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Fungal Biocontrol in Agriculture: A Sustainable Alternative to Chemical Pesticides – A Comprehensive Review

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Abstract

Fungal biocontrol agents (BCAs) have arisen as an ecologically sustainable agricultural substitute for conventional pesticides. This method provides valuable control over pests and plant diseases by utilizing fungi's naturally predatory and competitive characteristics, thereby minimizing the use of harmful synthetic chemicals. The mode of action is reviewed, and fungal BCAs are discussed, including *Trichoderma spp., Beauveria bassiana*, and *Metarhizium anisopliae,* whose pathogenicity, outcompeting ability, and production of secondary metabolites are known to inhibit pathogens. Employed as bio-controls, fungal BCAs also bring many environmental and health benefits by lowering pesticide resistance potential, minimizing ecological impact, and increasing soil health. In addition, compared to broad-spectrum chemical pesticides, fungal biocontrol agents are more specific and do not disturb beneficial organisms. These BCAs hold great promise, but their widespread use is limited by environmental sensitivity, high production costs, and limited shelf life of the formulation. Formulation and genetic engineering innovations are overcoming these challenges by improving the efficiency and scalability of fungal biocontrol products, including the multiple applications of synergistic compounds. In the face of climate change and the urgent need for sustainable agricultural methods, these fungal biological control agents (BCAs) will play an integral role in IPM, enabling sustainable, diverse, and resilient ecosystems that contribute to agricultural sustainability for the future. This review highlights the potential of fungal biocontrol as an effective tool for ensuring food security in the post-antibiotic era, with further development necessary to harness its complete potential on a global scale.

Keywords: Biocontrol; Sustainable Agriculture; Pests; Microbial Bio-pesticides; Fungi

1. Introduction

Biological control (biocontrol) uses living organisms (predators, parasites, pathogens, or competitors) to suppress pest populations in agricultural systems. It uses natural processes to reduce pest populations and plant diseases and regulate the soil ecosystems. Biocontrol is vital to sustainable food production, providing a natural, effective, and environmentally friendly means of controlling pests and disease and protecting agroecosystems and agricultural economies [1]. For instance, fungal biocontrol agents use fungi that directly attack pests and pathogens or compete with them, thus limiting their influence on crops.

Biocontrol is an essential aspect of sustainable agriculture and has considerable environmental, economic, and health benefits [2]. This decreases the use of artificial pesticides that can harm non-target organisms and pollute ecosystems. Biocontrol agents (biological control agents), such as natural predators or antagonists, co-evolve with pests and offer a sustainable solution with minimal development of resistance. This strategy contributes to biodiversity conservation, improves the resilience of agricultural systems, and is economically beneficial over the long term. Roberts (1874) first

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used the word "antagonist" in microbiology when he showed that bacteria and *Penicillium glaucum* had antagonistic effects in liquid cultures [3]. In 1921, Hartley conducted the first direct effort to apply the biological management of plant infections by inoculating soil with microorganisms thought to have hostile potential [4]. He introduced thirteen antagonistic fungi into forest nursery soils as an inoculum to prevent damping-off brought on by *Pythium debaryanum*. In addition to reporting the first use of a known antimycotic-producer antagonist in plant disease management, Weindling (1932 and 1934) detailed the ability of *Trichoderma lignorum* (*T. viride*) to suppress plant-pathogenic fungi via mycoparasitism. Later, Weindling (1941) noticed that *Trichoderma* species generated a toxin called gliotoxin to treat plant pathogenic fungi, including *Rhizoctonia* and *Sclerotinia*. This was the first report on using a known antimycotic-producing antagonist to control a plant disease. Research on the antagonism of plant pathogens was significantly boosted by A. Fleming's 1928 discovery of penicillin, its purity, and its use in the pharmaceutical business [5].

The use of fungal antagonists to treat various plant diseases may be expanded, thanks to recent developments in biotechnological techniques. Over the last several decades, many investigations and tests have been carried out to find novel fungal BCAs and evaluate their effectiveness in various environmental settings. Chemical pesticides and biocontrol agents were two opposite lines used to control pests, and pests differ in environmental consequences and sustainability. Chemical pesticides are often effective against target pests but can also negatively impact non-target organisms, such as beneficial insects, wildlife, and even humans. They may contaminate soil and water, disrupt ecosystem balance, and allow pest populations to develop resistance. This leads to pest resistance to the chemicals, resulting in more chemical use. Generally, higher doses or new chemicals contribute to further environmental damage [6].

Examples of fungi and yeast that Governor Basi will be monitoring as biocontrol are fungi and yeast species that are increasingly recognized as valuable partners in plant health and yield because they can reduce the reliance on harmful chemicals and synthetic pesticides, enhancing food performance and agricultural production. Plant diseases result in a 10-30% reduction in annual crop productivity, and despite the availability of modern farming practices, including effective water management strategies and disease-resistant crop varieties, those pathogens that do not respond are controlled using chemical means [7]. However, biocontrol agents, particularly fungal species with antagonist characteristics, provide an effective solution where these pathogens are naturally controlled. The effectiveness of these biocontrol systems is affected by UV light, temperature, pH, and abiotic and biotic stresses [8]. Hence, improving these fungal biocontrol agents' stress tolerance and functional capacity is essential for their commercial utilization and effectiveness.

Agricultural pest management is key to ensuring global food production systems by preventing the damaging impact of various diseases, insects, and weeds on crops. The solution for all these nightmares came from pest control, which has been practiced since ancient times when farmers used different methods to repel, damage, or destroy them, such as natural ingredients, crop rotation, etc. But then, in the 20th century, when modern agriculture established itself, chemical pesticides became the primary pest control method for their immediate impact and ease of use [9]. Chemical pest management revolutionized agriculture, enabling farmers to make higher yields with less crop loss. Broad-spectrum herbicides target a variety of pests, including weeds, fungi, and insects [10]. But even though they have their benefits, having a high dependence on artificial chemicals has caused significant issues, including pollution of the environment, pest resistance, and adverse effects on biodiversity. The problems prompted the development of integrated pest management (IPM) approaches that use a combination of chemical, mechanical, biological, and cultural approaches to reduce pesticide use and provide more sustainable pest management. Herein, biocontrol methods, particularly fungi, have attracted attention as effective and environmentally friendly means for controlling agricultural pests to minimize ecological destruction.

