through organic acid secretion and soil pH reduction	Bacteria	*Bacillus circulans, Bacillus subtilis, Pseudomonas striata, Bacillus polymyxa, Micrococcus, Agrobacterium, Aerobacter, Flavobacterium*
	Wheat	Facilitates phosphorus solubilization	Fungi	*Penicillium spp. Aspergillus awamori, Trichoderma*
Phosphorus-Mobilizing		Transfers phosphorus from the soil to plant roots	Mycorrhiza	*Arbuscular mycorrhiza, Glomus spp., Gigaspora spp. Acaulospora spp., Scutellospora spp., Sclerocystis spp.*
Potassium-Solubilizing		Breaks down potassium silicates by secreting organic acids, making potassium more accessible to plants	Bacteria	*Bacillus mucilaginous, Bacillus circulans, Bacillus edaphicus, Arthrobacter spp.*
		Decomposes silicates to mobilize potassium	Fungi	*Aspergillus niger*
Potassium-Mobilizing	Wheat, Maize	Converts unavailable forms of potassium into plant-absorbable forms	Bacteria	*Bacillus spp.*
		Mobilizes potassium to enhance plant uptake	Fungi	*Aspergillus niger*
Micronutrient-Solubilizing	Onion, Maize, Pumpkin	Oxidizes sulfur into sulfate, making it bioavailable for plants	Sulfur-Oxidizing Bacteria	*Thiobacillus spp.*
	Wheat, Maize	Solubilizes zinc through proton release, chelation, acidification, and oxidation-reduction reactions	Zinc-Solubilizing Microbes	*Mycorrhiza, Pseudomonas spp., Bacillus spp.*
Plant Growth-Promoting	Rice, Bitter Gourd, Gladiolus, Chrysanthemum, Petunia, Pinus	Enhances root growth, increases nutrient availability, and boosts crop productivity by producing phytohormones	Plant Growth-Promoting Rhizobacteria (PGPR)	*Pseudomonas spp., Agrobacterium, Pseudomonas fluorescens, Arthrobacter, Erwinia, Bacillus, Rhizobium, Enterobacter, Streptomyces, Xanthomonas.*

Biofertilizers, developed by institutions like BRRI and BARI, are promoted as safe, eco-friendly inputs that can boost rice yields by 15-20%. Despite this potential, adoption faces significant challenges. A study in Chapainawabganj revealed that about 52% of farmers had low knowledge of biofertilizers, though 67% showed a moderately favorable attitude toward adoption. Key limitations include low farmer awareness, inadequate promotion, unpredictable performance, high cost, inconsistent availability, and logistical hurdles due to specific storage needs. The dominance of subsidized chemical fertilizers further hinders adoption. The study found that knowledge correlated positively with socio-demographic factors, while attitude correlated with education and training. To increase adoption, researchers recommend prioritizing increased publicity, organized training, and addressing issues of affordability and accessibility to capitalize on the farmers' willingness to adopt. (Hasan *et al.,* 2025).

Future perspectives of biofertilizers

The growth of biofertilizers in Bangladesh will be driven by increasing demand for organic and safer food, aligning with sustainable agriculture goals. Future efforts will leverage cutting-edge technologies like metagenomics and next-generation sequencing to develop more effective microbial formulations. Research will focus on creating precision platforms for location-specific recommendations and developing stress-tolerant microbes, such as saline-tolerant Rhizobium for coastal regions. To ensure success, national standards and regulations for biofertilizer quality and shelf life are crucial to build farmer trust. The government should shift subsidies to promote these sustainable practices. Policymakers must prioritize targeted training and on-field demonstrations to enhance farmer awareness and ensure that biofertilizer supplies are affordable and easily accessible. This multi-faceted approach, combining biofertilizers with compost and green manure, is key to long-term soil health and productivity. (Hasan *et al.,* 2025). The composition and variety of the rhizosphere community are often influenced by the genetic diversity of plants and the characteristics of the soil. Recent developments in next generation sequencing techniques allowed significant improvement in interpreting the functioning of microbiomes specifically inhabiting the crop rhizosphere (Gupta *et al.,* 2021). Next-Generation Sequencing (NGS) techniques like metabarcoding and meta-omics are essential for soil microbiome characterization but are limited by high costs, time, and laboratory restrictions, preventing their use for rapid, in-situ environmental monitoring. Biosensing technology offers a complementary solution to overcome these limitations. Already successful in biomedical applications, biosensors can be adapted for rapid, field-based soil studies. Key biosensing components for soil applications include stable reagents like aptamers and the use of multiplex sensors to handle microbial complexity. The integration of machine learning can aid in analyzing large, complicated datasets. Furthermore, using a smartphone as a portable optical reader could provide a cheap, rapid, and field-applicable data-analyzing device. Applying this rich, interdisciplinary field to soil microbiology promises significant advancements. (DeFord and Yoon, 2024). Generally, it is estimated that bulk soil in general contains 10^6 to 10^9 bacterial cells per gram of soil and there is remarkable ten-fold enrichment of bacterial numbers in the rhizosphere zone (Wang *et al.*, 2020; Glick and Gamalero, 2021). But in Bangladesh there is no specific numbers for the rhizosphere soil. For modern soil microbiological understanding, the structure, diversity and functions of rhizosphere microbiome and their interactions with different environmental factors, traditional approaches are complemented with modern omics-based approach based on next-generation sequencing (NGS) technologies (Gupta *et al.*, 2021; Raghu *et al.*, 2021). Quantitative Stable Isotope Probing (qSIP) is a powerful technique that measures the growth rates and metabolic activity of individual microbial taxa within their native communities. It tracks the uptake of stable isotopes by combining traditional Stable Isotope Probing (SIP) with qPCR and high-throughput sequencing.The modified SIP method involves collecting DNA in multiple density fractions after isopycnic centrifugation and sequencing each separately. This produces taxon-specific density curves for labeled and non-labeled treatments, allowing calculation of the density shift for individual taxa.By expressing this density shift relative to the non-labeled control, the technique precisely isolates and quantifies isotopic enrichment. qSIP was demonstrated in soil, revealing strong taxonomic variations in ^{18}O and ^{13}C assimilation following exposure to ^{18}O water or ^{13}C glucose, highlighting the benefit of this quantitative approach. (Hungate *et al.*, 2015). Bangladesh is shifting from chemical dependence to sustainable biofertilizers to combat soil degradation, pollution, and the need for safe food. This transition is crucial due to the country's high population density and declining soil health. National institutions (BINA, BARI, BAU) are leading research to isolate indigenous beneficial microbes like Rhizobium, Azotobacter, and PSB for developing crop-specific biofertilizers. These microbes promise to revitalize deteriorating agricultural soils by enhancing nutrient availability, regulating phytohormones, and controlling pathogens. The strategy involves the combined use of biofertilizers with organic amendments (compost) and reduced chemical fertilizers. Current focus areas include improving formulation through cell protectants and advanced techniques like microencapsulation and nano-immobilization to ensure product efficacy and preserve soil fertility for increased crop yields.

Conclusion

Biofertilizers, featuring beneficial microorganisms, are a promising method to increase crop production and reduce reliance on chemical fertilizers, fostering sustainable and eco-friendly agriculture. These microbes enhance the availability of nutrients like N, P, K, Zn, and S, regulate phytohormones, and suppress plant diseases. Amending biofertilizer strains with organic materials, protectants, and nanoparticles improves their longevity and efficacy. Technological advancements like next-generation sequencing, gene editing, and omics-based biology offer powerful tools to manipulate these microbes and plants, providing long-term solutions for boosting crop productivity and global food security.

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