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Bio-fertilizers in Modern Agriculture: Types and Improving Soil Health and Nutrient Efficiency

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Modern agriculture depends heavily on chemical fertilizers to meet the food demands of a growing population; however, their excessive use has led to soil degradation and environmental hazards. Bio-fertilizers have emerged as sustainable alternatives that enhance soil fertility through natural processes such as nitrogen fixation, phosphorus solubilization and potassium mobilization. These preparations contain beneficial microorganisms that colonize the rhizosphere or plant interior, improving nutrient availability, promoting plant growth and reducing reliance on synthetic fertilizers. Nitrogen-fixing bacteria, phosphate-solubilizing microbes, potassium-solubilizing bacteria and mycorrhizal fungi play distinct roles in nutrient cycling, increasing the uptake of N, P, K and essential micronutrients. Additionally, bio-fertilizers improve soil structure, water-holding capacity and microbial activity while suppressing soil-borne pathogens. Despite limitations, including short shelf life, environmental sensitivity and the need for farmer awareness, bio-fertilizers contribute significantly to sustainable agriculture by enhancing soil health, crop productivity and long-term ecological sustainability.

Introduction

Modern agriculture has changed significantly to meet the food demands of a rapidly growing population, particularly in developing countries. The introduction of the Green Revolution increased food production; however, it involved excessive use of synthetic fertilizers, which degraded soil health and created risks to the environment and human health. Over time, bio-fertilizers have emerged as sustainable alternatives that enhance soil fertility through natural processes such as nitrogen fixation and nutrient solubilization. Continuous farming without balanced inputs leads to soil nutrient depletion, making eco-friendly practices essential for long-term agricultural productivity. Bio-fertilizers improve crop growth, protect plants from stress and reduce dependence on chemical fertilizers. In India, where agriculture supports the economy and depends heavily on monsoons, bio-fertilizers play a crucial role in sustaining soil health and maintaining crop yields.

Bio-fertilizer

Bio-fertilizer is a substance that contains living microorganisms which, when applied to seeds, plant surfaces or soil, colonize the rhizosphere or the interior of the plant and promote growth by increasing the supply or availability of primary nutrients to the host plant.

Types of bio-fertilizer

Bio-fertilizers are classified into different types depending on the type or group of microorganisms they contain. The table below shows the classification of bio-fertilizers on the basis of the different types of microorganisms used. The different types of bio-fertilizers include:

Group	Example
Nitrogen fixing bio-fertilizers	
Free living	*Azotobacter, Bejerinkia, Clostridium, Klebsiella, Anabaena, Nostoc*
Symbiotic	*Rhizobium, Frankia, Anabaena, Azollae*
Associative symbiotic	*Azospirillum*
Phosphate solubilizing bio-fertilizers	
Bacteria	*Bacillus megaterium var, Bacillus subtilis, Bacillus circulans*
Fungi	*Penicillum Spp. Aspergillus awamori*
Phosphate mobilizing bio-fertilizers	
Arbuscular Mycorrhiza	*Glomus Spp., Gigaspora Spp., Acaulospora Spp. Scutellospora Spp. and Sclerocystis Spp.*
Ectomycorrhiza	*Laccaria Spp. Pisolithus Spp, Boletus Spp. and Amanita Spp.*
Orchid Mycorrhiza	*Rhizoctonia solani*
Potassium solubilizing and mobilizing bio-fertilizers	
Bacteria	*Bacillus mucilaginosus, Pseudomonas paenibacillus*
Fungi	*Aspergillus spp., Penicillum Spp*
Plant growth promoting Rhizobacteria	
Pseudomonas	*Pseudomonas fluorescens*

Nitrogen fixing bio-fertilizers (NFB): Examples include *Rhizobium* spp., *Azospirillum* spp. and blue-green algae. These microorganisms work by fixing atmospheric nitrogen and converting it into organic forms in the soil and in the root nodules of legumes, thereby making nitrogen available to plants. Nitrogen-fixing bio-fertilizers are crop-specific bio-fertilizers.

Phosphate solubilizing bio-fertilizers (PSB): Phosphate-solubilizing microorganisms such as *Bacillus* spp., *Pseudomonas* spp. and *Aspergillus* spp. play a vital role in improving phosphorus availability in soils. Most soil phosphorus exists in insoluble forms that plants cannot absorb directly. These beneficial bacteria and fungi convert insoluble phosphates into soluble forms by releasing organic acids that lower soil pH around the root zone. This process dissolves bound phosphates and makes phosphorus readily available for plant uptake.

