



Biocontrol: Unlocking sustainable strategies for plant disease management in agriculture: A review

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Abstract

Biocontrol involves application of live microorganisms such as bacteria, fungi, viruses, protozoans and nematodes in farming practices to kill the insects on crop plant. Biocontrol agents (BCAs) inhibit the growth or germination of phytopathogens by secretion of antimicrobial metabolites. *Trichoderma* species coil around the hyphae of *Rhizoctonia solani* pathogen, thereby secreting chitinase and glucanases a cell wall degrading enzyme. They have many advantages as they act on pathogens without harming beneficial organisms or non-target species. BCAs are fast growing colonizers occupies the infection sites or compete to phytopathogens for essential nutrients like iron via siderophores production before it can establish an infection. *Bacillus* species secrete antimicrobial compounds like *Graminearum* which stop growth of plant pathogens and lowers the frequency of crop illnesses. A sustainable balance between pests and their natural enemies can be established through a variety of methods like inoculative releases, which apply small doses of biocontrol agents gradually over time or introduction of large numbers of BCAs in farming practice to suppress pest populations. Use of genetically engineered biocontrol agents having great specificity and efficacy have been made possible by rDNA technology. In traditional farming there is tremendous use of synthetic pesticides to kill insects, fungi, bacteria. They are harmful environment and farmer consumer also, and increase cost of production. To achieve sustainability and lower the crop production cost. use of biocontrol agents in integrated pest management (IPM), which stresses the approach of integration of cultural, biological, chemical practices in farming in a comprehensive manner to achieve pest control. Entomopathogenic microorganisms (EPs) include *Bacillus thuringiensis* (Bt), *Beauveria bassiana*, and *Metarhizium anisopliae* fight with harmful insects that spread plant diseases, providing potential alternatives to synthetic pesticides for plant protection. Farmers can increase their crop productivity but also environmental impact can be lowered. Global food security can be guaranteed by incorporating use of biological controls into agricultural practices. The main objective of this review is to highlight the applications of biocontrol agents in plant protection.

Keywords: Biocontrol agents, bioinsecticides, plant protection, integrated pest management, pesticides

Introduction

The tremendous increase in global population will be reached nearly to 10 billion by 2050, which will create challenges for the agricultural sector. To achieve the "Zero Hunger" goal, increase in agricultural food production must escalate significantly. Plants which provide 90% of human calories and 80% of protein are under threat from biotic and abiotic stressors. Biotic stressors are the phytopathogenic microorganisms, including fungi, bacteria, viruses, and oomycetes, nematodes are the primary cause of crop loss. Recent reports suggest that microbial diseases cause 20–40% yield losses worldwide which lead to an annual economic deficit of approximately \$40 billion (Jaiswal *et al.*, 2022) [7]. In History, major catastrophes occurred in farming in 1840, a Irish Potato Famine disease caused by *Phytophthora infestans* and in 1970 Southern Corn Leaf Blight pandemic was reported in the United States are the examples of vulnerability of food systems. For decades, the farmers applied strategy for managing these biotic threats to crop plants has been the heavy application of synthetic agrochemicals, pesticides in agriculture. Initially these chemicals were effective, but the widespread overuse of these chemical pesticides has triggered a cascade of Modern Environmental Health Hazards (MEHHs), including soil degradation, water contamination, and the emergence of pesticide resistant pathogenic strains (Ayaz *et al.*, 2023; Nguyen *et al.*, 2025) [1, 11]. Hence there is an urgent need to transition towards use of biocontrol in crop disease management, it utilizes beneficial microbes to suppress

plant pathogens and bolster plant immunity within a sustainable framework.

