

Bioagents: A Green Pathway towards Sustainable Agriculture

Pooja G. K¹. and Pavithra R².

¹Senior Research Fellow, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga

²Research Associate, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, India

SUMMARY

Sustainable agriculture aims to ensure food production while conserving natural resources, maintaining soil health and minimizing adverse environmental impacts. The excessive and continuous use of synthetic pesticides and fertilizers has raised concerns related to environmental contamination, pesticide resistance, disruption of beneficial microorganisms and food safety. In this context, bioagents have emerged as important biological tools for promoting sustainable and environmentally responsible crop production. Bioagents are beneficial microorganisms that suppress plant pathogens and insect pests while supporting plant growth and soil health. Important microbial bioagents such as *Trichoderma* spp., *Bacillus* spp., *Pseudomonas fluorescens*, *Bacillus thuringiensis*, *Beauveria bassiana* and *Metarhizium anisopliae* contribute to crop protection through mechanisms including competition, antibiosis, mycoparasitism, production of antimicrobial compounds, nutrient solubilization and activation of plant defence mechanisms. Their application can help to reduce dependence on synthetic pesticides, improve nutrient availability, enhance root development, maintain soil biological activity and strengthen plant resilience against biotic and abiotic stresses. However, bioagents should not be considered complete substitutes for chemical pesticides; rather, their effective integration with cultural, biological, mechanical and need-based chemical measures under integrated crop and disease management can provide more sustainable crop protection. Wider adoption of quality bioagent formulations, appropriate application methods and suitable strain selection can contribute to productive, profitable, environmentally safe and climate-resilient agricultural systems.

INTRODUCTION

Agriculture is the backbone of food and nutritional security and provides livelihood to millions of farming families. However, modern agriculture faces several challenges, including declining soil fertility, increasing incidence of pests and diseases, climate variability, rising cost of agricultural inputs and concerns related to excessive use of chemical pesticides and fertilizers. Although synthetic agrochemicals have played an important role in increasing crop production, their indiscriminate and continuous use can contribute to environmental contamination, disruption of beneficial microorganisms, development of pesticide resistance and concerns regarding food safety. In this context, sustainable agriculture aims to produce sufficient food while conserving natural resources and maintaining the health of agricultural ecosystems. One of the promising approaches towards this goal is the use of bioagents or biological control agents. Bioagents are beneficial living organisms that can suppress plant pathogens, insect pests and other harmful organisms while also improving plant growth and soil health (Lee *et al.*, 2023). Among the widely used microbial bioagents are *Trichoderma* spp., *Bacillus* spp., *Pseudomonas fluorescens*, *Bacillus thuringiensis* (Bt), *Beauveria bassiana*, *Metarhizium anisopliae* and several beneficial fungi and bacteria. These microorganisms can act through multiple mechanisms, including competition, antibiosis, parasitism, production of antimicrobial compounds, nutrient solubilization and activation of plant defence mechanisms. The multifunctional nature of microorganisms such as *Trichoderma* and *Bacillus* makes them particularly valuable components of sustainable crop production system.

What are Bioagents?

Bioagents are naturally occurring beneficial organisms used to suppress pests and diseases or promote plant growth. They may include beneficial fungi, bacteria, viruses, nematodes and other microorganisms. In crop production, microbial bioagents are particularly important because they can establish themselves in the rhizosphere or on plant surfaces and interact with both plants and harmful organisms. For example, *Trichoderma* species are important fungal bioagents used against several soil- and seed-borne plant pathogens. They can directly attack pathogens through mycoparasitism, compete for nutrients and space, produce antimicrobial metabolites and stimulate plant defence responses. *Trichoderma* can also function as a plant growth promoter and biostimulant, making it a multifunctional microorganism for sustainable agriculture (Woo *et al.*, 2023). Similarly, *Bacillus* and

Pseudomonas species are important plant growth-promoting rhizobacteria (PGPR). They colonize the rhizosphere and can suppress pathogens through antibiosis, siderophore production, secretion of lytic enzymes, competition for nutrients and space, and induction of systemic resistance in plants. Thus, bioagents are not merely substitutes for chemical pesticides. They can form an important component of an integrated crop management system, where biological, cultural, mechanical and chemical methods are combined judiciously.

Major Roles of Bioagents in Sustainable Agriculture

1. Biological management of plant diseases

One of the most important applications of bioagents is the management of plant diseases. Beneficial microorganisms can suppress fungal, bacterial and nematode pathogens without leaving the same type of persistent chemical residues associated with some conventional pesticides. *Trichoderma* is one of the most extensively studied fungal bioagents. It suppresses pathogens through mycoparasitism, competition, antibiosis and production of cell-wall-degrading enzymes. It can also colonize plant roots and stimulate local and systemic plant defence mechanisms. These properties make *Trichoderma* useful against several soil-borne and foliar pathogens. Bacterial bioagents such as *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Bacillus velezensis* and *Pseudomonas fluorescens* produce a wide range of antimicrobial compounds and enzymes. They can also occupy ecological niches around plant roots and thereby prevent pathogenic microorganisms from becoming established (Zhang *et al.*, 2023). A meta-analysis covering more than two decades of research found that *Bacillus*-based biological control treatments substantially reduced plant disease compared with untreated controls, demonstrating the potential of these organisms as practical disease-management tools.

