

Biological Control Strategies in Plant Disease Management

Ria Mukhopadhyay*

School of Agriculture, Swami Vivekananda University,
Telinipara, Barrackpore, North 24 Parganas, West Bengal
700121, India

*Corresponding author: riam@svu.ac.in

Abstract

Plant diseases pose a significant threat to global agricultural productivity, leading to substantial economic losses and environmental impacts from chemical pesticides. Biological control strategies, which leverage natural enemies of pathogens, present an eco-friendly and sustainable alternative to chemical-based disease management. This approach utilizes antagonistic microorganisms, such as bacteria, fungi, and viruses, to suppress plant pathogens through competition, parasitism, and induction of host resistance.

Key biological control agents include *Trichoderma* spp., *Bacillus* spp., and *Pseudomonas fluorescens*, which have demonstrated efficacy against a wide range of plant pathogens. These agents not only inhibit pathogen growth but also enhance plant vigor and immunity. Recent advancements in molecular biology and biotechnology have facilitated the development of more effective bio-control products by unraveling the mechanisms of pathogen suppression and plant-microbe interactions.

Integrating biological control into holistic plant disease management systems offers numerous advantages, such as reduced pesticide residues, preservation of beneficial soil microbes, and improved environmental health. However, challenges such as inconsistent field performance, limited shelf life, and mass production constraints must be addressed to ensure wider adoption.

Keywords : Biological control, plant disease, management

Introduction

Plant diseases inflict severe losses on crop yield and quality worldwide. Estimates suggest that diseases and pests cause 20–30% losses in global harvests, undermining food security. Traditional control relies heavily on synthetic pesticides and fungicides, but these have significant drawbacks: environmental contamination, non-target toxicity, and development of resistant pathogens. In response, the biological control of plant diseases — using natural antagonists of pathogens — has gained traction as an eco-friendly, sustainable approach. This review explores the principles, agents, mechanisms, recent advances, and practical considerations of biological control. We emphasize key microbial agents (e.g. *Trichoderma*, *Bacillus*, *Pseudomonas*), their modes of action (antibiosis, competition, parasitism, induction of resistance), and how modern biotechnology is enhancing biocontrol efficacy. We also discuss integration into pest management and the challenges (field inconsistency, shelf life, production) that must be overcome for wider adoption.

Impacts of Plant Diseases and Pesticide Use

Plant diseases, caused by fungi, bacteria, viruses, nematodes, and oomycetes, are major constraints on agriculture. They reduce yields, diminish product quality, and incur economic costs. For example, fungal pathogens alone can destroy large fractions of staple crops if unchecked. Such losses are especially urgent given a growing population and rising food demand. Concurrently, intensive farming has led to heavy pesticide use. Chemical fungicides and bactericides can be effective short-term, but they pose problems: accumulation of toxic residues in food and soil, killing of beneficial organisms, and pollution of water and air. Furthermore, pathogens can evolve resistance to chemicals, diminishing their usefulness. The environmental and health costs of pesticides have led regulators and consumers to demand safer alternatives. In this context, biological control leveraging natural antagonists of pathogens emerges as a promising solution.

Biological control aim to minimize chemical inputs and use multiple tactics (cultural, genetic, biological) for crop protection. Indeed, current trends emphasize reducing reliance on chemicals: many countries mandate IPM practices and support biocontrol research. By exploiting microbes already present in the ecosystem, biocontrol can suppress diseases with lower environmental impact. In practice, microbial biocontrol agents (BCAs) are now registered and marketed worldwide as niche “biofungicides” or “biopesticides”. However, these products are still relatively few compared to chemical pesticides, and field efficacy can be variable. A deep understanding of biocontrol mechanisms and improved technologies are helping to develop more robust products for broad adoption.

Principles and Mechanisms of Biological Control

Definition of Biological Control

In plant pathology, biological control is defined as the suppression of disease or the pathogen itself by other living organisms (often microorganisms). The antagonists (BCAs) can be bacteria, fungi, viruses (bacteriophages or mycoviruses), and even protozoa or nematodes, but most commonly bacteria and fungi are used (Lahlali et al. 2022). Crucially, the antagonist need not kill the pathogen outright; reducing disease through interference or induced host defenses also counts as biological control. BCAs may be applied preventively or curatively and can act at different stages: in soil (suppressing root pathogens), on foliage, or in storage (post-harvest pathogens).

