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Trichoderma: Multitalented Biocontrol Agent

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ABSTRACT

Trichoderma is a genus of fungi that has been widely studied for its ability to act as a biocontrol agent against plant pathogens. This review summarizes recent research on the mechanisms of action of Trichoderma as a biocontrol agent and its potential for use in sustainable agriculture. Trichoderma can control plant pathogens through various mechanisms, including competition for nutrients and space, mycoparasitism, and induction of systemic resistance in the host plant. The effectiveness of Trichoderma as a biocontrol agent depends on various factors, such as the species and strain used, the timing and method of application, and the environmental conditions. In addition to its biocontrol properties, Trichoderma can also promote plant growth and health by improving nutrient uptake and stress tolerance. However, the implementation of Trichoderma as a biocontrol agent in agriculture faces some challenges, such as the lack of standardized methods for production and application, and the need for further research to understand its interactions with other soil microorganisms. Overall, Trichoderma shows great potential as a sustainable alternative to chemical pesticides in agriculture, and further research and development are needed to maximize its efficacy and integration into farming practices.

Key words: Plant Protection, Mycoparasitism, Biocontrol Agent.

INTRODUCTION

Plant pathogens such as viruses, bacteria, fungi, and nematodes can infect crops in the field or during post-harvest storage, causing significant losses in agricultural production and posing a threat to global food security (Zafar et al., 2020). The use of living organisms, known as antagonists, is a promising approach to manage plant diseases through biological control. Biocontrol has several advantages over chemical pesticides, including the prevention of pathogen resistance, avoidance of environmental contamination, prevention of secondary pest proliferation, compatibility with organic production, and meeting the requirements of profitable markets with regard to chemical residue limits on fruits and vegetables (Poveda, 2021; Ren et al., 2019). Trichoderma, among 25 fungal antagonists, has been identified as the genus with the highest potential for biocontrol of plant fungal diseases. Trichoderma has gained increasing importance due to its fungicidal and fertilizing properties (Ferreira & Musumeci, 2021). The fungi provide various beneficial effects on plants in exchange for sucrose provided by the plants, including stimulating rapid plant growth, improving nutrient uptake, modifying the rhizosphere, and enhancing tolerance to biotic and abiotic stressors (Manzar et al., 2022). Trichoderma spp. employs various tactics to combat plant diseases, such as antibiosis, mycoparasitism, competing for nutrients and space, enhancing plant growth, and triggering plant defense mechanisms.

Mycoparasitism

Trichoderma is a widely distributed fungus in soil, where it plays a crucial role in the suppression of plant diseases caused by pathogenic fungi. One of the main

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mechanisms by which Trichoderma achieves this is through its mycoparasitic activity. Mycoparasitism is the process by which one fungus feeds on and parasitizes another fungus. Trichoderma is known to be a successful mycoparasite, as it can interact with a wide range of other fungi in the soil (Shahriar et al., 2022).

When Trichoderma comes into contact with a pathogenic fungus, it can use a variety of mechanisms to attack and inhibit the growth of the target fungus. One such mechanism is the production of cell-wall degrading enzymes, such as chitinases, glucanases, and proteases. These enzymes can break down the cell walls of the target fungus, leading to its death. Trichoderma can also use its hyphae (filamentous structures) to penetrate the cell walls of the target fungus and consume it, a process known as mycoparasitism (Bhandari et al., 2021). Mycoparasitism is a complex process involving the recognition, attachment, penetration, and digestion of the host. Trichoderma utilizes various strategies to parasitize its host, including hyphal coiling, antibiosis, and secretion of hydrolytic enzymes. Hyphal coiling is a common mycoparasitic mechanism used by Trichoderma, which involves the wrapping of its hyphae around the host hyphae, leading to the formation of a knot-like structure. This physical interaction disrupts the host's hyphal growth and nutrient uptake, leading to its eventual death (Takudzwa et al., 2022). Antibiosis is another mechanism used by Trichoderma, where it secretes antibiotics that inhibit the growth of other fungi. Trichoderma produces a wide range of antibiotics, including gliotoxin, gliovirin, and trichokonins, which have been shown to be effective against many plant pathogens. Finally, Trichoderma also secretes hydrolytic enzymes, including chitinases, cellulases, and proteases, which can degrade the host's cell wall and release nutrients for Trichoderma's growth (Brunner et al., 2005).

