Review Article

Revolutionary Role of Trichoderma in Sustainable Plant Health Management: A Review

ABSTRACT

The use of chemical pesticides in agricultural practices has led to significant concerns related to health and the environment in the last few decades. Consequently, there has been a growing interest in finding alternative approaches for controlling pests and diseases that are effective and environmentally friendly. Among these alternatives, *Trichodermaharzianum* has gained attention due to its remarkable ability to combat various crop pathogens in sustainable form.Biocontrolagents have gained prominence as eco-friendly substitutes for conventional chemical pesticides in disease management and crop improvement. *T.harzianum*, a common filamentous fungus, has emerged as a promising biocontrol agent due to its multifaceted strategies for suppressing diseases and promoting crop growth. This fungus employs a range of mechanisms, such as competition, mycoparasitism, and the induction of plant defense responses. Furthermore, *T.harzianum* directly attacks and preys upon other fungal pathogens by releasing enzymes that break down their cell walls, reducing pathogen populations.The biocontrol agent,also ,stimulates the innate immune system of plants, triggering the production of antimicrobial compounds like pathogenesis-related proteins and secondary metabolites. This enhances the plant's ability to resist diseases. Additionally, *T. harzianum*fosters plant growth by aiding nutrient absorption, improving soil structure, and generating growth-promoting substances like auxins and cytokinins.Field studies have substantiated the efficacy of *T. harzianum*in managing a wide array of plant diseases caused by fungi, bacteria, and nematodes whether used as a seed treatment, soil application, or foliar spray, *T. harzianum* establishes a beneficial presence early in the plant's life cycle, providing enduring protection.In conclusion, *T. harzianum*holds immense potential as a biocontrol agent to sustainably safeguard crops.*Trichoderma* species play a pivotal role in managing plant diseases due to their versatile mechanisms, including mycoparasitism, competition, and the elicitation of plant defenses. As global agriculture seeks alternatives to chemical pesticides, leveraging *T. harzianum's* potential offers a valuable avenue toward resilient and environmentally safe crop production.

1. INTRODUCTION

Trichoderma spp. are regarded as one of the most effective fungal biocontrol agents for controlling various plant diseases as well as stress brought on by abiotic factors, as has been highlighted in a number of scientific communications and publications to date. *Trichoderma* spp. are frequently used as soil applications, seed treatments, and seedling root dips to manage various plant diseases, promote plant growth, and increase crop output (Bahadur and Dutta, 2022; Kumar et al., 2020; Harman et al., 2004).The ability of Trichoderma to reduce abiotic stresses and the exact mechanisms involved, as well as its capacity to manage various plant stresses like osmotic, salinity, chilling, and heat stress, have all been the subject of recent publications. Trichoderma can withstand physiological stress, such as low seed quality brought on by seed aging (Singh et al., 2020). Under challenging conditions, one common detriment to plants is the accumulation of harmful reactive oxygen species (ROS). Trichoderma possesses the capacity to ameliorate the damage caused by ROS accumulation in stressed plants. For instance, when seedlings undergo osmotic stress, treating seeds with Trichoderma reduces lipid peroxidation. Enhancing plant resilience to abiotic stressors is a notable positive outcome of the Trichoderma-plant interaction, gaining increased attention due to the potential insight into its underlying mechanisms that could advance crop production techniques. Recent studies have revealed that select *Trichoderma* strains could potentially be harnessed for industrial purposes, producing diverse enzymes, growth hormones, and valuable secondary metabolites. In genetic engineering, Trichoderma is now employed for transgenic development. This review encompasses the advancements in understanding how these antagonistic fungi and their metabolites interact with plants, yielding substantial plant improvements to guard against various threats.

2:Mechanisms of TrichodermaAction

2.1 Competitive Interaction

A fundamental facet of biological control, competition transpires when multiple microorganisms vie for limited resources. The establishment of an introduced antagonist in the presence of native microflora can pose long-term challenges (Papavizas, 1985; Vinale et al., 2008). *Trichoderma*spp.possess enduring conidia and a wide range of substrate utilization, rendering a potent contender for resources (Sood et al., 2020).