Modes of Pathogen Suppression

Biocontrol agents employ multiple mechanisms to inhibit pathogens. These can be broadly categorized as direct antagonism and indirect effects.

- **Antibiosis (Antimicrobial Compounds):** Many BCAs secrete secondary metabolites that inhibit or kill pathogens. For example, *Bacillus* and *Pseudomonas* species are prolific producers of antibiotics (bacillomycin, iturin, surfactin, 2,4-diacetylphloroglucinol, phenazines, etc.). These

compounds (bacteriocins, lipopeptides, phenols) diffuse into the environment and disrupt pathogen metabolism or cell integrity. Filamentous bacteria (*Streptomyces*) and fungi also produce potent antifungal and antibacterial metabolites. Many of these molecules degrade quickly, reducing environmental persistence.

- **Parasitism and Predation:** Some BCAs attack pathogens directly. Fungal BCAs like *Trichoderma* species exhibit *mycoparasitism*, coiling around or penetrating fungal hyphae, and secreting lytic enzymes (chitinases, glucanases) to destroy the pathogen cell wall. Certain bacteria can similarly be predatory (e.g. *Myxobacteria* and *Lysobacter*). Viruses (bacteriophages) specifically infect and lyse bacterial pathogens, offering precise biological control of bacterial diseases.

- **Competition:** BCAs compete with pathogens for space and nutrients. A well-adapted BCA can colonize the root surface or phyllosphere, forming biofilms and consuming available resources, thereby denying pathogens a foothold. Siderophore production is a key aspect: many BCAs (notably fluorescent *Pseudomonas*) secrete high-affinity iron-scavenging molecules. By sequestering iron (Fe^{3+}), they starve pathogens that require iron for growth. Similarly, rapid niche occupation (e.g. fast spore germination) can preempt pathogen invasion.

- **Induced Host Resistance:** Some BCAs act indirectly by triggering the plant's own immune system. When plants perceive beneficial microbes, they can enter a "primed" state, mounting faster and stronger defenses upon pathogen attack. This is known as Induced Systemic Resistance (ISR) when elicited by non-pathogens, and Systemic Acquired Resistance (SAR) when triggered by mild pathogen infection. For instance, *Bacillus* and *Pseudomonas* can induce ISR via jasmonic acid/ethylene pathways, and some *Trichoderma* strains elicit SA-dependent SAR. The primed plant accumulates defensive enzymes, pathogenesis-related proteins, and phytoalexins, reducing disease severity.

- **Growth Promotion and Health:** Many BCAs produce plant hormones (auxins, cytokinins), solubilize phosphates,

or fix nitrogen, thus improving plant vigor. A healthy, well-nourished plant is more resistant to disease. Though not a direct control of pathogens, this growth promotion is a valuable feature: it enhances yield and may indirectly reduce disease incidence. For example, *Trichoderma* spp. are known to enhance root growth and nutrient uptake while *Pseudomonas fluorescens* can improve nutrient availability.

Key Biological Control Agents

Fungal BCAs: *Trichoderma* and Others

Fungi constitute some of the most widely used BCAs. *Trichoderma* species, filamentous soil fungi, are preeminent in controlling soil-borne plant pathogens (e.g. *Fusarium*, *Rhizoctonia*, *Pythium*). Many *Trichoderma* products (often strains of *T. harzianum* or *T. viride*) are commercially available. Their success stems from multiple capabilities: rapid growth, robust spore production, secretion of cell-wall-degrading enzymes (chitinases, glucanases), and induction of plant defenses. *Trichoderma* parasitizes pathogenic fungi (mycoparasitism) by penetrating hyphae and digesting their cell walls. It also produces antibiotics (e.g. gliotoxin, peptaibols) that suppress pathogens.

