Mini Review
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Molecular interactions of *Trichoderma*: from microbial competition to soil health promotion

Abstract

The increasing demand for sustainable solutions to agricultural pest and disease management has positioned *Trichoderma* fungi as a promising biological control agent. *Trichoderma* is not only capable of suppressing various plant pathogens but also promotes plant growth and strengthens natural plant defenses. This mini-review explores the molecular mechanisms underlying *Trichoderma's* ability to function as a biocontrol agent, focusing on nutrient competition, antibiotic production, mycoparasitism, and the induction of plant resistance. Additionally, advances in genomics and transcriptomics have facilitated a deeper understanding of the signaling pathways and genes responsible for *Trichoderma's* biocontrol effectiveness, including G-protein and MAPK pathways. Beyond pathogen suppression, *Trichoderma* plays a key role in enhancing soil health and establishing symbiotic relationships with plants, contributing to improved nutrient absorption and growth hormone production. However, challenges remain in translating laboratory success to large-scale field applications. This mini review highlights the need for further research on optimizing *Trichoderma* formulations, understanding its interaction with other beneficial soil organisms, and exploring genetic engineering to enhance its biocontrol capabilities. The future of *Trichoderma* lies in its integration into holistic, agroecological systems alongside other sustainable pest management strategies.

Keywords: *trichoderma*, biological control, molecular mechanisms, promoting plant growth, soil health

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Introduction

The need for sustainable solutions for controlling agricultural pests and diseases has driven the search for alternatives to conventional chemical products.[1,2] In this context, the use of biological agents, such as fungi from the *Trichoderma* genus, has gained increasing importance.[3,4] These fungi have proven to be highly effective not only in suppressing plant pathogens but also in promoting plant growth and activating their natural defenses.[5] One of the most fascinating aspects of *Trichoderma* is its ability to interact with other organisms in its environment, employing a series of complex molecular mechanisms that enable it to function as an efficient biological control agent.[6] In this mini review, I will explore the relevance of these molecular mechanisms, focusing on the different approaches *Trichoderma* uses to control pathogens, stimulate plant growth, and survive in competitive conditions. My analysis will be based on research presented in various scientific texts that review the main action mechanisms of *Trichoderma*, providing an understanding from both a general and molecular level.

Trichoderma as a biological control agent: a multifaceted agent

For decades, *Trichoderma* has been identified as a fungus with biocontrol properties due to its ability to suppress a wide variety of plant pathogens.[7–9] The key mechanisms that *Trichoderma* employs to exert control over pathogens include nutrient competition, the production of antibiotic compounds, mycoparasitism, and the induction of plant resistance.[10]

Nutrient and space competition: *Trichoderma* uses highly effective strategies to colonize plants, competing for space and nutrients with pathogens by invading areas such as plant tissues and the rhizosphere.[11] Its rapid growth and production of biochemical substances allow it to outperform pathogens in the competition.[12] Additionally, it excels in nutrient absorption, such as sugars, acid production that lowers soil pH, and siderophores that facilitate the absorption of essential minerals like iron, manganese, and magnesium.[13,14]

Production of antibiotics and antifungal compounds: Another important mechanism is the production of secondary compounds, such as antibiotics and other metabolites toxic to pathogens.[15] *Trichoderma* fungi secrete a variety of chemical substances, including harzianic acid, alamethicins, tricholin, peptaibols, antibiotics, 6-penthyl-α-pyrone, massoilactone, viridin, gliovirin, glisoprenins, and heptelidic acid, which inhibit the growth of other fungi in their environment.[16] This antibiotic mechanism becomes an effective tool for pathogen suppression without the need for direct physical contact.[17]

