



Fungal Biocontrol Agents: An Eco-Friendly Alternative to Chemical Pesticides

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Abstract

The excessive and indiscriminate application of chemical pesticides, insecticides, and fungicides in current agriculture has caused grave environmental concerns, threats to human health, and loss of biodiversity. Although the chemicals ensure immediate control of pests and diseases, long-term use causes soil and water pollution, bioaccumulation of residues in food chains, and the emergence of pest populations resistant to the chemicals. As such, there has been increasing need for sustainable and environmentally friendly alternatives to produce crops safely. Fungi-derived biological control agents (BCAs) have been promising alternatives to chemical inputs because of their ecological flexibility, target specificity, and compatibility with Integrated Pest Management (IPM) systems. Fungal BCAs suppress pests and pathogen by virtue of several mechanisms such as parasitism, antibiosis, and competition for resources, and induction of host plant resistance. Major classes are entomopathogenic fungi (*Beauveria bassiana*, *Metarhizium anisopliae*), mycoparasitic fungi (*Trichoderma* spp., *Gliocladium* spp.), endophytic and symbiotic fungi (*Piriformospora indica*, *Glomus* spp.), and herbicidal fungi (*Colletotrichum gloeosporioides*, *Fusarium oxysporum* f. sp. *strigae*). Fungi not only manage pests and diseases but also support plant growth promotion and ecological equilibrium. This article summarizes the promise of fungi to act as biocontrol agents, emphasizing their modes of action, advantages, disadvantages, and prospects for future use in sustainable agriculture. Their use has the potential to minimize dependency on chemical pesticides, favoring environmentally friendly farming practices.

INTRODUCTION

Agriculture forms the foundation of human society, and food security for an increasingly large global population necessitates incessant enhancement of crop productivity. During the last century, synthetic pesticides, insecticides, and fungicides have been instrumental in safeguarding crops against insects

and diseases. Widespread use of these has notably helped in the "Green Revolution" by improving yields and lowering crop losses globally. But excessive and indiscriminate application of these chemical inputs has generated grave issues regarding environmental deterioration, loss of biodiversity, pest resistance, and human and animal health hazards (Fravel, 2005; Sharma et al., 2017).

Chemical pesticides tend to be persistent in the environment, polluting soil, water, and food webs. Chronic health issues like cancer, hormonal disruptions, and neurological diseases have been associated with long-term exposure in humans. Further, helpful organisms like pollinators, natural enemies, and microorganisms in the soil are usually adversely affected, disrupting ecological equilibrium (Butt et al., 2001). Also, several diseases and insect pests have become resistant to popular chemicals used against them, rendering them ineffective in the long term (Hajek & Delalibera, 2010). All these pose a challenge to the development of safer and more environmentally friendly alternatives. Biological control, or biocontrol, provides a sustainable approach through the utilization of living organisms or their natural products to reduce pests and diseases. Of the several microbial groups investigated, fungi have proved to be very efficient biocontrol agents because of their special ecological functions, versatility, and ability to adapt (Harman et al., 2004; Mukherjee et al., 2013). Fungal biocontrol agents (BCAs) are widespread in soil and plant environments and can kill pathogens, insects, and weeds using more than one mechanism of action such as parasitism, antibiosis, and competition. Certain fungi also form mutualistic interactions with plants, supporting growth and eliciting systemic resistance. Many fungal genera have been tested and marketed as BCAs successfully. *Trichoderma* spp., for example, are used on a large scale against soil-borne pathogens; entomopathogenic fungi like *Beauveria bassiana* and *Metarhizium anisopliae* are efficient against insect pests; and herbicidal fungi like *Colletotrichum gloeosporioides* infect invasive weeds (Vega et al., 2009). Due to their natural property of producing hardy spores, they are well adapted for bulk application, and their specificity allows them to be harmless to beneficial organisms. Besides their biocontrol activities, fungi contribute to soil health enhancement and nutrient cycling. Mycorrhizal fungi, for instance, stimulate plant nutrient acquisition and stress resistance, thereby lowering the demand for chemical inputs indirectly (Sharma et al., 2017). Fungal biocontrol is therefore not just a plant protection measure but also the basis of sustainable agriculture.