Objectives of the Review

This article investigates the potential of fungal biocontrol as a sustainable alternative to chemical pesticides in agriculture. A brief overview of fungal biocontrol agents, their modes of action, and their applications in controlling diseases and pests is provided. Lastly, it presents the advantages of fungal biocontrol compared to chemical pesticides, discusses the challenges in their adoption, and highlights recent advancements and prospects in the field. By examining these factors, this study seeks to emphasize the importance of fungal biocontrol in the future of sustainable agricultural practices and addressing the crises of global food security.

2. Overview of Fungal Biocontrol Agents

Fungal biocontrol is the application of mycological organisms, whether naturally occurring or engineered, as biological control agents for controlling weeds, diseases, and agricultural pests [11]. A group of fungi known as biocontrol agents

(BCAs) employ various bioprocesses, including competition, parasitism, enzyme production, and production of secondary metabolites to control the pathogenic organisms. Fungal biocontrol is a sustainable alternative to chemical pesticides, thereby decreasing environmental pollution and harm to target and non-target organisms, as well as the development of resistance by pest and disease organisms. In nature, fungi serve as organic pest population control (the concept behind fungal biocontrol) whenever fungi take hold, pests die [12]. They metabolize limited nutrients in their environments and compete with pathogens and pests. Being a natural pest management tool, fungal biocontrol agents can reduce pest load in agricultural systems in a specific and sustainable way to maintain balance within the ecosystem. Integrating fungal biocontrol into pest management strategies enables farmers to reduce their dependence on chemical inputs, support biodiversity, and make their agricultural operations more sustainable.

2.1. Key Fungal Species Used as Biocontrol Agents

Fungi are well-studied and well-utilized as biocontrol agents, as many species have shown efficacy against a broad range of pests and diseases. In addition to fighting harmful diseases, these fungi contribute to increased soil health and root development [13], and nutrient uptake, promoting plant growth. *Beauveria bassiana* is a biocontrol agent that can manage insect pests like weevils, aphids, and whiteflies. Surviving fungus reproduces and spreads through the host's body while the infected insect lives, then kills it [14].

A second plant of importance is *Metarhizium anisopliae*, which has proven to be effective in the treatment of many insect pests, both on soil and foliar levels, such as termites, locusts, and beetles. This is primarily because more tolerant species adapted to various environmental conditions are robust choices for some agricultural systems. Additionally, the species *Verticillium lecanii,* which is now placed in the genus *Penicillium spp.,* is frequently utilized to manage aphids and whiteflies, sap-sucking pests that harm crops extensively [15]. Many biological control agents, such as *Paecilomyces lilacinus,* have been shown to reduce plant-parasitic nematodes, though the fungus can parasitize nematode eggs in the soil and decrease their population [16]. These fungi represent a key part of sustainable agriculture due to the environmentally friendly means they provide to suppress pests and diseases and reduce chemical pesticide use.

Table 1 Key Fungal Species Used as Biocontrol Agents

Fungal Species	Target Pest/Disease	Mode of Action	Application	Effectiveness
Trichoderma spp.	Root rot, damping-off, and soilborne fungi.	Competition for space/nutrients, production of antibiotics.	Soil treatment, seed treatment, foliar sprays.	Highly effective against soilborne pathogens like *Fusarium* and *Rhizoctonia.*
Beauveria bassiana	Insect pests (e.g., whiteflies, aphids).	Parasitic infection of insects via spores, producing toxins.	Foliar spray and soil application.	Effective against a wide range of insects, including pests resistant to chemical control.
Metarhizium anisopliae	Insect pests (e.g., termites, grasshoppers).	Infection via cuticle penetration, host-specific toxins.	Soil application, aerial spraying.	Effective against many agricultural and forest pests.
Paecilomyces lilacinus	Root-knot nematodes, soilborne pests.	Parasitism of nematodes, degradation of nematode eggs.	Soil application, root treatment.	Effective against nematode larvae and eggs.
Verticillium lecanii	Whiteflies, aphids, thrips.	Insect pathogen, a parasitic infection leading to host death.	Foliar spray.	Effective on multiple insect species, with low impact on non-target organisms.
Clonostachys rosea	Soilborne fungal pathogens.	Antagonism to fungal pathogens, competition for nutrients	Soil application, seed treatment.	Strong against soilborne fungi like *Fusarium* and *Pythium.*
Coniothyrium minitans	*Sclerotinia* species (e.g., *Sclerotinia sclerotiorum*).	Antagonistic activity against sclerotia,	Soil treatment, direct application to infected areas.	Effective against sclerotinia diseases in various crops.

		degradation of fungal sclerotia.		

3. Mechanisms of Fungal Biocontrol

Fungal biocontrol agent (BCAs), which can be widely applied for plant protection and insect management, applies several mechanisms. Overall, these strategies offer a multi-pronged approach to pest control, from directly burdening pests to bolstering plant defenses. The suppressive activity of fungal BCAs against insect pests is mainly attributed to direct infection. Fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* create insect plagues by using specialized enzymes to crack open their exoskeletons and decompose the protective coverings of the outside of the insect. Once inside, the fungus spreads rapidly, infecting the pest's tissues before eventually consuming the host from the inside out. The infection disrupts vital biological processes, leading to the pest's death. Depending on the situation, the process can happen relatively quickly, with symptoms appearing a few days after infection.