The Disadvantages of Synthetic Agrochemicals

The agricultural practice shifting towards use of biocontrol agents is not merely a preference but it's a necessity for sustainable agriculture raised due to the global misuse and overuse of traditional chemical interventions which possess the following risks.

a. Environmental and Health Risks

The Synthetic pesticides lack target specificity and affects non-target organisms including useful pollinators and soil microflora beneficial to plants growth. Furthermore; chemical residues in the food chain pose long-term health risks to consumers (Wan, N. F., *et al.*, 2025) [17]

b. Pathogen Resistance

Similar to antibiotic resistance emerged in phytopathogens; pest populations have evolved their genetic or behavioral pattern rapidly under the selection pressure of repetitive and inappropriate use of agrochemicals. This leads to a "treadmill effect" leading to necessity to farmers to apply higher and higher doses or more toxic compounds to gain the same level of pest control.

c. Soil Health Degradation

Continuous use of chemical compounds imbalanced the delicate balance of the rhizosphere micro biome, leading to reducing natural soil fertility and making plants more dependent on external applications of fertilizers.

Table 1: Comparison of synthetic pesticides and biological control agents

Feature	Synthetic Pesticides	Biocontrol Agents (BCAs)
1. Specificity	Broad spectrum activity often kills beneficial soil microbes.	High specificity i.e. targets specific pathogens
2. Environmental Impact	High (residues, contamination)	Low (biodegradable, eco-friendly)
3. Development of Resistance	Rapid and frequent resistance seen	Rare due to multimodal action
4. Cost	High (recurrent application)	lower due its self-sustaining growth
5. Mode of Action	Often a single biochemical target	Multiple (antibiosis, competition, ISR)
6. Stability	High (stable in various conditions)	Variable (affected by environmental conditions)

Biocontrol Agents (BCAs)

Biological control is a complex phenomenon which involves the interactions between the host plant, the pathogen, and the biocontrol agent. These mechanisms are generally categorized into direct and indirect actions (Bonatterra, A., *et al.*, 2022) [2].

Mechanisms and mode of action

a. Direct Mechanisms

Direct mechanisms involve a head-to-head confrontation between the BCA and the pathogen.

a. Antibiosis: The production and secretion of secondary antimicrobial metabolites including antibiotics, volatile organic compounds, or enzymes by BCAs that inhibit the growth or germination of phytopathogens (Villavicencio-Vásquez M., *et al.*, 2025) [16]. For example, *Bacillus* species secretes *Graminearum*, which is a Lipopeptides that disrupts fungal cell membranes leads to fungal growth inhibition (Hussain, S., *et al.*, 2024) [6]. Compound Iturin A is secreted by *B. subtilis* QST713 which targets the phytopathogen *Botrytis cinerea* and *R. solani* responsible for Damping off in field (Kloepper *et al.* (2004) [9].

b. Mycoparasitism (Hyperparasitism): A process where a BCA (usually a fungus) directly parasitizes another fungus. *Trichoderma* species are famous for this; they coil around the hyphae of pathogens like *Rhizoctonia solani*, secreting cell-wall-degrading enzymes (eg. chitinases and glucanases) to penetrate and consume the pathogen (Dutta P, *et al.*, 2023) [3]

c. Competition for Nutrients and Space: Many BCAs are rapid colonizers, they occupy the infection sites (niche exclusion) or sequestering essential nutrients like iron (via siderophores production) results in iron deficiency to the pathogen before it can establish an infection (Roca-Couso, R., *et al.*, 2021) [13]

b. Indirect Mechanisms

Indirect mechanisms focus on altering the host plant's physiology to resist attack.

a. Induced Systemic Resistance (ISR): ISR is triggered primarily by non-pathogenic root-colonizing bacteria i.e. Plant Growth Promoting Rhizobacteria or PGPR). ISR primes the plant's defense system, allowing it to respond more rapidly and intensely to future pathogen attacks (Jung J; *et al.*, 2024) [8]

b. Systemic Acquired Resistance (SAR): Typically triggered by a localized infection, leading to the production of salicylic acid and Pathogenesis-Related (PR) proteins throughout the plant (Fu, Z. Q., & Dong, X. (2013) [4].

c. Plant Growth Promotion: BCAs often act as biostimulants, they enhance nutrient uptake (phosphorus solubilisation, nitrogen fixation) and produces phytohormones like auxin, which lead to a more robust plant growth become capable to withstand in biotic stress (Villavicencio-Vásquez M *et al.*, 2025) [16]