2. Mechanisms of Fungal Biocontrol

Fungi function as biocontrol agents by a number of mechanisms:

Parasitism: Direct infection of pathogens (e.g., *Trichoderma* spp. against *Rhizoctonia*) (Harman et al., 2004).

Antibiosis: Production of metabolites and enzymes that suppress pathogen growth (Mukherjee et al., 2013).

Competition: Competing for space and nutrients with deleterious microbes (Cook & Baker, 1983).

Induced Resistance: Eliciting plant defense mechanisms to achieve improved tolerance (Sharma et al., 2017).

3. Major Groups of Biocontrol Fungi

Fungi are a highly heterogeneous and ecologically significant group of organisms with immense potential as biocontrol agents. Their capability to parasitize, compete, and antagonize various plant pathogens, insect pests, and weeds makes them extremely versatile. The most significant groups of fungal biocontrol agents are entomopathogenic fungi, mycoparasitic fungi, endophytic and symbiotic fungi, and herbicidal fungi.

Entomopathogenic Fungi

Entomopathogenic fungi are among the most widely studied microbial control agents for insect pests. They infect insects through direct penetration of the cuticle rather than ingestion, unlike bacteria or viruses (Hajek & Delalibera, 2010). Once inside, the fungus proliferates, producing toxins and ultimately killing the host. After death, the cadaver sporulates, releasing conidia that spread infection to other insects.

Beauveria bassiana – effective against whiteflies, aphids, beetles, and caterpillars; widely formulated as commercial biopesticides.

Metarhizium anisopliae – successfully used against locusts, termites, and root grubs.

Lecanicillium lecanii – controls soft-bodied insects such as aphids, mealybugs, and scales in horticultural crops.

Isaria fumosorosea – employed against thrips and whiteflies in greenhouse cultivation.

Mycoparasitic Fungi

Mycoparasitic fungi infect and parasitize other fungi directly. They inhibit soil-borne and leaf pathogens by wrapping around host hyphae,

breaking into them, and releasing hydrolytic enzymes like chitinases and glucanases (Harman et al., 2004). Mycoparasitic fungi are notable for their **dual role**: they both suppress plant pathogens and stimulate plant defense responses.

Trichoderma spp. – the most commercially exploited group; controls pathogens such as *Rhizoctonia solani*, *Fusarium oxysporum*, *Pythium spp.*, and *Sclerotinia sclerotiorum*. It also enhances plant growth through root colonization and secondary metabolite production.

Gliocladium virens – effective against damping-off diseases in vegetables and ornamentals.

Coniothyrium minitans – a specific biocontrol agent against *Sclerotinia spp.*, reducing sclerotial germination in soil.

Endophytic and Symbiotic Fungi

Endophytic fungi infect plant tissues non-pathogenically and tend to offer defense against herbivores and pathogens. Symbiotic fungi, especially mycorrhizal fungi, increase nutrient acquisition and resistance to abiotic stress, and indirectly decrease susceptibility to pathogens (Sharma et al., 2017).

Piriformospora indica – promotes root growth, induces systemic resistance, and enhances crop productivity.

Arbuscular Mycorrhizal (AM) fungi, e.g., Glomus spp. – improve nutrient uptake (especially phosphorus) and increase resistance to soil-borne pathogens.

Epichloë spp. – endophytes in grasses that produce alkaloids, deterring herbivory.

These fungi contribute not only to disease suppression but also to overall plant vigor and resilience.

Herbicidal Fungi (Bioherbicides)

Some fungi were shown to be prospective bioherbicides, used to control invasive weeds that compete with crops. They infect weed tissues and produce toxins, causing them to decrease in growth and die.

Colletotrichum gloeosporioides – used to control invasive weed *Mimosa pigra*.

Phytophthora palmivora – applied against *Morrenia odorata*.

Alternaria cassiae – effective against sicklepod (*Senna obtusifolia*).

Fusarium oxysporum f. sp. *strigae* – a promising bioherbicide against parasitic weed *Striga* in cereal crops.

Although bioherbicides are not as commercially established as biofungicides and bioinsecticides, they represent an emerging field in sustainable weed management.

Emerging Fungal Biocontrol Agents

With advances in molecular biology and genomics, new groups of fungi are being identified with potential as BCAs. For instance, entomopathogenic yeasts and genetically improved fungal strains are being developed to enhance field stability, virulence, and shelf life (Mukherjee et al., 2013).

