

Role of fungi in plant disease management

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ABSTRACT

Fungi are integral to plant health, acting both as pathogens and biocontrol agents. Pathogenic fungi like *Fusarium*, *Colletotrichum*, and *Puccinia* spp. cause diseases such as wilt, anthracnose, and rust, leading to major crop losses. These fungi invade plant tissues, block vascular systems, and produce toxins that impair growth and yield. Conversely, beneficial fungi such as *Trichoderma* spp. and arbuscular mycorrhizal fungi (AMF) enhance plant resilience. *Trichoderma* spp. suppress pathogens via mycoparasitism, antibiosis, and competition for nutrients and space. They also secrete enzymes like chitinases and glucanases that degrade pathogen cell walls. AMF form symbiotic relationships with roots, improving phosphorus uptake, water absorption, and stress tolerance. Both fungi types stimulate induced systemic resistance (ISR), priming plants to defend against future infections. Their integration into farming reduces reliance on chemical fungicides, lowering environmental toxicity. Combined use of AMF and *Trichoderma* has shown synergistic effects in controlling wilt diseases in tomato and melon. Field trials reveal up to 45% reduction in *Fusarium* wilt severity with AM inoculation. *Trichoderma harzianum* was more effective against *Verticillium* wilt, reducing severity by 34.45%. These fungi also improve root architecture and nutrient solubilization, boosting overall crop productivity.

Keywords: Fungi; Plant disease management; Pathogens; Biocontrol; *Trichoderma* spp.; Arbuscular mycorrhizal fungi (AMF); Antagonism; Antibiotics; Enzymes, disease suppression.

Introduction

Plant diseases need to be controlled to maintain the quality and abundance of food, feed, and fiber produced by growers around the world. Different approaches may be used to prevent, mitigate or control plant diseases. Beyond good agronomic and horticultural practices, growers often rely heavily on chemical fertilizers and pesticides. Biological control as it is applied to the suppression of plant diseases. Fungi are among the most diverse and ecologically vital organisms. Biological control is nothing but ecological management of community of organisms. It involves harnessing disease-suppressive microorganisms to improve plant health. Disease suppression by use of biological agents is the sustained manifestation of interactions among the plant (host), the pathogen, the biocontrol agent (antagonist), the microbial community on and around the plant and the physical environment. The biological control of plant diseases differs from insect biocontrol in following ways They drive nutrient cycling, improving soil fertility and structure. In agriculture, fungi display dual roles—harmful and beneficial. Pathogenic fungi like *Fusarium* and *Alternaria* cause severe crop losses. They invade plant tissues, reduce yield, and spread rapidly under moist conditions. Beneficial fungi such as *Trichoderma* and mycorrhizae foster plant health. They enhance root development, suppress pathogens, and boost nutrient uptake. Fungal biocontrol agents reduce chemical dependency in crop systems. This duality makes fungi both a challenge and a solution in farming. Harnessing their potential is key to sustainable agriculture{1} Seed treatment chemicals when used give protection only in the early stages of crop growth.

Chemicals used to control soil-borne diseases are uneconomical, less effective and leave residues in the soil and plants. Further, they are toxic to beneficial microorganisms in the soil. In certain cases, the plant pathogens develop resistance to fungicides and bactericides. Under the above circumstances, it becomes inevitable to develop a bio-based, eco-friendly, biodegradable plant derived pesticides or microbial pesticides in order to control plant pathogens. Biological control or biocontrol using antagonistic microorganisms offers a practical and economical alternative for the management of plant pathogens.

Ecological Diversity and Functional Roles of Fungi

Fungi play a key role in nutrient cycling by decomposing organic matter. They break down complex compounds into simpler forms accessible to plants. This process releases nitrogen, phosphorus, and trace minerals back into the soil. Such microbial activity enriches soil fertility and enhances plant growth. Overall, fungi help maintain ecological balance and sustain agricultural productivity{2} Mycorrhizal fungi develop dense hyphal networks that bind soil particles into stable aggregates. These structures improve soil porosity, boosting oxygen availability for roots and microbes. They enhance water retention by creating microchannels that hold moisture. Such activity reduces soil erosion and compaction, promoting healthy root development. Overall, mycorrhizae are vital for long-term soil structure and agricultural resilience{3} Would you like this formatted into a bilingual chart or infographic for outreach use? Mycorrhizal fungi produce hyphal networks that bind soil particles into stable aggregates. These aggregates improve soil porosity, allowing better airflow around roots.