Mycoparasitism: *Trichoderma* detects its host from a distance and responds by growing towards the pathogenic fungus.[18] Some studies suggest that *Trichoderma* strains produce non-volatile antibiotics that predispose the host fungus to infection before contact.[19] Moreover, *Trichoderma's* ability to detect and recognize its host seems to be mediated by specific lectins. These lectins bind to sugar residues on the host fungus's cell walls, triggering the formation of appressorium-like structures in *Trichoderma* that facilitate penetration.[20,21] After recognition, *Trichoderma* adheres to the pathogenic fungus and either coils around it or grows over its hyphae.[18] This mycoparasitic process also involves the production of hydrolytic enzymes that degrade the pathogen's cell walls, including chitinases, glucanases, and proteases, which synergistically destroy the pathogen's cellular structure.[22] The synergistic action of extracellular enzymes is particularly important as it significantly enhances the effectiveness of biological control.[18]

Induction of plant resistance: In addition to its ability to attack pathogens, *Trichoderma* also has the capacity to trigger defensive responses in plants.[23] By inducing systemic acquired resistance

(SAR) and induced systemic resistance (ISR), *Trichoderma* promotes the production of pathogenesis-related (PR) proteins and other antimicrobial compounds in plants. This not only protects plants from current infections but also provides them with a greater capacity to resist future pathogen attacks.[24]

Molecular mechanisms behind Trichoderma's biocontrol

As advances in genomic sequencing and transcriptomics have increased, scientists have been able to identify the genes and signalling pathways involved in mycoparasitism, secondary metabolite production, and interaction with plants.[25]

Pathogen detection and signalling: *Trichoderma's* ability to detect the presence of pathogenic fungi in its environment is key to its success as a biocontrol agent.[25] This process begins when *Trichoderma* detects compounds released by the pathogen, such as chitin or glucan fragments, which act as molecular signals. These signals activate transduction pathways in *Trichoderma*, including G protein pathways and mitogen-activated protein kinases (MAPK), which trigger the expression of genes related to the production of lytic enzymes and antimicrobial metabolites.[26]

G protein-mediated signalling pathway: In the case of mycoparasitism, pathogen detection activates a series of G protein-coupled receptors that initiate signalling cascades within the *Trichoderma* cell. These G proteins play a central role in regulating growth, metabolite production, and the formation of infection structures. For example, the gene *tga1*, which encodes a G protein subunit, has been identified as crucial for *Trichoderma's* mycoparasitism on pathogens like *Rhizoctonia solani*. Mutation or suppression of this gene significantly reduces Trichoderma's ability to overgrow and parasitize the pathogen.[27]

MAPK signalling pathway: Another key component in signalling is the MAPK pathway, which regulates *Trichoderma's* response to pathogens. Studies have shown that the overexpression of MAPK genes in *Trichoderma* increases chitinase and other hydrolytic enzyme production, enhancing its biocontrol capacity. In *Trichoderma virens* and *Trichoderma atroviride*, the MAPK pathway has also been found to regulate sporulation and the formation of coiling structures, suggesting that these pathways play a multifunctional role in fungal biology.[28,29]

Secondary metabolite production: Another fascinating aspect of *Trichoderma's* biocontrol ability is its capacity to produce a wide variety of secondary metabolites with antifungal and antibacterial properties. These compounds, such as peptaibols, terpenoids, and polyketides, are essential for inhibiting the growth of other microorganisms in their environment.[30] Advances in genomic sequencing have identified the genes responsible for the biosynthesis of these metabolites, and genetic manipulation of these pathways has shown that overproduction of certain compounds can enhance *Trichoderma's* efficacy as a biocontrol agent.[31]

Trichoderma's interaction with plants: beyond biocontrol

One of the most significant discoveries in *Trichoderma* research is its ability to establish symbiotic relationships with plants, which goes beyond pathogen control. *Trichoderma* not only protects plants from diseases but also acts as a plant growth promoter.[24] This ability is largely due to the interaction between the molecular signals emitted by the fungus and the plants.[32]

Plant growth stimulation: When *Trichoderma* colonizes plant roots, it not only protects them from pathogens but also improves their growth by facilitating nutrient absorption and stimulating the production of plant growth hormones such as auxins. Plants treated with *Trichoderma* have been shown to exhibit greater root development and increased tolerance to abiotic stress.[33]

