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Bioinoculants:

A sustainable alternative to agrochemicals

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Modern agriculture has heavily relied on synthetic agrochemicals to boost crop productivity, leading to significant increases in agricultural output. However, the widespread use of these chemicals had detrimental effects on the environment. Soil degradation, erosion, water contamination, and pesticide resistance are a few of those problems. Bioinoculants include a range of microorganisms with different properties and abilities that provide a sustainable solution to these problems. Rhizobium spp., Azospirillum spp., etc. act as plant growth-promoting rhizobacteria and play a key role in nutrient assimilation within the soil and from the environment through the nitrogen fixation process. On the other hand, Trichoderma spp., Pseudomonas spp., etc. play a crucial role in plant disease management. This article focuses on the role of bioinoculants in promoting overall plant growth with a focus on their application methods, dosage, performance on crops, challenges, and the current market trends in India.

Keywords: Bioinoculants, Microbial formulation, Nutrient assimilation, Sustainable agriculture

CHEMICAL fertilizers and pesticides have helped transform India from a food deficit nation to a food-secure nation. However, decades of careless usage of these chemicals have seriously harmed the environment. The degradation of soil health due to the overuse of chemical fertilizers has led to fertility loss, disrupted microbial communities, and loss of land productivity over time. Overuse of pesticides has harmed aquatic habitats and entered the food chain, posing a risk to human health. Furthermore, these chemicals have led to the loss of pollinators and beneficial insects. In response to these growing concerns, global focus has shifted towards sustainable agriculture practices. Bioinoculants have emerged as a promising solution in this context. These formulations of beneficial microorganisms offer eco-friendly ways to improve crop productivity and soil health by enhancing nutrient cycling, suppressing plant diseases, and promoting plant growth without causing environmental harm.

Bioinoculants

Bioinoculants are the formulations of beneficial microorganisms that improve soil fertility, enhance plant growth, and control phytopathogens. Unlike agrochemicals, bioinoculants work in harmony with nature and do not cause any environmental damage. They convert the unavailable form of nutrients into a readily available form, decompose organic matter, perform biological nitrogen fixation (BNF), and suppress other phytopathogens. Moreover, they enhance plant growth by producing bioactive compounds, such as phytohormones and enzymes, which enhance root and shoot development.

Bioinoculants are classified based on several factors such as their role in nutrient assimilation and plant disease management (nitrogen fixing bioinoculants, phosphorus fixing bioinoculants, biocontrol agents), mode of action (biofertilizers, biopesticides, phyto stimulants), formulations (carrier based bioinoculants, liquid based bioinoculants), etc. The most common examples of bioinoculants are *Rhizobium* spp., *Azospirillum* spp., *Azotobacter* spp., Phosphate Solubilizing Bacteria (PSB), *Bacillus* spp., *Trichoderma* spp., *Pseudomonas* spp. and Mycorrhizal fungi.

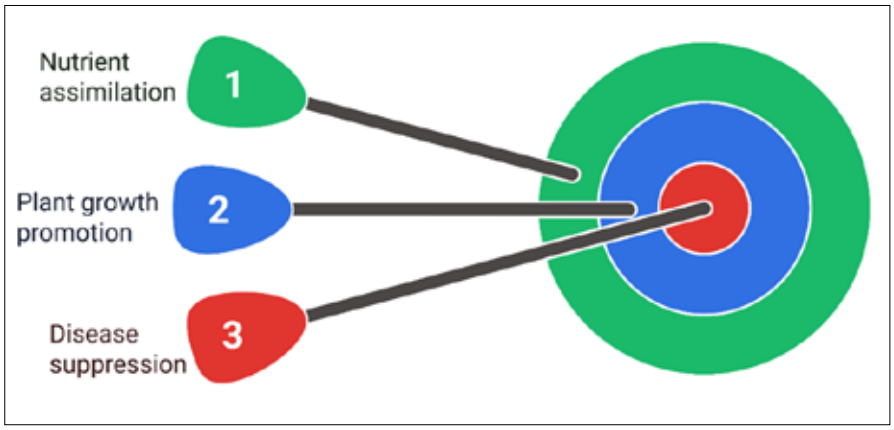
Trichoderma viride (A biocontrol agent)

Mechanism of action

Bioinoculants act via three mechanisms that are nutrient assimilation, plant growth promotion, and disease suppression.