The hyphae also create pathways that retain water and reduce runoff. This activity prevents erosion and boosts root development in crops. Such fungal interactions are essential for maintaining soil health and resilience{3}. sexually produced spores of *Pythium oligandrum*, oospores were used for the seed treatment of sugarbeet, cress and carrot to control damping-off diseases{4}.*Myrothecium verrucaria*, can parasitize hyphae of *Cochliobolussativus*{5}, Nutrient cycling by decomposing organic matter and releasing essential minerals into the soil. Symbiotic relationships like mycorrhizae that enhance plant nutrient absorption Disease suppression through beneficial fungi like *Trichoderma* acting as biocontrol agents. questration and soil structure improvement, supporting ecosystem stability. Production of bioactive compounds used in medicine, fermentation, and agriculture.

Arbuscular mycorrhizal fungi (AMF) and ectomycorrhiza are essential soil symbionts that form mutualistic associations with over 80% of terrestrial plants.AMF penetrate root cortical cells, establishing arbuscules that facilitate efficient nutrient exchange, particularly phosphorus and micronutrients. Ectomycorrhizae, commonly associated with forest trees, envelop root tips externally and enhance water and nitrogen uptake, while secreting enzymes to mobilize nutrients from organic matter. Both symbioses boost plant resilience to drought, salinity, and pathogen attack by modulating hormonal pathways and improving root architecture. *Fusarium oxysporum* is a soil-borne ascomycete fungus that belongs to a species complex comprising numerous host-specific strains known as *formaespeciales*. These specialized forms target particular crops, such as *F. oxysporum f. sp. lycopersici* in tomato, *f. sp. cubense* in banana, and *f. sp. ciceris* in chickpea. The pathogen typically enters the plant through wounds or natural openings in the roots, often facilitated by environmental stress or nematode activity. Once inside, it colonizes the root cortex and invades the xylem vessels, where it produces microconidia that travel upward through the transpiration stream. This systemic spread disrupts water and nutrient transport, leading to characteristic wilt symptoms.

The infection process is intensified by the secretion of cell wall-degrading enzymes such as cellulases and pectinases, along with phytotoxins that impair host physiology. As the fungus proliferates within the vascular system, it causes occlusion of xylem vessels, resulting in yellowing of lower leaves, stunted growth, and progressive wilting. A diagnostic feature of *Fusarium* wilt is vascular browning—visible as brown streaks in stem cross-sections. In advanced stages, plants may collapse entirely due to severe water stress.

Mycoparasitism is a biological interaction where one fungus (the mycoparasite) parasitizes another fungus (the host or prey). This direct antagonism is a cornerstone of fungal biocontrol strategies, especially in sustainable agriculture.

- **Necrotrophic Mycoparasites:** Kill and consume the host (e.g., *Trichoderma* spp.).
- **Biotrophic Mycoparasites:** Live within the host without immediately killing it (e.g., *Ampelomycesquisqualis*).
- **HemibiotrophicBehavior:** Some fungi, like *Trichoderma*, may start as biotrophs and shift to necrotrophy of Action: Step-by-Step Combat

Trichoderma and AMF serve as eco-friendly alternatives to synthetic agrochemicals:

- *Trichoderma* spp.suppress soil-borne pathogens via mycoparasitism, antibiosis, and competition, reducing the need for fungicides.

- AMF enhance nutrient uptake (especially phosphorus and micronutrients), decreasing reliance on chemical fertilizers.
- Their use aligns with integrated pest management (IDM) and organic farming principles, promoting long-term soil health. Biocontrol fungi like *Trichoderma*, *Beauveria*, and *Metarhizium* are biologically active
- **Spore Sensitivity:** Spores lose viability under UV exposure, high temperatures, and humidity fluctuations.
- **Carrier Limitations:** Common carriers (e.g. talc, peat) may not protect spores adequately or degrade over time.
- **Metabolite Breakdown:** Antifungal compounds such as peptaibols or gliotoxins degrade before reaching the pathogen.

Regulatory Barriers: The Bottleneck to Market Entry

- **Lengthy Registration Processes:** Approval requires extensive data on efficacy, safety, environmental impact, and non-target effects—often modeled after chemical pesticide protocols.
- **Lack of Harmonization:** Regulatory frameworks vary widely across countries and even states, making international commercialization difficult.
- **Limited Support for Native Strains:** Indigenous fungal isolates, despite ecological relevance, often lack standardized dossiers or global recognition, delaying their approval.
- **High Compliance Costs:** Small-scale innovators and academic institutions struggle with the financial burden of meeting biosafety and toxicology testing requirements.

Example: In India, only a few strains like *Trichoderma viride* and *T. harzianum* are registered under the Central Insecticide Board and Registration Committee (CIBRC), while promising strains like *T. asperellum* remain unregistered despite proven efficacy.

Challenge	Impact
Strain Variability	Different isolates of the same species may show divergent biocontrol traits.
Fermentation Techniques	Solid-state vs. liquid fermentation affects spore yield and metabolite profiles.
Carrier Materials	Talc, peat, or lignite carriers influence shelf life and delivery efficiency.
Quality Control Gaps	Absence of industry-wide standards for viability, purity, and potency.