Moreover, *Trichoderma* can colonize plant roots and act as a plant-growth promoter and ISR elicitor. For instance, inoculation with *T. asperellum* primes cucumber to reduce bacterial leaf spot by ~80%, linked to increased phenolic and jasmonate pathway activity. *Trichoderma*-colonized plants often show enhanced root architecture, yield increases, and systemic disease resistance. The genus is considered safe, low-cost, and broadly effective across crops.

Other fungi are used as BCAs too. *Penicillium* and *Clonostachys rosea* (formerly *Gliocladium*) have biocontrol properties. The hyperparasite *Ampelomyces quisqualis* attacks powdery mildews. Mycoviruses (fungal viruses) can attenuate pathogenic fungi; for example, the hypovirus in *Cryphonectria parasitica* drastically reduces chestnut blight virulence, a classical biocontrol success in Europe. However, such viral agents are specific and less widely commercialized.

Bacterial BCAs

Beneficial bacteria are central to biocontrol. Genera routinely exploited include *Bacillus*, *Pseudomonas*, *Streptomyces*, and *Burkholderia*.

- **Bacillus spp.:** These Gram-positive, endospore-forming rods are marketed as biopesticides (e.g. *B. subtilis* QST 713, *B. amyloliquefaciens* FZB24). *Bacillus* species produce a wide array of antimicrobial compounds (iturins, fengycins, surfactins) and volatiles. They compete well in soil and on roots due to spore resistance and rapid germination. Bacilli also induce ISR in plants and can solubilize phosphate or fix nitrogen. Modern studies reveal *Bacillus* quorum-quenching enzymes (lactonases) that disrupt pathogen communication, and “cry-for-help” signaling where stressed plants attract *Bacillus* strains. *Bacillus*-based products are thus potent, eco-friendly biofungicides (Pérez-García et al. 2022).

- **Pseudomonas spp.:** Fluorescent pseudomonads (e.g. *P. fluorescens*, *P. chlororaphis*) inhabit the rhizosphere. They produce yellow-green siderophores (pyoverdines), various antibiotics (2,4-DAPG, phenazines, HCN), and lytic enzymes. Pseudomonads are famous for controlling soil pathogens (like *Fusarium*, *Gaeumannomyces*) and nematodes. They excel at inducing ISR in plants through JA/ET signaling. Several *P. fluorescens* strains are formulated as seed or soil treatments. Their ability to quickly colonize roots and adapt to environmental conditions makes them versatile, though field results can vary.

- **Streptomyces spp.:** Actinomycetes produce a huge diversity of antibiotics (streptomycin, tetracycline, etc.) and are used against fungal and bacterial pathogens. Commercial products like *Streptomyces lydicus* WYEC 108 target root rot pathogens. Their filamentous growth allows good soil colonization, but mass-production is more complex.

- **Other Bacteria:** *Bacillus thuringiensis* is mainly insecticidal, but its role as a plant disease biocontrol is limited. *Burkholderia* and *Paenibacillus* species have shown antagonism to pathogens through antibiotic production and siderophores. Rhizobia (*Rhizobium*, *Bradyrhizobium*) can enhance plant health and

sometimes suppress pathogens indirectly. Nevertheless, the majority of bacterial biocontrol research and products focus on *Bacillus*, *Pseudomonas*, and related genera.

Viral and Other Agents

Bacteriophages (Phages): The viruses of bacteria have regained interest as precise biocontrols against bacterial plant diseases. Phages multiply in their host and can dramatically reduce populations of pathogens like *Erwinia amylovora* (fire blight) or *Pseudomonas syringae* on fruit surfaces. They are highly specific (tailored cocktails can target only the pathogen strain) and replicate in the field, potentially adapting to resistance. Several phage products for crop diseases are now registered or in development (Buttimer et al. 2017). However, UV sensitivity and narrow host range can limit efficacy, necessitating advanced formulations.

Entomopathogenic Viruses: While mainly used for insect control (baculoviruses), some viral biopesticides can incidentally suppress plant diseases by reducing vector populations.

Protozoa and Predatory Nematodes: Very rarely, free-living protozoa or predatory nematodes (targeting pathogenic nematodes) are used biocontrol agents. These have a limited scope in mainstream agriculture due to complexity of use.