4. Advantages of Fungal Biocontrol Agents

The use of fungi as biocontrol agents (BCAs) offers several ecological, agronomic, and socioeconomic benefits over traditional agrochemicals. Their wide range of biological tactics and inherent ability to adapt make them extremely useful for sustainable crop protection.

Environmentally Friendly

Fungal BCAs are biological entities that break down naturally without depositing toxic residues in soil, air, or water. Chemical pesticides, on the other hand, tend to linger, accumulate, and find their way into the food chain, causing long-term environmental risks. Fungal spores, once dispersed, either perish or become part of harmless soil microbial populations, keeping ecological equilibrium intact. Their application leads to less pollution and protects delicate ecosystems like wetlands, groundwater aquifers, and habitats for pollinators.

Target Specificity

Most fungal BCAs are specific in their action against particular pests or pathogens, reducing non-selective damage to pollinators, soil microbiota, and plants. For example, *Beauveria bassiana* is specific against whiteflies, aphids, and beetles but has no adverse effect on honeybees and other pollinators. This specificity is different from broad-spectrum chemical pesticides that kill pests

and beneficial organisms indiscriminately, upsetting natural biological control mechanisms.

Multiple Modes of Action

Unlike chemicals that often act through a single toxic pathway, fungi employ several mechanisms simultaneously:

Parasitism (e.g., *Trichoderma* coiling around and penetrating *Rhizoctonia* hyphae).

Antibiosis (secretion of antimicrobial metabolites such as peptaibols by *Trichoderma*).

Competition (outcompeting pathogens for nutrients or root colonization sites).

Induced Systemic Resistance (priming host plants to activate their defense genes).

This multiplicity reduces the risk of pests developing resistance, ensuring long-term effectiveness.

Cost-Effectiveness and Self-Perpetuation

Large-scale production of fungal BCAs is comparatively low-cost with basic substrates like grains, crop residues, or agro-industrial by-products. Fungi naturally propagate after application, particularly under warm and humid environments, ensuring continuous pest suppression without repeated reapplications. For instance, spores of *Metarhizium anisopliae* remain in soil for months and continue to infect root grubs year after year, reducing farmers' input costs.

Compatibility with Integrated Pest Management (IPM)

Fungi can be easily integrated in IPM packages together with cultural management (sanitation, crop rotation), mechanical means, and even low doses of selective chemicals. Their synergistic effect maximizes overall efficiency in pest control while minimizing dependence on chemicals. For instance, *Trichoderma harzianum* in combination with biofertilizers and resistant varieties has been successful in controlling damping-off and wilt of vegetables to the minimum.

Plant Growth Promotion

Certain fungal BCAs act in addition to pest management by positively stimulating plant growth and yields. *Trichoderma* spp. increase root elongation, enhance uptake of nutrients

(particularly nitrogen and phosphorus), and confer drought and salt tolerance. *Piriformospora indica* not only triggers induced resistance but also enhances biomass and yield in cereals and vegetables. Therefore, fungal BCAs are both protectants and bio-stimulants.

Safety to Humans and Animals

If properly applied, fungal BCAs are considered to be safe for agriculturalists, consumers, and animals. They do not deposit toxic residues in foods and potable water, unlike synthetic pesticides. Occupational exposures, pesticide poisoning, and long-term health risks are greatly minimized. Additionally, the formulations of fungi are biodegradable, which means there are no risks of long-term exposure to agricultural workers.

Biodiversity Conservation

The decrease in chemical dependence using fungal biocontrol saves useful organisms like pollinators, predators, parasitoids, and soil microorganisms. Fungi maintain healthy soil microflora, which maintains nutrient cycling and soil fertility. This creates a harmonious agro ecosystem where natural enemies and crops coexist, minimizing pest outbreaks, and ensuring long-term sustainability.

5. Challenges in the Adoption of Fungal Biocontrol Agents

Though they have been proven and possess ecological benefits, fungal biocontrol agents (BCAs) are confronted with a number of practical, economic, and biological issues that limit their adoption in large-scale conventional farming. The issues must be overcome to allow them to be integrated into extensive farming systems.