Table 1. Common bioinoculants used in Indian agriculture

Bioinoculant	Type of Microorganism	Mode of Action	Formulation	Benefits
Rhizobium spp.	Nitrogen-fixing bacteria	Biofertilizer	Carrier-based	Nitrogen fixation
Azospirillum spp.	Nitrogen-fixing bacteria	Phyto stimulant	Liquid-based	Nitrogen fixation, phytohormone production
Azotobacter spp.	Nitrogen-fixing bacteria	Biofertilizer	Carrier-based	Nitrogen fixation, phytohormone production
Phosphate Solubilizing Bacteria (PSB)	Phosphorus-fixing bacteria	Biofertilizer	Carrier-based	Phosphate solubilization
Bacillus spp.	Beneficial bacteria	Biopesticide	Liquid-based	Plant growth promotion, biocontrol
Trichoderma spp.	Fungal biocontrol agent	Biopesticide	Carrier-based	Plant growth promotion, biocontrol
Pseudomonas spp.	Beneficial bacteria	Phyto stimulant	Liquid-based	Plant growth promotion, biocontrol
Mycorrhizal fungi	Fungal symbionts	Biofertilizer	Carrier-based	Improves nutrient uptake,



Mechanism of action of bioinoculants

Nutrient assimilation

Nitrogen is a vital macronutrient required for plant growth. Nitrogen-fixing bioinoculants, such as *Rhizobium* and *Azotobacter*, convert atmospheric nitrogen into ammonia through biological nitrogen fixation (BNF). This process enhances soil nitrogen content while reducing the need for synthetic fertilizers. For instance, *Rhizobium* in symbiosis with legumes can fix up to 100 kg N/ha annually which can significantly boost crop production. Phosphate solubilizing bacteria (PSB) release organic acids and enzymes that dissolve insoluble phosphorus compounds in the soil, making them accessible to plants. Mycorrhizal fungi form symbiotic relationships with plant roots, which enhance nutrient uptake by extending the root surface area. Nutrient cycling by bioinoculants reduces the economic costs associated with chemical fertilizers making them important for promoting sustainable agriculture.

Plant growth promotion

Many bioinoculants directly promote plant growth through the production of phytohormones and other bioactive compounds. For example, *Azospirillum* spp. produce indole-3-acetic acid (IAA), gibberellins, and cytokinins. These phytohormones enhance overall plant growth by increasing water and nutrient uptake efficiency by stimulating root elongation and branching. Similarly, *Bacillus* spp. synthesize IAA and cytokinins, which promotes cell division and elongation. *Trichoderma*, another notable bioinoculant produces auxins and gibberellins, which stimulate both root and shoot growth. These growth-promoting activities ensure that plants establish stronger root systems and use water and nutrients more efficiently for their growth and development.

Secondary metabolites from *Trichoderma*.

Disease suppression

Disease suppression is one of the most desired benefits of bioinoculants. One key mechanism in disease suppression is competition, where beneficial microorganisms compete with pathogenic microbes for space and nutrients within the rhizosphere. This prevents the establishment of harmful organisms. Another way that bioinoculants inhibit disease is by antibiosis. Antimicrobial substances such as lytic enzymes and antibiotics, are produced by beneficial microbes that either directly kill or stop the growth of infections. For example, 2, 4-diacetyl phloroglucinol (DAPG), an antifungal substance that successfully manages soil-borne disease is produced by *Pseudomonas fluorescens*. Mycoparasitism is another form of biocontrol that involves direct interaction between bioinoculants and plant pathogens. Organisms like *Trichoderma* attach to the cell walls of fungal pathogens and degrade them using enzymes such as chitinases and glucanases. This not only controls the pathogen but also provides nutrients for the bioinoculant. Certain bioinoculants