- **Batch-to-Batch Inconsistency:** Farmers report variable results due to fluctuating spore counts and contamination risks.
- **Storage Sensitivity:** Lack of cold-chain infrastructure in rural areas compromises product stability
- **Limited Training:** Few extension programs explain optimal timing, dosage, and compatibility with fertilizers or pesticides.
- **Perceived Inefficacy:** Biocontrol agents often act slower than chemical pesticides, leading to skepticism.
- **Application Errors:** Misuse—such as applying in dry soil or incompatible mixtures—reduces efficacy.
- **Lack of Demonstration Trials:** Absence of visible field success stories hampers trust and uptake.

Pathogens and Their Effects:

Fungus	Disease Caused	Crops Affected	Strategy
<i>Fusarium</i> spp.	Wilt, root rot, blight	Cereals, legumes	Necrotrophy
<i>Colletotrichum</i> spp.	Anthrachnose	Fruits, vegetables	Hemibiotrophy
<i>Puccinia</i> spp.	Rust diseases	Wheat, barley	Biotrophy

- **Genetic variability:** Rapid mutation rates allow pathogens to evade plant defenses and develop resistance to fungicides.

- **Environmental adaptability:** Many pathogens thrive under diverse climatic and soil conditions, making control strategies inconsistent.
- **Overcoming host resistance:** Pathogens can suppress or bypass

Mechanism of Biocontrol agents

Because biological control can result from many different types of interactions between organisms, researchers have focused on characterizing the mechanisms operating in different experimental situations. In all cases, pathogens are antagonized by the presence and activities of other organisms that they encounter. Here, we assert that the different mechanisms of antagonism occur across a spectrum of directionality related to the amount of interspecies contact and specificity of the interactions (Table 2). Direct antagonism results from physical contact and/or a high-degree of selectivity for the pathogen by the mechanism(s) expressed by the BCA(s). In such a scheme, hyperparasitism by obligate parasites of a plant pathogen would be considered the most direct type of antagonism because the activities of no other organism would be required to exert a suppressive effect. In contrast, indirect antagonisms result from activities that do not involve sensing or targeting a pathogen by the BCA(s). Stimulation of plant host defense pathways by non-pathogenic BCAs is the most indirect form of antagonism. However, in the context of the natural environment, For instance, pseudomonads known to produce the antibiotic 2,4-diacetylphloroglucinol (DAPG) may also induce host defenses{6}. Additionally, DAPG-producers can aggressively colonize roots, a trait that might further contribute to their ability to suppress pathogen activity in the rhizosphere of wheat through competition for organic nutrients{7}. and this high chitinase- producing fungus, was also successfully used for the control of Drechslera teres infection of barley leaves by the seed treatment. Biocontrol of cocoa pod diseases with mycoparasite mixtures has been suggested by{8}.

1. Mycoparasitism

- Fungi like *Trichoderma* spp. Parasitize other fungi by coiling around their hyphae.
- They secrete **cell wall-degrading enzymes** (chitinases, glucanases) to penetrate and kill the pathogen.
- Example: *Trichoderma viride* attacking *Rhizoctonia solani*.

2. Antibiosis

- FBCAs produce secondary metabolites (e.g., gliotoxin, peptaibols) that inhibit or kill pathogens.

Challenges:

Issue	Description
Formulation stability	Maintaining viability of fungal spores
Field efficacy	Performance varies with climate and soil
Shelf life	Limited durability without additives
Regulatory barriers	Complex approval processes for commercialization

Advantages of Beneficial Fungi in Sustainable Agriculture

Feature	Benefit
Environmentally Safe	Reduces reliance on synthetic agrochemicals and minimizes pollution.
Organic Farming Compatibility	Suitable for certified organic systems and natural inputs.
Soil Health and Biodiversity	Promotes microbial diversity, improves structure, and boosts fertility.

IDM is a holistic, sustainable approach to managing plant diseases by integrating multiple strategies—cultural, biological, chemical, and educational—tailored to specific agroecosystems. It aims to reduce disease incidence below economic thresholds while minimizing environmental impact.

Components of IDM

Component	Description
Cultural Practices	Crop rotation, sanitation, deep ploughing, and residue management to disrupt pathogen life cycles.
Biologicals	Use of antagonistic fungi like <i>Trichoderma</i> spp. and mutualistic fungi like AMF (Arbuscular Mycorrhizal Fungi) to suppress pathogens and enhance plant health.
Monitoring & Forecasting	Disease surveillance, early warning systems, and predictive modeling to guide timely interventions.
Training & Outreach	Farmer education through extension programs, bilingual materials, and participatory workshops to promote adoption of IDM practices.