Major groups of Biocontrol Microorganisms

American Society for Microbiology reported the diversity of the microbial world provides a vast reservoir of potential BCAs

a. Fungal Biocontrol Agents

The genus *Trichoderma* and *Aspergillus* are well known PGPF fungi used as BCAs. They are highly adaptable in various soil types and improve phosphorus solubilisation and nutrient uptake; they induce systemic resistance, compete with pathogens for nutrients and space in rhizosphere soil. *T. harzianum*, *T. viride* are effective and widely used to control the pathogens like *Rhizoctonia solani* and *Fusarium graminearum* (wilt), *Sclerotinia* (rot), and *Pythium* which causes damping-off.

b. Bacterial Biocontrol Agents

Bacteria are capable of rapid growth and produce a wide array of secondary metabolites. The Heat resistant endospore forming capacity in *Bacillus subtilis*, make them ideal for commercial formulations with long shelf life in the field. *Pseudomonas fluorescens* colonizing the rhizosphere produce siderophores, an iron chelating agent to outcompete pathogens. Some strains e.g. *Pseudomonas fluorescens* CHA0 or Pf-5, showed biocontrol properties by protecting the roots of some plant species against phytopathogens like *Fusarium*, the oomycete *Pythium*, phytophagous nematodes, and insect pests.

c. Entomopathogenic Microorganisms

These are microbes specifically targeting insect pests that act as vectors for plant diseases.

Bacteria: Entomopathogenic microorganisms (EPs) include, *Beauveria bassiana*, and *Metarhizium anisopliae*, *Bacillus thuringiensis* (Bt) fight with harmful insects that spread plant diseases. *Bacillus thuringiensis* (Bt), a rod-shaped, Gram-positive bacterium having ability to survive in harsh or starvation conditions. They form highly resistant endospores with Calcium Dipicolinic Acid. *Bacillus thuringiensis* releases "Cry" toxins or crystal toxins during its spore-forming stage. When insects like a caterpillar consumes these crystals while feeding on plant leaves, the alkaline environment present in insects gut activates the crystal toxin, which then binds to specific receptors and creates holes in the gut wall, damages alkaline insect gut and kill the insect. The brilliance of Bt lies in its high degree

of specificity; because different cry genes target only specific pests, the cry toxin remains completely harmless to humans, birds, and beneficial insects, which make them one of the most effective and eco-friendly bio pesticides used in Indian fields today. By using EPs crops to stay healthier, it becomes an eco-friendly option to chemical pesticides. By using them, farms become more resilient. EPs are an important part of Integrated Pest Management (IPM), helping farmers to reduce chemical use and supporting sustainable agriculture.

Fungi: *Beauveria bassiana* and *Metarhizium anisopliae* are friendly fungi that help farmers naturally to fight insect pests. They land on the insect body, or may grow inside, and control the insect population. These fungi help in keeping crops disease free, helps farmers to protect the soil healthier, more balanced, in a Eco sustainable way and reduce dependence on pesticides.

Challenges in Field Applications

Despite the promise of BCAs, their transition from the laboratory to the field faced some challenges. The success of biocontrol in controlled greenhouse environments often fails to translate to the field due to multiple factors

- a. **Environmental sensitivity:** Unlike chemicals, BCAs are living organisms (Paganizza, V 2024) soil environments like extreme temperatures, UV radiation, and soil pH can significantly reduce their efficacy and multiplication rate (Haq *et al.*, 2024) ^[5].
- b. **Inconsistent colonization:** BCA must successfully compete with the indigenous soil microbiome to colonize the rhizosphere. If it fails to establish a "foothold," biocontrol efficiency is lost.
- c. **Shelf life and formulation process:** Maintaining the viability of microbes in a commercial package for months is technically difficult to achieve.
- d. **Regulatory Hurdles:** The registration process for biological use in the field is often as difficult as for chemicals; also the approval process is very lengthy; it may require 2-3 years to register.

Future Perspectives: The "Eco-Smart" Evolution

To overcome the current limitations, the next generation of biocontrol is being developed with integration of advanced biotechnology approaches:

a. Multi-Omics Approaches

By using metagenomics and proteomics, researchers can identify and screen the specific genes and proteins responsible for biocontrol. This approach allows for the selection of "elite" strains that are more resilient to environmental fluctuations and field conditions (Sarethy, *et al.*, 2021) ^[14].

b. Nano-Biopesticide

The use of nanotechnology to encapsulate BCAs or their secondary metabolites can protect them from UV degradation and to ensure a slow, controlled release in the soil, which prove to significantly increase the field efficiency.

c. Synthetic Microbial Communities (SynComs).