Table 2. Common bioinoculants used for disease suppression in crops

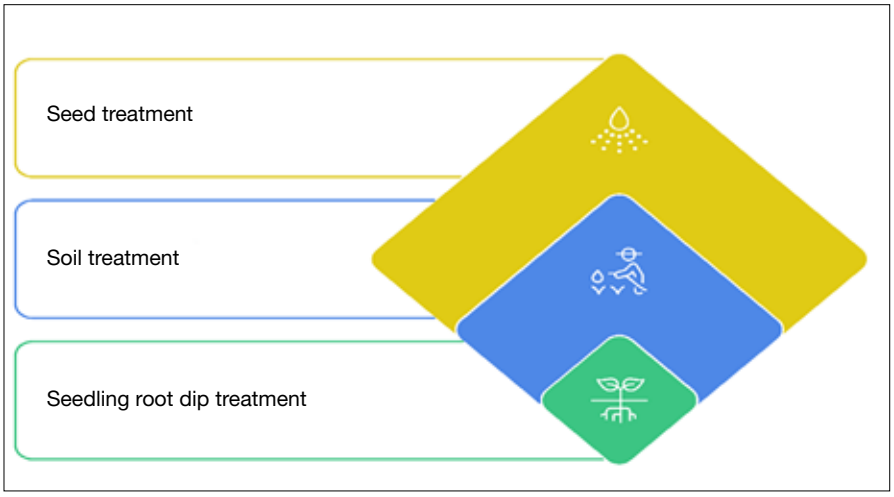
Crop	Pathogen	Bioinoculant	Mechanism
Rice	*Rhizoctonia solani*	*Pseudomonas fluorescens*	Antibiosis, ISR
Chickpea	*Fusarium oxysporum*	*Trichoderma harzianum*	Mycoparasitism
Tomato	*Ralstonia solanacearum*	*Bacillus subtilis*	ISR, competition
Soybean	*Fusarium solani*	*Bradyrhizobium* spp.	Antibiosis
Maize	*Fusarium graminearum*	*Bacillus Siamensis*	Competition
Rice	*Helminthosporium oryzae*	*Trichoderma harzianum*	Antibiosis
Cucumber	*Meloidogyne incognita*	*Trichoderma virens*	Mycoparasitism

help plants develop induced systemic resistance (ISR) which strengthens the plant's defense against infections. Bioinoculants increase the plant's resistance to infections by activating defense-associated genes and producing signaling molecules like salicylic acid.

Method of application and recommended doses

In India, the most preferred method of bioinoculant application is soil treatment due to its ability to treat larger areas effectively. *Mycorrhiza* is commonly applied @3–4 kg/acre by mixing the bioinoculant with organic matter or compost before applying it to the soil. Seed treatment of pulses with *Rhizobium* @5–10 ml/kg seed increases root nodulation which helps in better nitrogen fixation. Seed treatment of crops seeds with *Trichoderma* @5 g/kg seed helps to control seed-borne diseases. The seedling root dip method is particularly effective for crops like rice and transplanted vegetables. For example, dipping rice seedlings in a suspension of *Azospirillum* 500 ml in 50 liters of water.

The effectiveness of bioinoculants depends on their proper application methods and dosages. The choice of method depends on the crop type, soil conditions, and the specific bioinoculant formulation. For example, alkaline soils may require higher doses of phosphate-solubilizing bacteria (PSB) to release bound phosphorus. Different crops respond uniquely to bioinoculants. For instance, legumes benefit more from nitrogen-fixing bacteria like *Rhizobium.* While carrier-based formulations have a longer shelf life, liquid-based formulations are simpler to use but might need to be used right away.



Methods of application of bioinoculants

Trichoderma inoculated sorghum grains.