2. Reduction in dependence on chemical pesticides

Excessive dependence on synthetic pesticides can result in several undesirable consequences, including pesticide residues, environmental contamination and development of resistant pest and pathogen populations. Biological control offers an opportunity to reduce the frequency and quantity of chemical pesticide applications. However, bioagents should not necessarily be considered complete replacements for all chemical pesticides. Their greatest value lies in their integration into Integrated Pest and Disease Management (IPM/IDM) programmes. For example, farmers can combine resistant varieties, sanitation, balanced nutrition, proper irrigation, bioagents and need-based chemical application. Such an integrated approach can reduce unnecessary pesticide applications while maintaining effective crop protection.

3. Promotion of plant growth

The importance of bioagents extends beyond disease suppression. Several beneficial microorganisms can directly promote plant growth by improving nutrient availability and producing plant growth-promoting substances. Certain *Bacillus* species, for example, can contribute to nitrogen fixation, phosphorus and potassium solubilization, phytohormone production and improved nutrient acquisition. They can therefore function simultaneously as biocontrol agents and plant growth-promoting microorganisms. *Trichoderma* species can improve root development, nutrient uptake and plant vigour. Root colonization by beneficial microorganisms can create a more favourable rhizosphere environment and help plants tolerate certain biotic and abiotic stresses. Therefore, the use of bioagents can contribute not only to healthier plants but also to improved crop establishment and productivity.

4. Improvement of soil health

Healthy soil is the foundation of sustainable agriculture. Continuous application of chemical inputs without adequate organic matter management can negatively influence soil biological activity. Beneficial microorganisms can contribute to maintaining a biologically active soil environment. Bioagents interact with native soil microorganisms and plant roots, contributing to nutrient cycling and microbial diversity. Some beneficial bacteria solubilize nutrients that are otherwise unavailable to plants, while fungal bioagents such as *Trichoderma* can influence the rhizosphere microbial community. A biologically active soil can support better nutrient availability, root growth and natural suppression of certain soil-borne pathogens. Thus, bioagents can become an important component of soil health management.

5. Activation of plant defence mechanisms

Plants possess their own defence mechanisms against pathogens. Beneficial microorganisms can stimulate these defence systems even before a pathogen establishes infection. This phenomenon is commonly referred to as induced systemic resistance (ISR) or defence priming. Certain *Bacillus* and *Pseudomonas* strains can trigger biochemical and molecular changes in plants that enhance their ability to respond to subsequent pathogen attack. Similarly, *Trichoderma* can establish beneficial interactions with plant roots and stimulate systemic defence

responses. This mechanism is particularly valuable because the microorganism does not necessarily need to directly kill the pathogen. Instead, it can prepare the plant to respond more effectively to disease.

Important Bioagents Used in Agriculture

Several microbial bioagents have been developed for agricultural use.

1. *Trichoderma* spp.

Widely used against soil- and seed-borne fungal pathogens. Major mechanisms include mycoparasitism, antibiosis, competition, production of hydrolytic enzymes and stimulation of plant defence.

2. *Pseudomonas fluorescens*

A well-known PGPR used for suppression of several plant pathogens. It can colonize the rhizosphere effectively and suppress pathogens through competition, antimicrobial metabolites and induction of plant defence.



Trichoderma spp.



Pseudomonas fluorescens

3. *Bacillus* spp.

Important bacterial bioagents with multiple functions. They produce antimicrobial metabolites, siderophores and enzymes and can induce systemic resistance. Some species also promote plant growth.

4. *Bacillus thuringiensis*

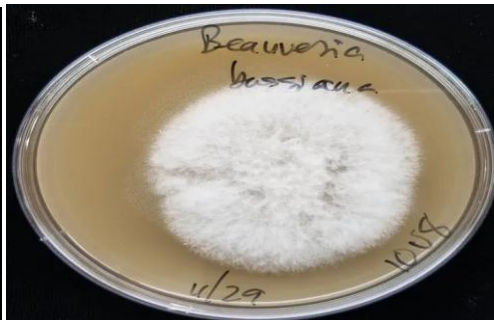
Commonly known as Bt, it is an important microbial insecticide used against several economically important insect pests. Its insecticidal proteins provide a biological alternative to certain synthetic insecticides.

5. *Beauveria bassiana* and *Metarhizium anisopliae*

The entomopathogenic fungi infect and kill several insect pests and have applications in biological insect-pest management. The diversity of these microorganisms demonstrates that biological control can address different categories of agricultural pests and diseases.



Bacillus subtilis



Beauveria bassiana

CONCLUSION

Bioagents represent one of the most promising biological tools for achieving sustainable agriculture. Their importance extends beyond simple disease and pest suppression. Beneficial microorganisms can protect plants from pathogens, promote plant growth, improve nutrient availability, enhance soil biological activity and stimulate plant defence mechanisms. Microorganisms such as *Trichoderma*, *Bacillus* and *Pseudomonas* demonstrate the potential of biological approaches to reduce excessive dependence on synthetic agrochemicals while maintaining crop health and productivity. Nevertheless, successful adoption requires proper strain selection, high-quality formulations, appropriate application techniques and integration with other components of integrated crop management. Rather than viewing bioagents simply as alternatives to chemical pesticides, they should be considered essential biological partners in modern sustainable agriculture. With increasing concerns over soil health, environmental sustainability, climate resilience and food safety, the wider adoption of bioagents can help

farmers move towards a production system that is productive, profitable, environmentally responsible and resilient for future generations.

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