Induction of systemic resistance in plants (ISR): A key aspect of the interaction between *Trichoderma* and plants is its ability to induce systemic resistance (ISR). This phenomenon involves plants treated with *Trichoderma* activating their internal defenses in response to fungal colonization. This includes the production of pathogenesis-related (PR) proteins and the accumulation of defensive metabolites, such as phytoalexins. These responses are activated through the salicylic acid (SA) and jasmonate (JA) signalling pathways, which are also involved in defense against pathogens.[24,34]

Future perspectives and conclusions

Understanding the molecular mechanisms behind *Trichoderma's* ability to act as a biological control agent has advanced significantly over recent decades, thanks to advancements in biotechnology, genomics, and transcriptomics techniques. However, while these discoveries have enabled the identification and optimization of more effective strains, the challenge now lies in translating this knowledge into large-scale practical applications that are economically viable, environmentally sustainable, and easily integrated into current agricultural systems. One critical aspect that still requires further investigation is the interaction of *Trichoderma* not only with pathogens but also with other beneficial microorganisms present in the soil, such as mycorrhizae and growth-promoting bacteria. The coexistence of these organisms in the rhizosphere raises key questions about the dynamics that emerge between them. How does the presence of *Trichoderma* influence soil microbial ecosystems? Can its intensive use unbalance these communities, and how does this affect microbial biodiversity and long-term soil health? Answering these questions is crucial to developing more integrated strategies that combine different biological agents synergistically.

On the other hand, the success of *Trichoderma* in laboratory and experimental field studies does not always translate into consistent results when applied on a large scale. Factors such as variability in soil conditions, climate, interactions with other soil microorganisms, and the fungus's adaptation to new environmental conditions can affect its effectiveness as a biocontrol agent. Future research should focus on identifying how to optimize *Trichoderma* formulations to adapt them to different soil types and crops. Additionally, more work is needed on developing more stable and durable formulations that can withstand adverse climatic conditions and ensure controlled release of bio-inputs. An approach that should be explored further is the genetic engineering of *Trichoderma* to enhance its biocontrol and plant growth-promotion capabilities. Manipulation of the genes responsible for the production of secondary metabolites, G-protein and MAPK signaling pathways, or mechanisms of plant interaction could lead to the development of strains with improved abilities for different environments and pathogens. However, this raises ethical and regulatory dilemmas regarding the use of genetically modified organisms in agriculture, especially in terms of environmental safety and public acceptance. The regulatory framework around biosafety must be addressed alongside scientific advances to ensure that these products can be implemented safely and responsibly. Another promising but still underexplored area is the potential of *Trichoderma* as a multifunctional agent that not only acts as a biological control agent but also promotes long-term soil health. The long-term effects of repeated *Trichoderma* use in agricultural soils should be studied in depth to determine whether its benefits accumulate over time or, on the contrary, whether there are limits to its effectiveness over successive agricultural cycles. Furthermore, investigating how *Trichoderma* can interact with regenerative agricultural practices, such as the use of cover crops and crop rotation, could open new avenues for its integration into sustainable agriculture.

Finally, while *Trichoderma* presents itself as a promising ecological alternative to chemical fungicides and pesticides, it is essential to recognize that it is not a one-size-fits-all solution for plant health problems. The future approach must be holistic and integrative, considering disease management from an agroecological perspective that includes the combined use of *Trichoderma* with other integrated pest management (IPM) strategies. In this context, farmer education and training are essential to ensure they understand how to effectively implement these new technologies and integrate them into their traditional agricultural practices. In conclusion, although *Trichoderma* offers immense potential as an agricultural bioinput, its long-term success will depend on further research into its ecological interactions, optimization in its formulation, and a collaborative approach among scientists, regulators, and farmers. Only through a greater understanding of its molecular mechanisms and a strategic and adaptable approach to its implementation can *Trichoderma* become a central pillar in the future of sustainable agriculture.

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Conflicts of interest

The authors declared that there are no conflicts of interest.

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