Formulation and Delivery Systems

FBCAs are formulated into powders, granules, or liquid suspensions to enhance shelf life and field efficacy. Techniques such as encapsulation, carrier-based delivery, and nanoformulations are being explored to improve stability and performance {9}

Advantages and Limitations

Advantages:

- Environmentally safe and biodegradable{10}
- Compatible with organic farming and IDM{11}
- Enhances soil microbial diversity and plant vigor

Limitations:

- Variable field efficacy due to environmental sensitivity
- Short shelf life of some formulations
- Regulatory hurdles in commercialization

Overview: High-throughput sequencing and comparative genomics allow researchers to identify specific virulence factors and beneficial traits in fungal strains.

Applications:

- o Discovery of genes responsible for chitinase production, ISR activation, and environmental resilience.
- o Targeted selection of strains with superior efficacy against specific pathogens or stress conditions.

Benefits:

1. Molecular Characterization for Precision Deployment

Advanced molecular tools are revolutionizing how biocontrol strains are selected, validated, and deployed:

Tools Used

- **Whole-Genome Sequencing (WGS):** Deciphers the complete genetic blueprint of biocontrol agents, identifying genes linked to virulence, stress tolerance, and metabolite production.
- **RNA-Seq:** Profiles gene expression under different environmental or host conditions, revealing functional traits like ISR induction or antifungal metabolite synthesis.
- **CRISPR-based Functional Validation:** Enables targeted gene editing to confirm roles of specific genes in biocontrol efficacy or stress resilience.

Strategic Strain Accuracy

Tailors strain selection to agroclimatic zones based on genomic markers for temperature, pH, and soil type adaptability.

- **Regulatory & IP Support:** Molecular data supports patent filings and accelerates regulatory approvals by demonstrating safety, specificity, and efficacy.

2. Synergistic Microbial Consortia: Fungal + Bacterial BCAs

Combining fungal biocontrol agents (e.g., *Trichoderma*, *Pochonia*) with beneficial bacteria (e.g., *Bacillus*, *Pseudomonas*) creates multitarget, resilient consortia.

Mechanisms of Synergy

- **Quorum Sensing Cross-Talk:** Microbes communicate via signaling molecules, coordinating biofilm formation, metabolite production, and niche colonization.
- **Enhanced ISR:** Dual activation of jasmonic acid and salicylic acid pathways primes plants against a wider range of pathogens.
- **Nutrient Solubilization:** Bacteria solubilize phosphorus and zinc; fungi enhance uptake via mycorrhizal-like associations.
- **Competitive Exclusion:** Consortia rapidly colonize rhizosphere niches, outcompeting pathogens for space and resources.

Formulation Advancements

- **Co-cultured Bioinoculants:** Stabilized blends of fungi and bacteria with synchronized growth and metabolite profiles.
- **Shelf-Life Optimization:** Use of cryoprotectants, encapsulation, and carrier matrices (e.g., talc, alginate) for long-term viability.

Benefits

- **Broader Spectrum Activity:** Targets fungi, bacteria, nematodes, and abiotic stress simultaneously.
- **Improved Rhizosphere Colonization:** Enhanced root adherence and persistence under field conditions.
- **Greater Adaptability:** Resilience across soil types, climates, and cropping systems.

3. Smart Formulations: Nanocarriers & Biofilm Technology

- **Nano emulsions:** Oil-in-water systems for hydrophobic metabolite delivery.

Polymeric Nanocarriers (e.g., Chitosan, Alginate):

- Controlled release of spores and metabolites.
- Protection from UV degradation, desiccation, and temperature fluctuations.
- Targeted delivery to infection sites via root exudate-responsive release.

Biofilm-Based Delivery

- **Embedded Fungi in Biofilms:** Mimics natural colonization, enhancing adhesion to root surfaces and persistence in soil microhabitats.
- **Synergistic Biofilms:** Co-formulated with bacteria to create multi-species biofilms with enhanced resilience and metabolite synergy.

Advantages

- **Extended Shelf Stability:** Reduced degradation during storage and transport.
- **Precision Targeting:** Responsive release based on soil pH, moisture, or plant signals.

- **Reduced Application Frequency:** Sustained activity minimizes repeat dosing.
- **Compatibility:** Integrates with drip irrigation, seed coating, and foliar spray systems.

Outlook for Sustainable Farming

- **Genetically Traceable:** Linked to molecular barcodes for strain authentication and performance tracking.
- **Regionally Adaptable:** Tailored to local soil, climate, and cropping systems using genomic and phenotypic data.
- **Digitally Deployable:** Integrated with mobile apps, IoT sensors, and AI platforms for crop stage-specific interventions.
- **Aligned with Certification Standards:** Compatible with organic, agroecological, and carbon-smart farming missions.

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