Several studies have reported the successful use of Trichoderma to control of plant pathogens. For example, *Trichoderma harzianum* has been shown to be effective in controlling various fungal pathogens, including Fusarium oxysporum, Phytophthora infestans, and Rhizoctonia solani, in different crops such as tomato, potato, and beans (Mukherjee, Horwitz, Herrera-Estrella, Schmoll, & Kenerley, 2013). Similarly, *Trichoderma asperellum* has been shown to be effective in controlling Botrytis cinerea, *Sclerotinia sclerotiorum*, and *Phytophthora capsici* in various crops, including tomato, pepper, and cucumber (Contreras-Cornejo, Macías-Rodríguez, Del-Val, & Larsen, 2016).

Competition

Trichoderma is a widespread and diverse genus of fungi that occupies various ecological niches, including soil, plant roots, and decaying plant material. Trichoderma species also interact with other fungi in their ecological niche. Competition for nutrients and space is a common mechanism of interaction among soil microorganisms. Trichoderma has been shown to compete with other fungi for these resources in the soil. For example, *Trichoderma harzianum* can outcompete *Rhizoctonia solani*, a soil-borne pathogen of many crops, for nutrients and space (Kredics et al., 2003). Similarly, Trichoderma virens can inhibit the growth of *Fusarium oxysporum*, a pathogen that causes wilt disease in many crops (Sharon, Chet, & Spiegel, 2011). These studies suggest that Trichoderma can act as a generalist competitor against other fungi in the soil ecosystem.

Trichoderma also exhibits specific competitive interactions with other fungi in their ecological niche. For example, *Trichoderma aggressivum* is a specialized mycoparasite that targets Armillaria species, which are soil-borne pathogens that cause root rot disease in many tree species (Druzhinina & Kubicek, 2017). *Trichoderma aggressivum* parasitizes Armillaria by coiling around its hyphae and releasing hydrolytic enzymes that degrade its cell wall. This interaction is an example of niche specialization, where Trichoderma has evolved to target a specific niche occupied by Armillaria in the soil ecosystem (An et al., 2022).

Furthermore, recent studies have shown that Trichoderma can also engage in cooperative interactions with other soil microorganisms. For example, Trichoderma can form mutualistic associations with plant roots, where it provides nutrients and protection against soil-borne pathogens in exchange for carbon compounds from the plant. Trichoderma can also cooperate with mycorrhizal fungi, where it can enhance the colonization and nutrient uptake of the plant root system (Thakur et al., 2019).

Trichoderma is a versatile fungus that exhibits various competitive and cooperative interactions in the soil ecosystem. Trichoderma can act as a generalist competitor against other fungi for resources in the soil, and it can also specialize to target specific niches occupied by other fungi. Furthermore, Trichoderma can engage in mutualistic interactions with plant roots and mycorrhizal fungi, highlighting its role in promoting plant growth and health in the soil ecosystem (Thakur et al., 2019).

Antibiosis

One of the primary mechanisms by which Trichoderma can control plant pathogens is through the production of antimicrobial compounds, a process known as antibiosis. Antibiosis is a phenomenon where one organism produces substances that are toxic or inhibitory to another organism's growth or development. Trichoderma strains produce a wide range of low-molecular-weight compounds, both volatile and nonvolatile, that hinder the growth of harmful plant pathogenic fungi. These compounds include antibiotics, mycotoxins, and phytotoxins that help in antagonism via antibiosis, competition, or hyperparasitism (Zhang et al., 2015).

Trichoderma also produces a range of enzymes such as glucanases, chitobioses, and chitinase, which can degrade the cell walls of pathogenic fungi, and antibiotics like viridin, gliotoxin, and peptaibols, which can disrupt various metabolic processes in pathogenic fungi. The debate around the effectiveness of Trichoderma as an antibiosis agent centers on the specificity and effectiveness of the compounds produced by Trichoderma. Some researchers have argued that Trichoderma's effectiveness against plant pathogens is highly dependent on the genetic factors and environmental conditions of both the Trichoderma strain and the pathogenic fungus it is targeting (Yang, 2017).