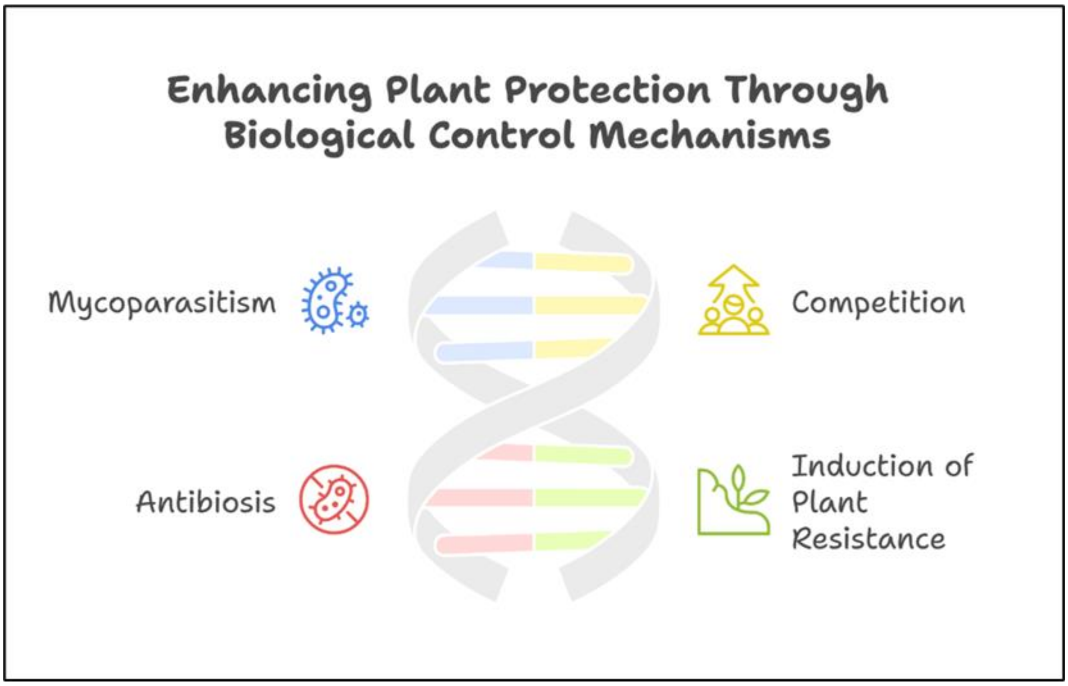

Figure 1 The mechanism of actions of biocontrol agents (BCAs) against plant pathogens

A variety of fungal biocontrol agents produce secondary metabolites, which are toxic substances that have the potential to directly affect pests. Fungal BCAs produce a wide range of secondary metabolites (mycotoxins, enzymes, and antibiotics), which play a prominent role in determining the efficacy of fungal BCAs [17]. *Metarhizium anisopliae*, for example, releases compounds that damage insects' nervous and digestive systems, leading to paralysis or death. These secondary metabolites also allow the fungus to outcompete or kill plant pathogens, making them practical for treating plant diseases and pests. Fungal BCAs can also stimulate the plant's defenses through the induction of systemic resistance. Certain fungi also trigger a plant's immune system, priming it to defend itself against potential threats from pests and diseases. Plants have a mechanism of defense known as induced systemic resistance (ISR), which enhances a plant's resistance to a broad array of pathogens, including infection and sparrows. For example, some fungi like *Trichoderma spp.* Stimulate the production of defense-related proteins in plants that strengthen their defenses and make them less susceptible to subsequent invasions from pests.

Fungal BCAs can also help to control diseases and pests through resource competition. These fungi colonize the rhizosphere or the surface of the plant and compete with harmful diseases and pests for resources and space. Competition reduces the damage that pests due to plants by preventing bugs from establishing and growing. Fungi like *Trichoderma spp.* can sometimes outcompete soilborne diseases by rapidly colonizing available space and depleting nutrients that the pathogens require to grow and spread.

Table 2 Advances in biocontrol techniques for managing pests in sustainable agriculture

Technique	Mechanism of Action	Target Pests	Advantages	Limitations
Insect Predators	Natural predation	Aphids, caterpillars, etc.	Environment-friendly, cost-effective	Slow acting
Parasitoids	Host parasitism	Bollworms, fruit flies, etc.	Highly targeted, Minimal non-target impact	Species-specific
Microbial Insecticides	Pathogenicity	Locusts, whiteflies, etc.	Biodegradable, low toxicity	Climate- sensitive
Botanical Insecticides	Chemical interference	Mealybugs, scale insects, etc.	Non-toxic, rapid degradation	Potential for resistance
Bio-fumigation	Fumigant action	Soil-borne pests	Sustainable, easy to apply	Limited scope
RNA Interference (RNAi)	Gene silencing	Colorado potato beetle, etc.	Highly targeted, no chemical residues	Expensive, regulatory hurdles
Pheromone Traps	Sexual confusion	Moths, beetles, etc.	Non-toxic, highly specific	Limited range
Sterile Insect Technique (SIT)	Sterilization	Tsetse flies, Mediterranean fruit flies	The long-term solution, area-wide control	High initial cost
Nematodes	Parasitism	Grubs, root-knot nematodes, etc.	Soil-friendly, natural	Specific conditions required
Augmentative Release	Population suppression	Whiteflies, thrips, etc.	Quick action, targeted	Needs frequent release

4. Advantages of Fungal Biocontrol Over Chemical Pesticides

Emerging based on their capacity as alternatives to conventional pesticides, Fungal Biocontrol Activities (BCAs) show promising potential in integrated agricultural pest and disease management [18]. They are a promising tool in sustainable farming practices as they have many significant advantages over synthetic chemical pesticides.