Mechanisms of Pathogen Suppression and Plant Response

Antimicrobial Metabolites and Enzymes

Microbial antagonists secrete a rich arsenal of bioactive compounds against pathogens. *Bacillus* species produce lipopeptides (iturins, fengycins) that create pores in fungal membranes. *Pseudomonas* produce phenazines and pyoluteorin that generate reactive oxygen. *Streptomyces* produce macrolides and polyenes. These antibiotics often degrade to harmless products after action. Volatile organic compounds (VOCs) like hydrogen cyanide (HCN) and ammonia also inhibit pathogens at a distance. BCAs also release cell-wall-degrading enzymes (chitinases, β -1,3-glucanases, proteases) that break down fungal cell walls. For example, *T. asperellum* induces high levels of chitinase and

glucanase when in contact with a pathogen, strengthening its mycoparasitic attack. These enzymes may also release elicitors to trigger plant defenses.

Understanding these molecular mechanisms has been advanced by genomics and proteomics. Sequencing BCA genomes reveals genes for known antifungal compounds; transcriptomics shows which genes are induced during pathogen confrontation. Biotechnological efforts include mutagenesis or engineering of strains to overproduce key enzymes or metabolites. For instance, genetically enhanced *Bacillus* strains with higher lipopeptide output are under study.

Competition and Colonization

Effective BCAs are often strong colonizers. For example, *Pseudomonas fluorescens* can form robust biofilms on roots, excluding pathogens physically. *Bacillus* spores germinate quickly and establish on plant surfaces. Competition for nutrients (especially iron via siderophores) is a key mode. Root-colonizing BCAs can lower soilborne pathogen inoculum by outcompeting them near the rhizosphere. Field trials often show that adding a BCA to soil reduces the pathogen's ability to infect roots, likely due to such niche competition.

Induced Systemic Resistance (ISR)

A major indirect effect is priming of plant immunity. When BCAs (or their cell extracts) colonize roots or foliage, they trigger signaling cascades in the plant. The result is a heightened defensive state, often mediated by jasmonic acid/ethylene or salicylic acid pathways. For instance, roots treated with *Trichoderma harzianum* show elevated expression of pathogenesis-related (PR) genes throughout the plant, conferring resistance even in distal tissues. This ISR is broad-spectrum: primed plants can fend off multiple pathogens and even some insects more effectively. Key studies show *Bacillus* and *Pseudomonas* isolates inducing ISR against fungal, bacterial, and viral pathogens. Thus, BCAs do not just fight pathogens directly; they enlist the plant's own defenses.

Plant Growth Promotion

While not directly combating pathogens, BCAs enhance plant growth and vigor, indirectly contributing to disease tolerance. Mechanisms include hormone production (indole-3-acetic acid by *Pseudomonas*, gibberellins by *Bacillus*), solubilization of minerals (phosphate-solubilizing *Bacilli*), and nitrogen fixation (in limited rhizobia cases). Nutrient-rich, well-developed plants recover faster from infections. For example, cucumber plants inoculated with growth-promoting rhizobacteria showed higher biomass and stronger root systems, correlating with less wilt from *Fusarium*. Many commercial BCAs list both “disease control” and “growth enhancer” as product claims.

Advances in Biotechnology and Product Development

Modern biology and biotechnology are refining biocontrol. Key advancements include:

- **Genomics and Omics:** High-throughput sequencing has catalogued microbial diversity and metabolic pathways. Genome mining of *Trichoderma*, *Bacillus*, *Pseudomonas* reveals novel antibiotic gene clusters. Metagenomics of disease-suppressive soils identifies consortia of beneficial microbes. These insights enable targeted strain selection. For instance, isolates can be screened for biosynthetic genes of interest before greenhouse tests.
- **Elucidating Mechanisms:** Molecular studies reveal how BCAs interact with plants and pathogens. The “cry-for-help” phenomenon describes how plants under attack release root exudates that recruit specific beneficial microbes (e.g. certain *Bacillus*). Understanding ISR signaling pathways allows us to choose or engineer BCAs that trigger the most effective immune responses in given crops.
- **Engineering and Synthetic Consortia:** Researchers are creating *synthetic microbial consortia*, mixing multiple BCA strains to broaden activity and stability. For example, combining a *Bacillus* with a *Trichoderma* can suppress both fungal and bacterial pathogens, and also improve plant growth more than either alone. Genetic engineering tools

(CRISPR, transposon mutagenesis) are also used to enhance desired traits. Although regulatory hurdles limit genetically modified BCAs, marker-assisted evolution and directed selection can improve strains.