Performance of bioinoculants in major Indian crops

Bioinoculants, which contain beneficial microorganisms, have shown promising results in improving crop yield and nutrient use efficiency when applied to crops. In India, *Rhizobium* is mostly used with pulse crops which leads to yield increase of 10–35%. PSB is used with all crops, and it gives an average yield increment of 5–30%. *Azotobacter* and *Azospirillum* are other important biofertilizers that gives an average yield increase of 10–20% in cereals and other crops.

Current market scenario in india

According to Fortune Business Insights, Indian biofertilizer market in 2021 was valued at USD 99.59 million. It's expected to grow from USD 110.07 million in 2022 to USD 243.61 million by 2029. Environmental concerns, government initiatives supporting sustainable agriculture, and rising consumer demand for organic products are the main factors driving this growth. Through programmes like the National Mission on Sustainable Agriculture (NMSA) and Paramparagat Krishi Vikas Yojana (PKVY), the Indian government is encouraging organic farming and eco-friendly techniques by providing subsidies and support to biofertilizer producers. The market is dominated by nitrogen-fixing biofertilizers like *Rhizobium*, *Azotobacter*, and *Azospirillum*. Vesicular Arbuscular Mycorrhiza (VAM) is the fastest-growing category, as these fungi improve soil structure. Apart from big businesses,

Table 3. Recommended doses and application methods for common bioinoculants

Bioinoculant	Crop	Application method	Recommended dose
Rhizobium	Pulses	Seed treatment	5-10 ml/kg seed
Azotobacter	Tomato	Seedling dip	0.2 kg/litre water
Trichoderma	Groundnut	Seed treatment	4 g/kg seed
Mycorrhiza	Maize	Soil application	4 kg/acre

Table 4. Efficacy of bioinoculants in major crops

Crop	Bioinoculant	Observed effects
Pulses, groundnut, soybean	*Rhizobium*	10-35% yield increase
Vegetables	*Azotobacter*	2-45% yield increase
Rice	*Azolla*	25- 30 % yield increase
Cotton	PSB	5-10% yield increase

startups are also manufacturing and selling biofertilizers to farmers, and agricultural producers. Several ICAR institutes, as well as central and state agricultural institutions, are involved in the commercial production of several biopesticides. The use of biopesticides accounts for about 9% of all pesticide use in India and is projected to reach as much as 50% of the pesticide market by 2050. The most common biopesticides are based on neem, *Trichoderma, Pseudomonas fluorescens,* and *Bacillus*. A growth rate of 2.5 percent is expected each year. The major private players in the pesticide industry are Biotech International Ltd., Pune Indore Biotech Inputs and Research Pvt. Ltd., International Panaacea Ltd., Ajay Biotech Ltd., etc.

Challenges and future prospects

Despite the benefits of bioinoculants, their widespread adoption faces challenges. Limited shelf life, variable performance across different agro-zones, and lack of farmer awareness hinder their use. These microbes also provide slower results compared to synthetic chemicals. Additionally, regulatory hurdles complicate their registration and commercialization. However, with increasing focus on sustainable agriculture, bioinoculants hold great potential. Future research should focus on location- and crop-specific studies, improving shelf life, and raising awareness through extension programs and government schemes. Subsidies for biofertilizers and biopesticides could boost adoption, contributing to sustainable agricultural production.

SUMMARY

Bioinoculants offer a sustainable solution to mitigate the adverse impacts of synthetic agrochemicals on agriculture and environment. By harnessing power of beneficial microorganisms, bioinoculants enhance soil fertility, improve nutrient availability, and suppress diseases without compromising ecosystem health. The growing market in India reflects their increasing importance. However, challenges such as variability in performance across environments, limited awareness among farmers, and slow efficacy compared to synthetic chemicals remains and needs to be addressed. With the combined support from researchers, policymakers, farmers, and industrial stakeholders bioinoculants have the potential to make Indian agriculture sustainable and environment friendly.

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