Variable Field Performance

Fungal BCAs tend to work optimally under laboratory and greenhouse conditions but yield variable results in open fields. Temperature, humidity, soil type, and UV radiation have strong impacts on fungal survival, germination, and infection efficiency. For example, entomopathogenic fungi such as *Beauveria bassiana* need high humidity for effective infection of insects, which may not always be possible in dry environments.

Sensitivity to Environmental Conditions

Fungal spores are extremely sensitive to abiotic stress like heat, desiccation, and ultraviolet radiation. These limit spore viability and persistence in the field and their long-term efficiency. There is a need for special formulations (oil-based, microencapsulation) to enhance stability, but these add cost to production.

Slower Mode of Action Compared to Chemicals

In contrast to chemical pesticides that provide instant knockdown effects, fungal BCAs typically require a few days to infect and kill target pests or pathogens. This reduced speed of action may dissuade farmers who prefer instant results, particularly in cases of intense pest infestation.

Limited Shelf Life and Storage Issues

Most of the fungal formulations have a short shelf life, especially in tropical storage conditions. Unfavorable temperature and storage infrastructure in rural areas further decrease the viability of the fungal spores, creating logistical hurdles in distribution and marketability.

Limitations in Mass Production and Formulation

Though fungi may be grown on low-cost substrates, bulk commercial production involves sophisticated fermentation technologies, sterile environments, and appropriate formulation methods. Up-scale production without compromising quality, spore viability, and field performance is a major limitation, particularly in the developing world.

Compatibility with Agrochemicals

While fungal BCAs are eco-friendly, they may not always be compatible with chemical pesticides or fertilizers applied in conventional farming. Certain fungicides can inhibit fungal growth and reduce their effectiveness, making integration into current farming practices more complex.

Knowledge and Awareness Gaps

Most farmers lack knowledge of fungal biocontrol technologies, their advantages, and how to apply them. They are discouraged by the lack of training,

limited extension service access, and the convenience of rapid-acting chemicals. Misconceptions regarding the safety and effectiveness of biocontrol agents also persist.

Regulatory and Commercialization Barriers

The approval and registration process for microbial biopesticides takes considerable time, is expensive, and complicated. Small and medium-scale companies or research institutes working on fungal BCAs encounter challenges complying with regulatory biosafety and quality control provisions. Additionally, low private sector investment hampers commercialization and mass availability.

Economic Considerations

While fungal BCAs are inexpensive in the long run, commercial formulations may occasionally be more expensive than chemical pesticides at the start. Without incentives, subsidies, or government encouragement, smallholder farmers might not adopt unfamiliar chemical inputs for fungal alternatives.

Future Prospects

Advances in biotechnology, formulation techniques, and nanotechnology are enhancing the efficiency of fungal biocontrol agents. Genetic engineering can help develop strains with improved stress tolerance and efficacy (Mukherjee et al., 2013). Wider adoption through government policies, farmer training, and commercialization will promote their role in sustainable agriculture.

Conclusion

Fungal biocontrol agents represent a sustainable, eco-friendly, and effective alternative to chemical pesticides in modern agriculture. Their diverse mechanisms—ranging from parasitism and antibiosis to competition and induction of host resistance—make them powerful tools for managing insect pests, plant pathogens, and weeds while simultaneously promoting plant growth and ecological balance. Unlike chemical inputs, they are biodegradable, target-specific, and compatible with Integrated Pest Management (IPM) strategies, thereby reducing environmental pollution and safeguarding biodiversity. However, despite these

advantages, several challenges still limit their large-scale application. Issues such as inconsistent field performance, sensitivity to environmental factors, limited shelf life, and slow action compared to chemicals remain significant barriers. Furthermore, inadequate farmer awareness, high production costs, and complex regulatory requirements have slowed down their commercialization and adoption. Future research should focus on developing advanced formulations with improved stability, enhancing mass production technologies, and exploring molecular approaches to strengthen fungal efficacy under diverse field conditions. In addition, government support, farmer training, and integration of fungal BCAs into national pest management policies are essential for their wider acceptance. In conclusion, fungi hold great promise as biocontrol agents, and their strategic use can play a pivotal role in reducing chemical dependence, enhancing crop productivity, and achieving sustainable agricultural systems.

Conflicts of Interest

The authors declare no conflicts of interest.

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