One of the most significant advantages of fungal biocontrol agents is their environmental safety. The fungi used in biocontrol are native and biodegradable, compared to chemical pesticides that can invade soil, water, and non-target organisms [19]. Once their biocontrol function is performed, they decompose non-toxically without any need for toxicity, significantly reducing the chances of environmental alteration. Such biodegradability prevents fungal BCAs from contaminating the environment or adding agrochemical residues to soil and water systems, thereby protecting the health of soil and water systems vital for sustainable agriculture.

Fungal biocontrol agents are often specific to the diseases and pests they affect. Since they are specific, they can mitigate some pest species while leaving pollinators, natural predators, and other non-target species unharmed. Some fungi, for example, only harm certain insects or plant diseases and do not affect other creatures. This contrasts with broad-spectrum chemical pesticides, which disturb the ecological balance and often harm various species, including beneficial ones such as earthworms and bees. The rise of chemical pesticide resistance is a growing problem in agriculture. Over time, pests and diseases can become resistant to pesticides, which causes them to be less effective and leads to farmers using more unsafe products or higher amounts. However, fungus biocontrol agents generally act via more complex mechanisms, like parasitism, resource competition, or the production of toxic compounds, which viruses and pests are less likely to evolve to resist quickly. This all-natural, holistic mode of action provides a long-lasting and sustainable solution for managing diseases and pests by reducing the risk of resistance emergence [20].

Fungus biocontrol agents are good for integrated pest management (IPM) strategies that stress hiring a range of techniques for controlling moths in an environmentally suitable way [21]. IPM reduces the reliance on chemical pesticides by integrating chemical, mechanical, cultural, and biological control methods. Fungal BCAs may be applied along with crop rotation, resistant crop types, and physical barriers to optimize pest control with minimal environmental effects. Quoting them, the article said, Fungal biocontrol is a fundamental part of IPM measures due to their integration, allowing even more realized and accurate pest control strategies. Overall, fungal biocontrol agents present several benefits as a much more effective, environmentally friendly, and viable alternative to chemical pesticides. They are likely to be widely used in agriculture in the future because of their ability to target specific pests, their environmental safety, and their compatibility with integrated pest management, especially during a time when concerns over the effects of chemical pesticide use have become an issue.

5. Agricultural Applications of Fungal Biocontrol

Entomopathogenic fungi are considered the field's most efficient and environmentally friendly insect pest management tools [22]. Various entomopathogenic fungi have been used for the biocontrol of insect pests that are a significant crop threat. Many insect species, such as aphids, whiteflies, beetles, and caterpillars, are primarily infected and killed by several entomopathogenic fungal species, such as *Beauveria bassiana*, *Metarhizium anisopliae*, and *Isaria fumosorosea* [23]. These fungi penetrate the insect's exoskeleton or produce toxic substances that disrupt the insect's physiological processes. Depending on the fungus species and the surrounding circumstances, the infected pest dies within days to a week.

The ideal edge for fungal biocontrol in pest management is targeting pests that result in little or no risk to non-target animals, including predators and beneficial insects, pollinators, and natural pest-killing agents. Since they biodegrade independently and do not contribute to pesticide residues, they also do not affect environmental systems much. Fungal BCAs are an eco-friendly and effective alternative to chemical pesticides, which enable their use in Integrated Pest Management (IPM) programs and help reduce the problem of pest resistance, which is the main challenge with using chemical pesticides [24].

5.1. Plant-Pathogen Management for Fungal Diseases

Fungal BCAs have also effectively controlled various plant diseases, including bacterial, viral, and fungal pathogens. Many fungi, such as *Trichoderma spp. and Clonostachys rosea*, are known to act as biocontrol agents for different plant diseases by competing with the pathogens for nutrients and space, generating antibiotics, or fighting the pathogen directly through parasitism [25].

For example, *Trichoderma spp.* is well known for suppressing soilborne pathogens responsible for several root rot and damping-off diseases of crops (*Fusarium*, *Rhizoctonia*, and *Pythium*) [26]. *Beauveria bassiana* and *Metarhizium anisopliae* have effectively controlled diseases caused by bacteria such as Xanthomonas and Pseudomonas and diseases caused by fungi like *Botrytis* and *Alternaria.* Using fungal BCAs to control plant diseases reduces the need for chemicals (chemical fungicides), which can harm the environment, non-target species, and human health. When chemical inputs are limited in organic farming, fungus biocontrol agents are very beneficial. Diseases can be efficiently controlled, and their use can aid healthy soil ecosystems [27].

Table 3 Management of Plant Pathogens Using Biocontrol Agents

Pathogen Type	Pathogen Examples	Fungal Biocontrol Agents	Mode of Action	Application Method
Fungal Diseases	*Fusarium*, *Rhizoctonia*, *Pythium*, *Sclerotinia*	*Trichoderma spp.*, *Clonostachys rosea*	Antagonism, mycoparasitism, and production of lytic enzymes.	Soil application, seed treatment, foliar spray.
Bacterial Diseases	*Xanthomonas*, *Pseudomonas*, *Erwinia*	*Beauveria bassiana* and *Metarhizium anisopliae*	Antibiosis, induced systemic resistance, and competition for nutrients.	Soil treatment, seed treatment, foliar spray.
Viral Diseases	*Tobacco mosaic virus*, *Cucumber mosaic virus*	*Beauveria bassiana*, *Trichoderma spp.*	Induced resistance and inhibition of virus replication in the plant.	Foliar spray, seed treatment.

5.2. Weed Management Using Fungal Pathogens

Because they are a biological alternative to herbicides that can cause adverse ecological and environmental repercussions, fungal BCAs can also be very valuable in controlling weeds. Some fungal species, such as *Fusarium spp., Colletotrichum gloeosporioides*, and *C. truncatum*, among others, have been researched as pathogens of certain weed species to manage troublesome weeds, including Ragweed, Canada thistle, dandelions, and cocklebur [28]. When fungi are used to control weeds, the fungi typically infect the weed plants and cause diseases that restrict the growth and spread of the plants by causing weakness or death. This approach, known as "bioherbicide" application, explicitly targets the weed species without damaging other plants or the overall ecosystem, making it a more environmentally friendly option than conventional chemical herbicides. They can be applied via seed treatment, foliar spray, and soil inoculation, as with BCAs based on fungi. However, they will be much more effective for controlling weeds and reducing weed pressure if combined with other strategies (e.g., crop rotation or mulching) [29].