2.2 Nutrient and Space Competition

Trichoderma spp. are rapidly proliferating fungi with persistent conidia and a broad substrate utilization capacity. They present robust competition for nutrients and space against other microorganisms that contribute to plant diseases (Tyśkiewicz et al., 2022). Weaker competitors among microorganisms often perish due to starvation. Trichoderma's competition for nutrients has been identified as a biocontrol mechanism against various plant pathogens. These fungi produce siderophores that sequester iron, hindering pathogenic microorganism growth by rendering iron inaccessible once chelated. Importantly, *Trichoderma* strains,also, compete for space and essential exudates from seeds and roots that trigger the germination of propagules of plant pathogenic fungi in soil. Moreover, they possess the capability to utilize a wide array of substrates including herbicides, fungicides, and phenolic compounds. The ability of Trichoderma to reduce abiotic stresses and the exact mechanisms involved, as well as its capacity to manage various plant stresses like osmotic, salinity, chilling, and heat stress, have all been the subject of recent publications.Trichodermais now used in genetic engineering for the creation of transgenics. This study includes a compilation of the most current developments and advances in our understanding of the various roles played by these antagonist fungi and their metabolites in interactions with plants, as well as how these alterations result in significant improvements for plants that help defend them from various threats. *Trichoderma* species have been recognized as capable of harming other fungi for more than 60 years. Additionally, researchers are aware of them as potential biological control agents (Naher et al., 2014; Sundaramoorthy and Balabaskar, 2013). Some studies have discovered that *Trichoderma* species can eliminate plant diseases and promote plant development (Ibrahim et al., 2020; Garnica-Vergara et al., 2016). Besides, *Trichoderma*spp.has been proven their ability to detoxify toxic compounds and fasten degradation of organic material (Yadav, 2021; Sharma et al., 2012). *Trichoderma*spp.are able to speed up growth, take up nutrients, and alter the rhizosphere under field conditions all contribute to their success in the soil ecosystem and their function as natural decomposers. Additionally, theyhave the potential to withstand adverse conditions and tremendous effectiveness against plant pathogenic diseases Benítezet al., 2004; Harman, 2006). The unknown effects of *Trichoderma* spp. on soil microbial population(tions(Check) have been noted by a number of investigators.According to Halifuet al. (2019), *Trichoderma*spp.exude cell wall-degrading enzymes such as cellulase, xylanase, and glucanases, which interfere with microbial cells' ability to assimilate nutrients in the rhizosphere. This review gives insights into various mechanisms used by Trichoderma to alleviate the stresses with special emphases on how it induces resistance and various uses of Trichoderma in plant disease management.