Researchers are designing synthetic microbial communities (SynComs), which is a consortium in which multiple microbes work synergistically as one microbe. They might provide antibiosis, while another triggers ISR and a third promotes root growth, creating a holistic defense shield to crop (Minchev Z, *et al.*, 2021) ^[10]. Different individual microorganisms were the most effective in controlling the root pathogen. Based on the study on microbial consortia for biocontrol of root *Fusarium oxysporum* and foliar (*Botrytis cinerea*) pathogens in tomato, the following key findings reported, highlight the potential of these microbial combinations. The consortia showed an extended functionality, very effectively controlling both pathogens under any of the application schemes, found always achieving the same protection levels as the best performing single strains. The efficacy of microbial consortia containing compatible beneficial microorganisms, including bacteria and fungi, for the development of stable and versatile biological control products provide broader plant protection against a wider range of diseases, a resilient and effective tool for sustainable agriculture.

d. Nano biotechnology

Nanotechnology is useful to bridge the gap between laboratory success and field reliability through "smart" delivery systems. By utilizing the nano encapsulation approach, BCAs or their potent metabolites are packed inside microscopic and biodegradable shells, which act as protective barriers against heat and UV rays, ensuring the microbes remain viable for much longer periods. After controlled release in the field, these nano-shells allowed opening only under specific conditions such as a change in soil pH or the presence of enzymes secreted by a pathogen, ensuring that the biocontrol response is triggered exactly when and where it is needed most. This precision increases the efficacy of the treatment, improves the "stickiness" of the product, preventing it from being washed away by heavy rainfall.

Conclusions

The unlocking of sustainable agriculture requires a fundamental reimagining of the farming practices. Biocontrol represents a fundamental shift in how we achieve agricultural health. The integration of BCAs applications into Integrated Pest Management (IPM) programs will become the standard practice. Biocontrol, empowered with nanotechnology, provides a sustainable tool for plant diseases management. Unlocking the full potential of biocontrol agents in agriculture is not just a scientific goal; it is a prerequisite for ensuring global food security and a healthy environment for the 10 billion people of 2050.

Biocontrol practices provide the necessary tools to manage plant diseases without the environmental destruction caused by traditional chemicals. Thus, integrating BCAs with other sustainable practices can further boost agricultural resilience and ecofriendly food production. Biocontrol agents which are live microbes like *Bacillus thuringiensis*, *Bacillus papillae*, *Metarhizium anisopliae* and *Beauveria bassiana* or, viruses like NPV can be advantageous to overcome the side effects of synthetic pesticides and ecofriendly pest control solutions the transition to biology-based farming is not only environmental initiative, but it is a strategic necessity. By working in harmony with the microbial world, we can build

a resilient global food supply capable of feeding 10 billion populations while preserving the planet's health for future generations. Thus, this review has focused the importance of sustainable ecofriendly strategies that enhance economic and safe agricultural productivity. The positive results of BCAs on crop productivity and environmental sustainability are evident; there is urgent need of further research to optimize formulations to improve BCA application and assessment of long-term efficacy in diverse environmental, agro ecological conditions in India.