Fungal biocontrol agents (BCAs) are extensively used for crop protection. They are a natural and sustainable solution for managing plant diseases and controlling weeds and insect pests. Fungal BCAs promote biodiversity, a healthier environment, and the overall sustainability of agricultural systems due to their reduced reliance on chemical pesticides and herbicides [30]. Their use in pest control systems, particularly organic agriculture and integrated pest management (IPM) programs, holds tremendous promise for the future of sustainable agriculture.

6. Challenges in the Adoption of Fungal Biocontrol

Fungal biocontrol agents (BCAs) are promising sustainable pest management tools, but practical obstacles must be addressed before they can be fully integrated into agroecosystems [31]. The effectiveness of fungal BCAs can vary widely depending on the environment. Temperature, humidity, soil type, and exposure to ultraviolet radiation are just a few variables that could determine how well the fungi survive and remain active, so estimating how well they will perform under field conditions is challenging. Some fungi, for instance, may flourish in tightly controlled laboratory conditions but struggle to grow in harsh outdoor environments. The efficacy of such alternatives in pest management may be reduced due to their environmental dependence, which would be an obstacle to their reliability and consistency as a pest control solution, making it hard for farmers to trust them as a complete measure.

Since fungal BCAs originate from biological sources, their shelf life is always limited. They need to remain viable and effective over time (e.g., regulated humidity or refrigeration) if they are to be beneficial. Fungal spores may lose their ability to infect and control pests if improperly preserved. That makes it hard to distribute the goods, especially in areas with unreliable storage facilities. They are also more complicated and expensive than chemical pesticides, which are more stable and easier to store since they don't need refrigeration and careful handling.

Fungal BCAs can be expensive to produce, especially commercially, compared to synthetic chemical pesticides [32]. Fungal agents require specific growth media, conditions, and time for their development, increasing costs. It remains challenging for output to be scaled up to meet global needs in agriculture while maintaining affordability and quality. Thus, the cost of fungal BCAs is very high, which many farmers cannot afford, especially small-scale farmers or farmers in developing countries. Two critical innovations are needed to ensure widespread use: reducing production costs and improving efficiency in the large-scale production of fungal agents.

Fungus biocontrol agents must undergo rigorous regulatory assessments before they are approved for use in different countries. Although these rules ensure the environmental impact, safety, and effectiveness of biocontrol products, the review process is also expensive and protracted. The regulatory environment for biocontrol agents is less established than for chemical pesticides, which may delay product approval and market launch. Moreover, farmers might be less likely to use fungal BCAs because they lack experience with their application, think they are less effective than chemical options, or question their reliability [33]. Getting past these market and regulatory barriers will require more education, awareness, and a demonstration of the long-term benefits of fungal biocontrol.

These challenges include regulatory issues, a short shelf life, the cost of manufacture, and unpredictable environmental factors, which are all barriers to widely applying fungal biocontrol agents in agriculture. To harness their potential as environmentally friendly and effective alternatives, fungal BCAs are still confronted with challenges that must be overcome through technological advancements, research, and legislation. If we can overcome these obstacles, we will have more applications of fungal biocontrol incorporated into pest management plans and contribute to the transition towards more environmentally friendly methods of agriculture.

7. Innovations and Future Prospects

With advances continually improving the efficacy, scalability, and versatility of fungal biocontrol agents (BCAs), they are poised to have a successful future. Several essential development areas make fungal BCAs much more efficient and broad-spectrum regarding agricultural applications [34]. One of the most significant advances in fungal biocontrol is the development of various formulation technologies, including encapsulation technologies and nano-formulations. These methods promise to improve the stability, shelf life, and efficacy of fungal BCAs by protecting the fungus spores from environmental stresses like heat, UV radiation, and desiccation. For example, fungi-related agents can be applied under controlled conditions in nano-formulations that enhance their shelf life and aid their application against a specific pathogen or disease. Encapsulation increases the efficacy and reliability of the biocontrol process by protecting the fungal spores from detrimental environments and improving their potential to invade the host pest or disease.

It is exciting to consider the possibility of enhancing the efficacy of fungal BCAs via genetic engineering or strain enhancement. By changing the organism's genetic makeup, researchers can create fungus strains with higher virulence, greater tolerance to environmental stress, and the ability to target specific pests. Scientists can genetically modify fungi for more powerful toxins, efficient enzymes, or enhanced survival strategies in hostile conditions. By enhancing strains, fungi can become more metabolically capable across a broader range of environmental conditions, thus reducing the dependence on the environment that is presently limiting their consistency in field performance.

A promising trend in fungal biocontrol is investigating synergistic effects when combined with other biocontrol agents or bio-stimulants. Fungal BCAs can be more effective in controlling diseases and pests when combined with other beneficial microbes, which may be other bacteria or fungi. These combinations may act through complementary processes, such as improved suppression of pathogens, increased competition for nutrients, or enhanced resistance of plants. Combining fungal BCA with bio-stimulants or compounds that can help in plant development and stress tolerance can further improve pest resistance and enhance plant health, making pest control holistic. As climate change induces more extreme weather patterns and shifts in pest dynamics, the need to develop climate-resilient biocontrol methods is increasingly pressing [35]. To remain effective amidst changing circumstances, fungal BCAs must show better resilience in response to temperature fluctuations, drought, and UV (ultraviolet) radiation. By selecting or developing fungal strains capable of thriving across a wide range of climatic conditions, researchers may ensure the continued viability of fungal BCAs in light of global climate concerns. Moreover, condition-resilient carbon-based formulations , such as those that protect fungal spores from freezing or desiccation, could enhance their field efficacy and expand their application to several geographical zones and cropping seasons.