For example, Filizola et al. investigated the degree of antagonism and antibiosis of trichoderma fungi against Fusarium strains and found that the specificity of the interaction between the antagonist and potential phytopathogen is determined by genetic factors and the environment. Therefore, the effectiveness of trichoderma as an antibiosis agent may be limited to specific plant pathogenic fungi, and the production of effective antimicrobial compounds by trichoderma may depend on specific environmental conditions (Filizola et al., 2019).

Another aspect of the debate around trichoderma's effectiveness as an antibiosis agent is the potential impact of Trichoderma on non-target organisms. Trichoderma is a soil-borne fungus, and its application as a biocontrol agent can result in the introduction of non-native organisms to the soil environment. Some researchers have raised concerns about the potential impact of Trichoderma on non-target organisms such as beneficial soil microbes, earthworms, and other soil organisms. Therefore, the effectiveness of Trichoderma as an antibiosis agent must be carefully evaluated in the context of specific environmental conditions and the potential impact on non-target organisms (Poveda, 2021).

Trichoderma as Nematicidal Agent

Numerous studies have reported the nematicidal activity of Trichoderma against a variety of plant-parasitic nematodes. For example, in a study by Kumar (2020), the nematicidal activity of *Trichoderma harzianum* was evaluated against the root-knot nematode Meloidogyne incognita in tomato plants. The researchers found that application of *T. harzianum* significantly reduced nematode population density in the soil and improved plant growth and yield compared to the untreated control.

Similarly, a study by Mukherjee et al. (2012) investigated the nematicidal activity of *Trichoderma virens* against the root-knot nematode Meloidogyne javanica in tomato plants. The researchers found that application of *T. virens* significantly reduced nematode population density and improved plant growth compared to the untreated control. Other studies have reported the nematicidal activity of specific compounds produced by trichoderma. For example, in a study by Zhang et al. (2021), the nematicidal activity of the compound harzianic acid, produced by *Trichoderma harzianum*, was evaluated against the root-knot nematode Meloidogyne incognita in tomato plants. The researchers found that application of harzianic acid significantly reduced nematode population density and improved plant growth compared to the untreated control.

In addition to its nematicidal activity, Trichoderma has also been shown to have other beneficial effects on plants, such as improving nutrient uptake and enhancing plant growth. For example, a study by (Contreras-Cornejo, Macías-Rodríguez, Del-Val, & Larsen, 2016) investigated the effects of Trichoderma on tomato plants grown in soil infested with the root-knot nematode Meloidogyne incognita. The researchers found that application of trichoderma improved plant growth, nutrient uptake, and resistance to nematode infection. Overall, the literature suggests that Trichoderma has significant potential as a nematicidal agent for controlling plant-parasitic nematodes. Further research is needed to optimize the use of Trichoderma for nematode control, including identifying the most effective strains and application methods. Various crops, including guava, tomato, okra, mungbean, and Indian ginseng, have shown reduction in plant-parasitic nematodes *Meloidogyne* spp. due to the nematicidal properties of *Trichoderma* spp. (Sharon et al. 2001).

Biochemical and Molecular Defense Response Induced by Trichoderma

Trichoderma induces various biochemical and molecular defense responses in plants, leading to enhanced resistance against various pathogens. Trichoderma induces the production of ROS, phytohormones, and the activation of defense-related genes, leading to the activation of the plant's immune response. Trichoderma also induces systemic acquired resistance in plants, leading to enhanced resistance against various pathogens. Trichoderma has been shown to induce the production of both salicylic acids, and jasmonic acid in plants, leading to the activation of the plant's defense response. Trichoderma has been shown to induce the expression of various defense-related genes, such as pathogenesis-related (PR) genes, chitinases, glucanases, and peroxidases. These genes play a crucial role in the plant's defense against pathogens (Sood et al., 2020).

Trichoderma as a Biofertilizer

Trichoderma has been found to promote plant growth and increase nutrient uptake in various major crops. This effect is due to the ability of Trichoderma to produce plant growth-promoting substances such as indole acetic acid (IAA), gibberellins, cytokinins, and auxins. Trichoderma also solubilizes phosphorus by secreting organic acids such as citric, malic, and gluconic acid, which can convert insoluble phosphorus into plant-available forms. In addition, Trichoderma can fix atmospheric nitrogen by forming symbiotic associations with plant roots or by producing ammonia.