References

1. Ayaz M, Li C, Ali Q, Zhao W, Chi Y, Shafiq M, *et al.* Bacterial and fungal biocontrol agents for plant disease protection: Journey from lab to field, current status, challenges, and global perspectives. *Molecules*,2023;28(18):6735. <https://doi.org/10.3390/molecules28186735>
2. Bonaterra A, Badosa E, Daranas N, Francés J, Roselló G, Montesinos E, *et al.* Bacteria as Biological Control Agents of Plant Diseases. *Microorganisms*,2022;10(9):1759. <https://doi.org/10.3390/microorganisms10091759>
3. Dutta P, Mahanta M, Singh SB, Thakuria D, Deb L, Kumari A, *et al.* Molecular interaction between plants and Trichoderma species against soil-borne plant pathogens. *Front. Plant Sci*,2023;14:1145715. doi: 10.3389/fpls.2023.1145715
4. Fu ZQ, Dong X. Systemic acquired resistance: turning local infection into global defense. *Annual review of plant biology*,2013;64:839–863. <https://doi.org/10.1146/annurev-arplant-042811-105606>
5. Haq IU, Rahim K, Yahya G, Ijaz B, Maryam S, Paker NP, *et al.* Eco-smart biocontrol strategies utilizing potent microbes for sustainable management of phytopathogenic diseases. *Biotechnology Reports*,2024;44:e00859. <https://doi.org/10.1016/j.btre.2024.e00859>
6. Hussain S, Tai B, Ali M, Jahan I, Sakina S, Wang G, *et al.* Antifungal potential of lipopeptides produced by the *Bacillus siamensis* Sh420 strain against *Fusarium graminearum*. *Microbiology spectrum*, 2024;12(4):e0400823. <https://doi.org/10.1128/spectrum.04008-23>
7. Jaiswal DK, Gawande S, Soumia PS, Krishna R, Vaishnav A, Ade AB, *et al.* Biocontrol strategies: An eco-smart tool for integrated pest and diseases management. *BMC Microbiology*, 2022, 22(1). <https://doi.org/10.1186/s12866-022-02744-2>
8. Jung J, Ahn S, Kim D-H and Riu M. Triple interactions for induced systemic resistance in plants. *Front. Plant Sci*,2024;15:1464710. doi: 10.3389/fpls.2024.1464710
9. Kloepper JW, Ryu CM, Zhang S Induce systemic resistance and promotion of plant growth by *Bacillus* spp. *Phytopathology*,2004;94:1259-1266.
10. Minchev Z, Kostenko O, Soler R, Pozo MJ. Microbial Consortia for Effective Biocontrol of Root and Foliar Diseases in Tomato. *Front. Plant Sci*,2021;12:756368. doi: 10.3389/fpls.2021.756368
11. Nguyen HT, Pham TT, Nguyen PT, Dinh NCG Le MT, Nguyen TD, Nguyen TT, *et al.* Microbial biocontrol in agriculture: From mechanistic understanding to field application. *Discover Plants*, 2025, 2(1). <https://doi.org/10.1007/s44372-025-00421-y>
12. Paganizza V. Biocontrol Agents: Risks and Opportunities from Farm to Fork. *European Journal of Risk Regulation*,2025;15(2):280–291. doi:10.1017/err.2024.58
13. Roca-Couso R, Flores-Félix JD, Rivas R. Mechanisms of Action of Microbial Biocontrol Agents against *Botrytis cinerea*. *Journal of fungi (Basel, Switzerland)*,2021;7(12):1045. <https://doi.org/10.3390/jof7121045>
14. Sarethy Indira Saharan, Anurag. Genomics, proteomics and transcriptomics in the biological control of plant pathogens: a review. *Indian Phytopathology*, 2021, 74. 10.1007/s42360-020-00302-2.
15. The Microbial World: Foundation of the Biosphere: This report is based on an American Academy of Microbiology colloquium held January 19-21, 1996, in Palm Coast, Florida. The colloquium was supported by the National Science Foundation, the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce, the U.S. Department of Energy, and the American Society for Microbiology. Washington (DC): American Society for Microbiology, 1997. Available from: <https://www.ncbi.nlm.nih.gov/books/NBK562919/> doi: 10.1128/AAMCol.19Jan.1996
16. Villavicencio-Vásquez M, Espinoza-Lozano F, Espinoza-Lozano L, Coronel-León J. Biological control agents: mechanisms of action, selection, formulation and challenges in agriculture. *Front. Agron*,2025;7:1578915. doi: 10.3389/fagro.2025.1578915
17. Wan N F, Fu L, Dainese M, Kiær LP, Hu YQ, Xin F, *et al.* Pesticides have negative effects on non-target organisms. *Nature communications*,2025;16(1):1360. <https://doi.org/10.1038/s41467-025-56732-x>