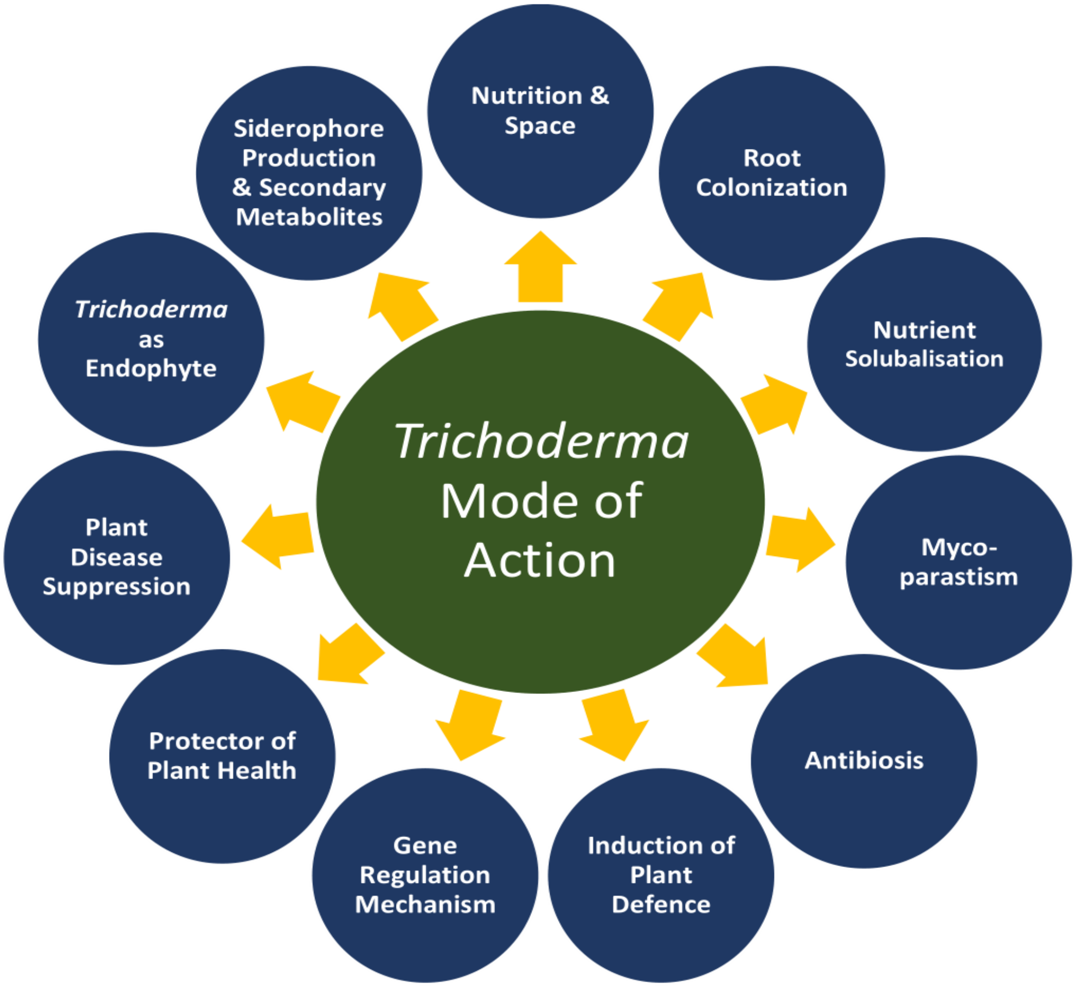

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Fig. 1.Various modes of action used by Trichoderma.

2.3 Root Conlization

*Trichoderma*spp.play a pivotal role in enhancing the uptake of macro- and micronutrients by plants in agricultural fields. This enhancement is achieved by solubilizing nutrients and ensuring the availability of essential elements such as phosphorus (P) and micronutrients like iron (Fe), manganese (Mn), copper

(Cu), and zinc (Zn). Trichoderma employs four distinct mechanisms to achieve nutrient solubilization: enzymatic hydrolysis facilitated by phytase, redox reactions mediated by ferric reductase, chelation through siderophores, and acidification using organic acids. This array of mechanisms allows Trichodermato solubilize various minerals including phytase, Fe_2O_3,CuO, and metallic Zn, although it remains ineffective in solubilizing compounds like $Ca_3(PO_4)2$ or MnO_2. Analytical techniques such as high-performance liquid chromatography (HPLC) have revealed the presence of organic acids such as lactic acid, citric acid, tartaric acid, and succinic acid in Trichodermacultures. Furthermore, *Trichoderma*-treated plants demonstrate significant increases in both plant biomass dry matter (92%) and

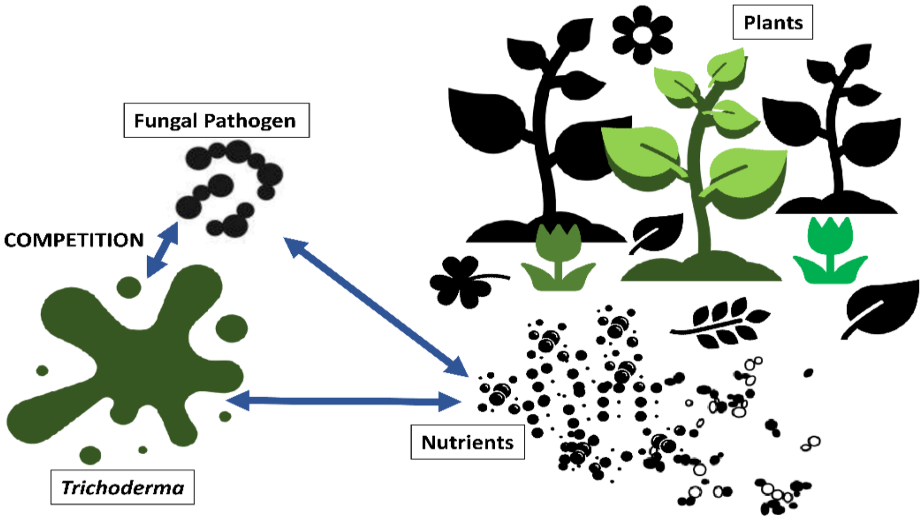

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Fig. 2.Mechanism of action by competition.

copper uptake (42%) compared to untreated controls. Notably, specific Trichoderma isolates display anenhanced ability to solubilize insoluble tricalcium phosphate, particularly in chickpeas. *T.harzianum* has been found to augment phosphorus uptake in treated plants. Additionally, the secretion of gluconic and citric acids by Trichodermacontributes to soil acidification, promoting the solubilization of phosphates, micronutrients, and mineral components, including iron, magnesium, and manganese (Ghazanfar et al., 2018; Benitez et al., 2004; Vinale et al., 2008).