- **Formulations and Delivery:** Innovations in formulation (e.g. freeze-drying, microencapsulation, talc carriers) greatly improve shelf life and field performance. Studies show that encapsulating bacterial cells in alginate or adding prebiotic carriers extends viability beyond months. Seed coatings with dry BCAs protect seeds during storage and give a head start to beneficial colonization. Liquid formulations with UV protectants or surfactants increase BCA survival on leaves. These advances address historic weaknesses of biocontrol products.

- **Regulatory and Production:** Scale-up fermentation methods produce large volumes of BCA cultures. Fermenters for bacteria (liquid culture) and fungi (solid substrate) have been optimized. However, ensuring consistency and purity is still challenging. Regulatory science is adapting: the EU Green Deal targets 50% pesticide reduction by 2030, recognizing biopesticides as key. Harmonizing approval pathways for microbial agents can speed commercialization.

In summary, biotechnology is rapidly strengthening biocontrol. As Xu et al. (2024) note for *Bacillus*, new mechanisms like quorum-sensing interference and microbial consortia are frontiers for improving green agriculture. Likewise, Collinge et al. (2022) report that increased use of BCAs, supported by mechanistic understanding, can meaningfully reduce chemical inputs.

Integration into Disease Management

Integrating BCAs into an overall Integrated Pest Management strategy is crucial. Instead of viewing them as standalone solutions, BCAs work best in concert with resistant cultivars, cultural controls, and limited chemicals. For example, a fungicide spray might be replaced by an earlier soil treatment with *Bacillus*, followed by a *Trichoderma* soil drench, and a later nutrient solution with bacterial biofertilizer.

Advantages and Environmental Benefits

- **Reduced Chemical Residues:** By replacing or lowering pesticide use, BCAs leave little to no harmful residues in food or the environment. They biodegrade and self-limit. This makes biological control appealing for organic farming and sensitive ecosystems (e.g. near waterways).
- **Preservation of Beneficial Organisms:** Chemical broad-spectrum fungicides often kill helpful mycorrhizae, rhizobia, and insect allies. In contrast, BCAs tend to be specific to pathogens or are even integrated into the soil microbiome without harming other microbes. For instance, a *Bacillus* strain in the rhizosphere can boost microbial diversity by stabilizing the soil environment, whereas a fungicide might wipe out many species.
- **Plant and Soil Health:** As noted, BCAs can improve plant vigor. Healthier plants resist pests better. Moreover, the use of BCAs often aligns with improved soil health practices (reduced soil sterilants, less run-off). Healthy soils rich in microorganisms can suppress diseases naturally over time.
- **Human and Ecosystem Safety:** Most BCAs are non-toxic to humans and animals. They align well with stringent environmental regulations. As Wend *et al.* (2024) observe, microbial pesticides “may be less toxic than chemical pesticides, be very specific to the target, decompose quickly, and be less likely to cause resistance”.

Complementarity and IPM

BCAs are rarely a “silver bullet”. They function best as part of an IPM plan. For example, crop rotation can reduce pathogen load, biological agents can then suppress remaining inoculum, and targeted minimal chemical treatments can handle outbreaks. Many studies show that combining BCAs with reduced fungicide rates can maintain control levels while cutting chemical usage in half. Importantly, BCAs are usually compatible with other IPM elements. They can be tank-mixed with low-toxicity fungicides or used alongside biofertilizers.

Farmers’ adoption of BCAs often increases when education and extension emphasize integration. The transition to

biocontrol also aligns with consumer and retailer demands for “low-residue” and “sustainably produced” crops.