Different researches claimed positive effects of Trichoderma on plant growth and nutrient uptake. For instance, Zhang et al. (2020) found that *Trichoderma harzianum* improved the growth of cucumber by promoting root development and increasing nutrient uptake. Similarly, El-Sayed et al. (2022) reported that *Trichoderma longibrachiatum* enhanced the growth and yield of wheat by increasing the uptake of nitrogen, phosphorus, and potassium. In another study, Saravanakumar et al. (2018) found that *Trichoderma viride* improved the growth and yield of rice by increasing root growth and nutrient uptake.

Trichoderma can induce systemic resistance in plants, making them more resistant to pathogen attack. This effect is due to the ability of Trichoderma to produce secondary metabolites such as peptaibols, gliotoxin, and trichokonins, which have antifungal and antibacterial properties. Trichoderma can also reduce the damage caused by abiotic stresses by producing osmolytes such as proline and trehalose, which help plants to maintain cellular homeostasis under stress conditions (Sood et al., 2020).

Several commercial formulations of Trichoderma are available in the market for use as biofertilizers. These formulations contain high concentrations of Trichoderma spores and are usually applied to the soil or plant roots. The effectiveness of these formulations depends on several factors such as the strain of Trichoderma used, the application rate, and the environmental conditions. For instance, Saratale et al. (2022) reported that the application of Trichoderma viride at a concentration of 1 x 10^9 spores per gram of soil increased the growth and yield of chickpea by 32% and 35%, respectively.

Moreover, Trichoderma has the ability to solubilize and mobilize nutrients such as phosphorus, iron, and zinc, which are often present in soil in an insoluble form. This makes these nutrients more accessible to plants and allows them to grow and develop more efficiently. Additionally, Trichoderma can fix atmospheric nitrogen, making it available to plants in a usable form.

Trichoderma for Insect Pest Control

Trichoderma, a genus of filamentous fungi, is a potential biocontrol agent for insect pests. Various Trichoderma species have shown promising results against a broad spectrum of insect pests. Trichoderma has several mechanisms of action against insect pests which involved synthesis of secondary metabolites like chitinases, proteases, and lipases, which have insecticidal properties. Trichoderma also produces volatile organic compounds that repel insects or attract their natural enemies, and induces plant resistance against insect pests. Furthermore, Trichoderma colonizes the soil and plant root systems, thereby competing with insect pests for nutrients and space. Trichoderma can be applied as a soil amendment or foliar spray. Soil applications involve incorporating trichoderma spores or inoculum into the soil, which allows the fungi to colonize the rhizosphere and provide long-term control of insect pests. Foliar applications involve spraying Trichoderma spores or inoculum directly onto the plant foliage, which provides short-term control of insect pests (Poveda, 2021).

Recent research have shown that Trichoderma can be effective against a range of insect pests, including aphids, whiteflies, thrips, and mites. For example, *Trichoderma harzianum* and *Trichoderma asperellum* have been shown to reduce the population of aphids and whiteflies on cucumber plants. Trichoderma also showed efficacy against thrips and mites on tomato plants. Trichoderma species also produce chitinases and proteases that can degrade the exoskeleton and cuticle of insects, leading to mortality or reduced growth and development. For instance, the chitinase produced by *Trichoderma harzianum* has been reported to cause mortality in the larvae of the fall armyworm *Spodoptera frugiperda*, a significant pest of maize and other crops (Ferreira & Musumeci, 2021).

Although trichoderma has shown potential as a biocontrol agent for insect pests, there are some limitations to its use. One of the major challenges is the variability in efficacy among different Trichoderma strains and species, and the need to identify the most effective strains for specific insect pests. Furthermore, the effectiveness of Trichoderma may be affected by environmental conditions such as temperature, moisture, and pH. Another challenge is the cost of production and application of Trichoderma, which may limit its use in some agricultural systems (Berini et al., 2016). Trichoderma has the potential to be a valuable biocontrol agent for insect pests, with several mechanisms of action and application methods available. However, the variability in efficacy among different Trichoderma strains and species, and the need to optimize application methods and environmental conditions, remain significant challenges.