However, the future for fungal biocontrol is bright, with formulation technologies, genetic engineering, synergistic techniques, and climatic resilience set to overcome current limitations and expand its scope of use in agriculture. By improving the scalability, efficiency, and environmental adaptability of fungal BCAs, these advances will ensure their viability in sustainable pest control for decades. Applications of fungal biocontrol will retain a significant role in integrated pest management systems, meanwhile, as these developments unfold, ensuring a more resilient and healthy agricultural ecology.

8. Use Cases & Success Stories

Chemical pesticides, on the other hand, work quickly but are short-lived, while fungal BCAs like *Beauveria bassiana* offer focused pest management that is long-lasting, mainly when employed in Integrated Pest Management (IPM) approaches. In Mexico, for example, *B. bassiana* significantly suppressed whitefly populations and reduced viral disease transmission, effects not possible with conventional pesticides. The species-specificity of fungal BCAs further saves beneficial insects and helps maintain the ecological balance, and their biodegradability aids in preventing environmental pollution and the development of pesticide resistance. Tomato cultivation in California highlighted the contributions of *B. bassiana* to soil biodiversity conservation by replacing chemical nematicides, which pollute soil and water, with entomopathogenic fungi.

Although first costs for fungal BCAs are higher than for certain chemical pesticides, the more excellent long-term economic outlook, limited need for applications, plus no toxic residues outweigh initial outlays. This fits with daily organic farm demands for zero residues and sustainable methods. In addition, unlike synthetic pesticides, fungal BCAs possess little or no toxicity to non-target organisms, including pollinators and natural enemies, increasing agroecosystems' resilience. They represent a move toward environmentally friendly farming by reducing threats to human health and ecosystems [36]. Fungal BCAs are critical in developing more resilient, low-impact pest management systems as agriculture moves toward sustainable production practices globally. The transition alleviates ecological and health worries and helps preserve farming's economic viability in a climate-aware future.

8.1. Fungal Biocontrol Programs That Worked

a) ***Beauveria bassiana* is used for controlling root-knot nematodes in tomato (California, United States)** [37]. These nematodes are known for causing damage to plant roots, resulting in stunted growth and decreased yields. The fungus *B. bassiana* was applied to the soil, where it managed to colonize the nematodes, inhibiting their development and resulting in a significant decrease in their numbers. In garlic, the *B. bassiana* recombinant improved tomato growth and reduced reliance on chemical nematicides while decreasing soil contamination, illustrating the potential of fungal BCAs for sustainable soilborne pest management.

b) **Whiteflies Control in Cotton and Vegetables (Mexico):** In Mexico, *Beauveria bassiana* and *Metarhizium anisopliae* are effectively used to control whiteflies (*Bemisia tabaci*) in cotton and vegetable crops [38]. These fungi infect whiteflies through spores that penetrate their exoskeleton. As a result, farmers witnessed a dramatic decline in whitefly populations without the hazards posed by chemical insecticides to the environment. It has also been demonstrated to be effective at controlling plant viruses transmitted by whiteflies, including tomato-yellow-leaf curl virus, through this biocontrol method.

c) **Control of Wheat *Fusarium* Head Blight (FHB) in Europe:** In 2016, there were successes in fungal BCA (biocontrol agents) using *Trichoderma spp.* for the control of wheat fusarium head blight (FHB), which is caused by the *Fusarium* fungus and affects grain quality and yields in Europe [39]. For example, *Trichoderma harzianum* is generally used in wheat fields in trays to suppress the growth of Fusarium and prevent mycotoxin production for both yield and food safety. Bio-fungicides have also attracted significant attention in other row crops. However, it's restricted because it may need a sequenced treatment. Field trials in wheat show that Trichoderma reduced disease incidence, improved quality, and increased yield, showing its potential for inclusion in integrated disease management strategies for wheat growers.

9. Conclusion

Fungus-based biocontrol agents (BCAs) offer an environmentally responsible alternative to synthetic pesticides in modern agriculture. These fantastic fungi manage diseases and pests by parasitism, competition, and the production of enzymes and poisons. By harnessing the power of these natural enemies, farmers can significantly reduce their reliance on chemical pesticides, helping to prevent environmental pollution and preserving beneficial insects. (Unlike broad-spectrum chemical pesticides, which can disrupt entire ecosystems, fungal BCAs are often quite specific to the pests or diseases they target, minimizing collateral damage.) Furthermore, these fungi's various modes of action prevent pests from developing resistance, a genuine concern in the face of using so many chemical pesticides.

Fungus biocontrol agents should be used with sustainable farming methods such as Integrated Pest Management (IPM). IPM encourages a multifaceted approach to pest control using physical, cultural, and biological processes with judicious spraying of chemical pesticides as appropriate. By implementing fungal BCAs, farmers can achieve this by reducing soil disruption and diversity in their fields and establishing a more sustainable, balanced ecosystem. Ongoing research and development are addressing the limitations, but challenges remain, including optimizing fungal function in various environmental conditions and ensuring consistent product quality and availability. Advances in formulation technologies, genetic engineering, and synergy strategies have enhanced the efficacy and reliability of fungal BCAs.