Phosphate mobilizing bio-fertilizers *(*PMB): Examples include mycorrhiza. These microorganisms work by scavenging phosphates from deeper soil layers and mobilizing insoluble phosphorus in the root zone. They form a close association with plant roots and help in transporting phosphorus to plants more efficiently.

Potassium solubilizing bio-fertilizers (KSB): Examples include *Bacillus* spp. and *Aspergillus niger*. Potassium in the soil occurs mostly as silicate minerals, which are inaccessible to plants. These minerals become available only when they are slowly weathered or solubilized. Potassium solubilizing microorganisms solubilize silicates by producing organic acids that cause the decomposition of silicates and help in the removal of metal ions, thereby making potassium available to plants.

Potassium mobilizing bio-fertilizers (KMB): An example of a potassium-mobilizing bio-fertilizer is *Bacillus* species. These microorganisms work by mobilizing the inaccessible forms of potassium (silicates) present in the soil. Some phosphate-solubilizing bio-fertilizers, such as *Bacillus* spp. and *Aspergillus* spp., have been found to mobilize potassium as well as solubilize phosphorus.

Advantages of Bio-fertilizers

1. Increase crop growth and yield by 20–30% through improved nutrient availability.
2. Perform well under semi-arid and dryland conditions, making them suitable for rainfed farming.
3. Improve soil structure, water-holding capacity, and soil organic carbon.

4. Enhance the availability of N, P, K and micronutrients, and produce natural growth-promoting substances.
5. Suppress soil-borne pests and diseases through beneficial microbial activity.
6. Reduce chemical fertilizer use, especially phosphorus, by up to 25%.
7. Are eco-friendly and non-polluting, leaving no harmful residues in soil and water.
8. Support sustainable agriculture by improving soil health and long-term productivity.

Limitations of Bio-fertilizers

1. Bio-fertilizers do not supply nutrients instantly and may not meet crop requirements under high-input farming systems.
2. Their effectiveness decreases when exposed to high temperatures or direct sunlight.
3. Short shelf life affects the survival and activity of beneficial microorganisms.
4. Field performance depends on soil moisture, temperature, and overall soil conditions.
5. Poor-quality carrier materials can reduce the efficiency of bio-fertilizer products.
6. Lack of farmer awareness regarding proper storage and application limits their effectiveness.

How bio-fertilizers improve soil nutrients Availability?

Bio-fertilizers improve soil nutrient availability by converting nutrients into plant available forms through diverse biological processes carried out by beneficial microorganisms. Nitrogen-fixing bio-fertilizers such as *Rhizobium* establish a symbiotic association with leguminous crops and fix atmospheric nitrogen, contributing approximately 40–200 kg N ha^{-1} $year^{-1}$, which significantly reduces the need for synthetic nitrogen fertilizers. Free-living nitrogen-fixing bacteria like *Azotobacter* also enrich soil nitrogen by contributing about 15–25 kg N ha^{-1} annually, particularly in non-leguminous cropping systems. Phosphate-solubilizing microorganisms enhance phosphorus availability by secreting organic acids such as citric, gluconic and oxalic acids, which dissolve insoluble phosphate compounds present in the soil. This biological solubilization allows a reduction in chemical phosphorus fertilizer application by 25–50% without adversely affecting crop yield. Similarly, potassium-solubilizing bacteria mobilize soil bound potassium from silicate minerals through the production of organic acids and chelating substances, thereby improving potassium availability and uptake by plants.

Mycorrhizal fungi play a crucial role in nutrient acquisition by forming symbiotic associations with plant roots. Their extensive hyphal networks increase the effective root surface area, enabling plants to access nutrients beyond the depletion zone. This association significantly enhances the uptake of phosphorus, zinc, copper and other micronutrients, especially in nutrient deficient soils. In addition to nutrient mobilization, bio-fertilizers improve microbial activity in the rhizosphere, enhance nutrient cycling and promote better root growth through the production of growth-promoting substances. Overall, the use of bio-fertilizers improves soil fertility, enhances nutrient use efficiency and reduces dependence on synthetic fertilizers, contributing to sustainable and environmentally friendly agricultural practices.