Trichoderma for Plant Growth Regulation

One of the main mechanisms through which Trichoderma promotes plant growth is by producing plant growth hormones such as auxins, gibberellins, and cytokinins. These hormones are involved in various plant developmental processes such as cell division, elongation, and differentiation. Trichoderma can produce these hormones either directly or indirectly by inducing their production in the plant. For instance, *Trichoderma harzianum* can produce indole acetic acid (IAA), a type of auxin, which promotes root growth and branching in tomato plants. Similarly, *Trichoderma atroviride* can produce gibberellins, which stimulate plant growth and development in maize (Li et al., 2020; Mona et al., 2017).

Another mechanism through which Trichoderma promotes plant growth is by enhancing nutrient uptake and utilization efficiency. Trichoderma can solubilize insoluble nutrients such as phosphorus and iron, making them more available to plants. Trichoderma can also produce enzymes such as proteases, cellulases, and chitinases that can degrade complex organic compounds in the soil, releasing nutrients that can be taken up by plants (Turaeva et al., 2020).

Apart from these mechanisms, Trichoderma can also improve plant growth by regulating plant water relations. Trichoderma can increase plant water uptake and reduce water loss by enhancing root growth and reducing transpiration. Trichoderma can also improve plant tolerance to abiotic stresses such as drought and salinity by increasing the production of osmoprotectants such as proline and trehalose (Li et al., 2015). Trichoderma is a versatile biocontrol agent that can also promote plant growth and development through various mechanisms. Trichoderma can produce plant growth hormones, enhance nutrient uptake, induce systemic resistance against pathogens, regulate plant water relations, and improve plant tolerance to abiotic stresses (Poveda, 2021).

Trichoderma's ability to produce IAA has been demonstrated in various studies. For example, in one study, *Trichoderma harzianum* was found to produce IAA in both culture media and in association with tomato roots. The authors also observed that *T. harzianum*-inoculated plants had increased root and shoot growth and higher dry weight compared to non-inoculated plants (Doni et al., 2017). Similarly, in another study, *T. atroviride* was found to produce IAA in the rhizosphere of pepper plants, leading to improved root and shoot growth. Apart from IAA, Trichoderma also produces other phytohormones, including gibberellins (GAs) and cytokinins (CKs), which can modulate plant growth and development (Colla et al., 2015). In one study, *T. atroviride* was found to produce GAs and CKs in the presence of rice roots. The authors observed that *T. atroviride*-inoculated rice plants had increased tiller number, biomass, and yield compared to non-inoculated plants. In another study, *T. harzianum* was found to produce CKs in vitro, and the authors observed that T. *harzianum*-inoculated tomato plants had increased shoot growth, leaf area, and dry weight compared to non-inoculated plants (Hussain et al., 2022). Trichoderma can also produce compounds that promote stress tolerance and enhance plant growth under adverse environmental conditions. For example, in one study, *T. harzianum* was found to produce abscisic acid (ABA) in the presence of tomato roots, which increased the plant's tolerance to drought stress. The authors observed that *T. harzianum*-inoculated tomato plants had lower leaf water potential and higher relative water content compared to non-inoculated plants under drought stress (Tyśkiewicz, Nowak, Ozimek, & Jaroszuk-Ściseł, 2022).

Conclusions

In conclusion, Trichoderma has emerged as a promising biocontrol agent for sustainable agriculture due to its ability to control plant pathogens through various mechanisms and promote plant growth and health. The use of Trichoderma in crop protection offers several advantages over traditional chemical pesticides, such as reduced environmental impact, lower risk of developing resistance, and compatibility with other biological control agents. However, the implementation of Trichoderma as a biocontrol agent in agriculture requires further research and development to optimize its efficacy and integration into farming practices. Standardization of production and application methods, selection of appropriate strains and formulations, and consideration of environmental factors are critical for the successful implementation of Trichoderma in crop protection. In addition, understanding the interactions between Trichoderma and other soil microorganisms is essential for maintaining the ecological balance in the soil ecosystem. Overall, Trichoderma holds great promise as a sustainable alternative to chemical pesticides and deserves further attention and investment to realize its potential for sustainable agriculture.

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