Fungal biocontrol used on plants has many benefits, as demonstrated by successful case histories worldwide. For example, *Beauveria bassiana* has been used in Mexico to reduce whiteflies, which spread plant viruses. Fungal BCAs are also effective against soilborne infections, increasing the yield of crops and reducing the use of toxic chemical fungicides. For fungal biocontrol to fully deliver on its promise in the future, it is necessary to continue to invest in their research and development and increase farmer awareness and adoption. By addressing the barriers that currently limit the use of these biological agents and expanding the range of contexts in which they might be applied, we can help move towards a more ecologically conscious and sustainable agricultural future that balances food security and healthy ecosystems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Rai PK. Degradation of Agriculture Systems by Invasive Alien Plants and Agroecological Approaches for Sustainable Restoration. In: Prasad MNV, Kumar C, editors. Agroecological Approaches for Sustainable Soil Management. 1st ed., Wiley; 2023, p. 23–47. https://doi.org/10.1002/9781119911999.ch2.

[2] He D-C, He M-H, Amalin DM, Liu W, Alvindia DG, Zhan J. Biological Control of Plant Diseases: An Evolutionary and Eco-Economic Consideration. Pathogens 2021;10:1311. https://doi.org/10.3390/pathogens10101311.

[3] Mazaro SM, Meyer MC, Dias-Arieira CR, Dos Reis EF, Bettiol W. Antagonistic Fungi Against Plant Pathogens for Sustainable Agriculture. In: Rajpal VR, Singh I, Navi SS, editors. Fungal diversity, ecology and control management, Singapore: Springer Nature Singapore; 2022, p. 607–37. https://doi.org/10.1007/978-981-16-8877-5_29.

[4] Hilário S, Gonçalves MFM. Endophytic Diaporthe as Promising Leads for the Development of Biopesticides and Biofertilizers for a Sustainable Agriculture. Microorganisms 2022;10:2453. https://doi.org/10.3390/microorganisms10122453.

[5] Kumari A, Tapwal A. Trichoderma: a Beneficial Antimycotic Agent and Insights on Its Utilization in Nanoparticle Synthesis. BioNanoSci 2023;13:1399–417. https://doi.org/10.1007/s12668-023-01170-6.

[6] Rezende-Teixeira P, Dusi RG, Jimenez PC, Espindola LS, Costa-Lotufo LV. What can we learn from commercial insecticides? Efficacy, toxicity, environmental impacts, and future developments. Environmental Pollution 2022;300:118983. https://doi.org/10.1016/j.envpol.2022.118983.

[7] Richard B, Qi A, Fitt BDL. Control of crop diseases through Integrated Crop Management to deliver climate-smart farming systems for low- and high-input crop production. Plant Pathology 2022;71:187–206. https://doi.org/10.1111/ppa.13493.

[8] Saberi Riseh R, Hassanisaadi M, Vatankhah M, Soroush F, Varma RS. Nano/microencapsulation of plant biocontrol agents by chitosan, alginate, and other important biopolymers as a novel strategy for alleviating plant biotic stresses. International Journal of Biological Macromolecules 2022;222:1589–604. https://doi.org/10.1016/j.ijbiomac.2022.09.278.

[9] Legros M, Marshall JM, Macfadyen S, Hayes KR, Sheppard A, Barrett LG. Gene drive strategies of pest control in agricultural systems: Challenges and opportunities. Evolutionary Applications 2021;14:2162–78. https://doi.org/10.1111/eva.13285.

[10] Md Shahriar Kabir, Md Mahedi, A K M Kanak Pervez, Md Jahangir Alam, Shabrin Jahan Shaili. Bibliometric analysis of "precision agriculture" in the Scopus database. World J Adv Res Rev 2025;25:1087–98. https://doi.org/10.30574/wjarr.2025.25.3.0733.

[11] Collinge DB, Jensen DF, Rabiey M, Sarrocco S, Shaw MW, Shaw RH. Biological control of plant diseases – What has been achieved and what is the direction? Plant Pathology 2022;71:1024–47. https://doi.org/10.1111/ppa.13555.

[12] Costa CA, Guiné RPF, Costa DVTA, Correia HE, Nave A. Pest control in organic farming. Advances in Resting-state Functional MRI, Elsevier; 2023, p. 111–79. https://doi.org/10.1016/B978-0-323-99145-2.00003-3.

[13] Asghar W, Craven KD, Kataoka R, Mahmood A, Asghar N, Raza T, et al. The application of Trichoderma spp., an old but new useful fungus, in sustainable soil health intensification: A comprehensive strategy for addressing challenges. Plant Stress 2024;12:100455. https://doi.org/10.1016/j.stress.2024.100455.

[14] Islam W, Adnan M, Shabbir A, Naveed H, Abubakar YS, Qasim M, et al. Insect-fungal-interactions: A detailed review on entomopathogenic fungi pathogenicity to combat insect pests. Microbial Pathogenesis 2021;159:105122. https://doi.org/10.1016/j.micpath.2021.105122.

[15] Sam-on MFS, Mustafa S, Yusof MT, Mohd Hashim A, Ku Aizuddin KNA. Exploring the Global Trends of Bacillus, Trichoderma and Entomopathogenic Fungi for Pathogen and Pest Control in Chili Cultivation. Saudi Journal of Biological Sciences 2024;31:104046. https://doi.org/10.1016/j.sjbs.2024.104046.

[16] Kumar KK, Arthurs S. Recent advances in the biological control of citrus nematodes: A review. Biological Control 2021;157:104593. https://doi.org/10.1016/j.biocontrol.2021.104593.

[17] Palmieri D, Ianiri G, Del Grosso C, Barone G, De Curtis F, Castoria R, et al. Advances and Perspectives in the Use of Biocontrol Agents against Fungal Plant Diseases. Horticulturae 2022;8:577. https://doi.org/10.3390/horticulturae8070577.

[18] Palmieri D, Ianiri G, Del Grosso C, Barone G, De Curtis F, Castoria R, et al. Advances and Perspectives in the Use of Biocontrol Agents against Fungal Plant Diseases. Horticulturae 2022;8:577. https://doi.org/10.3390/horticulturae8070577.