Challenges and Limitations

Despite the promise, several hurdles must be addressed for broader adoption of biological control:

- **Inconsistent Field Performance:** Unlike standardized chemicals, living BCAs respond to environmental variables. Field trials often show variable efficacy due to soil type, moisture, temperature, and crop conditions. A strain that works in a greenhouse may fail in a dry field. Understanding and mitigating this variability is an active research area. Strategies include selecting robust strains, using local isolates, or employing consortia to cover multiple conditions.
- **Shelf Life and Storage:** Many biocontrol microbes have limited shelf stability. Viability can decline over months. Wend *et al.* highlight that “limited shelf life ... is a disadvantage”, noting that 18 months is considered the minimum standard for a commercial product. For example, *Pseudomonas fluorescens* formulations may only remain viable for a few months, whereas *Trichoderma* can last longer. Advances in formulation (as above) are helping, but long-term storage remains a challenge, especially in hot climates. Transportation and storage under the cold chain increase costs.
- **Mass Production and Cost:** Scaling up production of BCAs to millions of units poses technical challenges. Bacterial fermentation is relatively straightforward, but fungal spore production requires sterile solid substrates and careful drying. Quality control to ensure high counts of active cells/spores per package is critical. These processes can be costlier than synthesizing a chemical. As Wend *et al.* note, current biopesticides tend to be more expensive and slightly less efficacious than conventional products. Economies of scale and improved methods are gradually lowering prices, but cost remains a barrier for resource-poor farmers.
- **Regulatory Hurdles:** Approval processes for biocontrol agents can be lengthy and inconsistent between regions. Safety data (non-target effects, pathogenicity) must be compiled.

In some countries, BCAs are regulated similarly to drugs, requiring extensive trials. This delays market entry of new products. The EU and US are working on faster registration for microbial agents, but complexity remains. Notably, Wend *et al.* report that despite promising growth, biopesticides still represent <10% of the market, partly due to regulatory bottlenecks.

- **Awareness and Adoption:** Many growers distrust BCAs due to past inconsistent experiences. Extension work is needed to demonstrate effective use (proper application timing, environmental conditions). Integrated approaches and reliable data on return on investment can help convince practitioners.

In summary, while biological control agents have clear environmental and safety advantages, practical constraints of stability, efficacy, and cost must be solved. Ongoing research on formulations, consortia, and application technologies aims to overcome these issues.

Future Directions

Looking ahead, the biocontrol field is rapidly evolving. Key future trends include:

- **Precision Biocontrol:** Using sensor data and predictive models to apply BCAs at optimal times (e.g. before rainfall triggers disease). Drone or robotic delivery of microbe-laden sprays could target hotspots.
- **Plant-Microbiome Engineering:** Selecting crop varieties that recruit beneficial microbes naturally. Some breeding programs consider plant root exudates that attract BCAs.
- **Climate Resilience:** Developing BCAs that remain active under extreme conditions (drought-tolerant spores, UV-resistant formulations) will expand applicability.
- **Genome Editing:** Although controversial, CRISPR might be used to edit BCA strains for safety (e.g. remove toxin genes) or potency.
- **Microbiome Consortia:** Moving from single-strain products to well-defined microbial communities with synergistic

functions. Synthetic ecology approaches could yield “living biofungicides” that establish beneficial soil flora.

- **Regulatory Innovation:** Frameworks that emphasize ecological impact and risk/benefit balance may accelerate approvals. International harmonization (e.g. under FAO guidelines) will help global market growth.

In conclusion, biological control of plant diseases harnesses nature’s own defenses to create safer, sustainable agriculture. The accumulating body of research (molecular, field, product development) paints a clear picture: antagonistic microbes like *Trichoderma*, *Bacillus*, and *Pseudomonas* can significantly reduce disease while improving plant health. Advances in biotechnology and integrative management amplify their impact. However, overcoming challenges of consistency, shelf life, and production is critical for widespread adoption. With concerted research and policy support, biocontrol is poised to play an ever-greater role in feeding the world safely and sustainably.

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