[19] Bamisile BS, Siddiqui JA, Akutse KS, Ramos Aguila LC, Xu Y. General Limitations to Endophytic Entomopathogenic Fungi Use as Plant Growth Promoters, Pests and Pathogens Biocontrol Agents. Plants 2021;10:2119. https://doi.org/10.3390/plants10102119.

[20] Singh A, Shraogi N, Verma R, Saji J, Kumar Kar A, Tehlan S, et al. Challenges in current pest management practices: Navigating problems and a way forward by integrating controlled release system approach. Chemical Engineering Journal 2024;498:154989. https://doi.org/10.1016/j.cej.2024.154989.

[21] Angon PB, Mondal S, Jahan I, Datto M, Antu UB, Ayshi FJ, et al. Integrated Pest Management (IPM) in Agriculture and Its Role in Maintaining Ecological Balance and Biodiversity. Advances in Agriculture 2023;2023:1–19. https://doi.org/10.1155/2023/5546373.

[22] Quesada-Moraga E, González-Mas N, Yousef-Yousef M, Garrido-Jurado I, Fernández-Bravo M. Key role of environmental competence in successful use of entomopathogenic fungi in microbial pest control. J Pest Sci 2024;97:1–15. https://doi.org/10.1007/s10340-023-01622-8.

[23] Ebani VV, Mancianti F. Entomopathogenic Fungi and Bacteria in a Veterinary Perspective. Biology 2021;10:479. https://doi.org/10.3390/biology10060479.

[24] Bueno AF, Panizzi AR, Hunt TE, Dourado PM, Pitta RM, Gonçalves J. Challenges for Adoption of Integrated Pest Management (IPM): the Soybean Example. Neotrop Entomol 2021;50:5–20. https://doi.org/10.1007/s13744-020-00792-9.

[25] Lahlali R, Ezrari S, Radouane N, Kenfaoui J, Esmaeel Q, El Hamss H, et al. Biological Control of Plant Pathogens: A Global Perspective. Microorganisms 2022;10:596. https://doi.org/10.3390/microorganisms10030596.

[26] Akber MA, Fang X. Research Progress on Diseases Caused by the Soil-Borne Fungal Pathogen Rhizoctonia solani in Alfalfa. Agronomy 2024;14:1483. https://doi.org/10.3390/agronomy14071483.

[27] Mahedi M, Shaili SJ, Nurnobi M, Shihab A. ADOPTION OF ORGANIC FARMING PRACTICES: A COMPREHENSIVE REVIEW OF TRENDS, DETERMINANTS, AND CHALLENGES 2025;8:26–45.

[28] Evidente A. Specialized Metabolites Produced by Phytotopatogen Fungi to Control Weeds and Parasite Plants. Microorganisms 2023;11:843. https://doi.org/10.3390/microorganisms11040843.

[29] Sharma G, Shrestha S, Kunwar S, Tseng T-M. Crop Diversification for Improved Weed Management: A Review. Agriculture 2021;11:461. https://doi.org/10.3390/agriculture11050461.

[30] Pérez-Pizá MC, Sautua FJ, Szparaga A, Bohata A, Kocira S, Carmona MA. New Tools for the Management of Fungal Pathogens in Extensive Cropping Systems for Friendly Environments. Critical Reviews in Plant Sciences 2024;43:63–93. https://doi.org/10.1080/07352689.2023.2268921.

[31] Ayaz M, Li C-H, Ali Q, Zhao W, Chi Y-K, 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;28:6735. https://doi.org/10.3390/molecules28186735.

[32] Tyagi A, Lama Tamang T, Kashtoh H, Mir RA, Mir ZA, Manzoor S, et al. A Review on Biocontrol Agents as Sustainable Approach for Crop Disease Management: Applications, Production, and Future Perspectives. Horticulturae 2024;10:805. https://doi.org/10.3390/horticulturae10080805.

[33] Fenta L, Mekonnen H. Microbial Biofungicides as a Substitute for Chemical Fungicides in the Control of Phytopathogens: Current Perspectives and Research Directions. Scientifica 2024;2024:1–12. https://doi.org/10.1155/2024/5322696.

[34] Pérez-Pizá MC, Sautua FJ, Szparaga A, Bohata A, Kocira S, Carmona MA. New Tools for the Management of Fungal Pathogens in Extensive Cropping Systems for Friendly Environments. Critical Reviews in Plant Sciences 2024;43:63–93. https://doi.org/10.1080/07352689.2023.2268921.

[35] John A, Riat AK, Ahmad Bhat K, Ganie SA, Endarto O, Nugroho C, et al. Adapting to climate extremes: Implications for insect populations and sustainable solutions. Journal for Nature Conservation 2024;79:126602. https://doi.org/10.1016/j.jnc.2024.126602.

[36] Sheikh MdM, Riar TS, Pervez AKMK. Integrated Farming Systems: A Review of Farmers Friendly Approaches. AJAEES 2021:88–99. https://doi.org/10.9734/ajaees/2021/v39i430564.

[37] Azevedo LH, Moreira MFP, Pereira GG, Borges V, De Moraes GJ, Inomoto MM, et al. Combined releases of soil predatory mites and provisioning of free-living nematodes for the biological control of root-knot nematodes on 'Micro Tom tomato.' Biological Control 2020;146:104280. https://doi.org/10.1016/j.biocontrol.2020.104280.

[38] Sani I, Ismail SI, Abdullah S, Jalinas J, Jamian S, Saad N. A Review of the Biology and Control of Whitefly, Bemisia tabaci (Hemiptera: Aleyrodidae), with Special Reference to Biological Control Using Entomopathogenic Fungi. Insects 2020;11:619. https://doi.org/10.3390/insects11090619.

[39] Powell AJ, Vujanovic V. Evolution of Fusarium Head Blight Management in Wheat: Scientific Perspectives on Biological Control Agents and Crop Genotypes Protocooperation. Applied Sciences 2021;11:8960. https://doi.org/10.3390/app11198960.