2.4Mycoparasitism

The process of mycoparasitism involves the antagonist fungus parasitizing other fungi responsible for causing plant diseases. The role of *Trichoderma* spp. as a biocontrol agent was first recognized by Weindling (1932), who also observed mycoparasitic behavior in *Trichoderma*. Moreover, in 1988, Wells documented instances where *T. lignorum* (*viride*) hyphae coiled around and terminated *R. solani* growth. A specific *Trichoderma* species exhibits chemotropic growth towards its target hosts, attaching to them, enveloping their hyphae, and subsequently infiltrating the points of contact. Recent ultrastructural and histochemical analyses propose that Trichoderma hyphae, entwined at interaction sites with their hosts, undergo localized cell wall degradation.Investigations using electron microscopy have demonstrated that the antagonist, *Trichoderma* spp., enzymatically degrades host cell walls during interactions with *Sclerotiumrolfsii* or *Rhizoctoniasolani*. As indicated by studies by Ghasemi *et al*., (2019), Abdel-Rahim and Abo-Elyousr (2018), and Mukherjee *et al*., (2008) mentioned that*Trichoderma*spp. release extracellular enzymes including -(1,3)-glucanases, chitinases, lipases, and proteases when cultured on the cell walls of pathogenic fungi. Additionally, predominant *Trichoderma* species generate a variety of secondary metabolites, such as non-ribosomal peptides, terpenoids, pyrones, and indole-derived compounds. Within the rhizosphere, reciprocal signaling occurs between Trichoderma,and plants, leading to alterations in physiological and biochemical processes in both entities. For instance, the presence of fungal auxin-like compounds prompts various *Trichoderma* strains to stimulate root branching, thereby increasing shoot biomass through cellular processes like proliferation, expansion, and differentiation. Concurrently, *Trichoderma*spp.contribute to systemic resistance, augments plant nutrient uptake, and *mitigate* disease development when coexisting with plant roots.

2.5 Antibiosis

In the context of antibiosis, *Trichoderma* spp.emit volatile compounds that exhibit toxicity towards surrounding pathogenic microorganisms. These volatile substances exert a lethal impact on the pathogenic entities, either preventing disease occurrence or repressing its progression.Trichoderma generates secondary metabolites that confer a competitive advantage against diverse microorganisms. These volatile metabolites yield benefits encompassing symbiosis, metal transport, and differentiation, among others (Adnan, 2019; Demain and Fang, 2000). Antibiotic agents, constituting volatile lytic enzymes or toxins, selectively target and dismantle the pathogens. Notably, *Trichoderma* spp. generate a repertoire of volatile substances, including lactones, alcohols, terpenes, and specific compounds such as Trichodermin, Viridin, Viridiol, Gliotoxin, and Gliovirin (Singh et al., 2020). These volatile compounds collectively undermine the viability of adjacent pathogenic microorganisms, thereby mitigating disease incidence.

2.6. Induction of Plant Resistance by *Trichoderma* spp.

Numerous investigations (Adnan *et al*., 2019; Yedidia et al., 2003; Hanson et al., 2004) elucidate that *Trichoderma* spp. elevate the expression of plant genes associated with chitinase, glucanase, and peroxidase production, augmenting the plants' defense mechanisms against pathogenic bacteria. Biopriming of seeds with Trichodermaenhances plants' resilience against pathogenic assaults (Harman, 2004). The rapid proliferation and spore production of Trichoderma, coupled with its strategic timing of invasion (Kumar and Khurana, 2021; Kumar *et al*., 2020), facilitate effective disease management. By secreting antibiotics and possessing cell wall-degrading enzymes like cellulases, chitinases, and glucanases, *Trichoderma* spp. establish competitive dominance (Ghasemi et al., 2020; Vinale*et al*., 2008).Furthermore, pretreatment of plants with *Trichoderma* species triggers a hypersensitive response, systemic acquired resistance (SAR), and induced systemic resistance (ISR) (Gupta and Bar, 2020; Benitez *et al*., 2004; Vinale*et al*., 2008). For instance, exposure to Trichodermainduced substantial physiological modifications in tomato plants, ultimately enhancing their resistance to diseases (Alfano *et al*., 2007). Preconditioning cucumber plants with

Trichoderma spp., as reported by Yedidia et al. (2003),which prompted systemic responses involving defense genes expressing phenylalanine and hydroperoxides lyase, alongside the systemic accumulation of phytoalexins combating *Pseudomonas syringae*pv. *lachrymans*. This priming led to a hypersensitive reaction and the elicitation of SAR and ISR mechanisms (Gupta and Bar, 2020; Benitez *et al*., 2004; Vinale et *al*., 2008). Such interactions exemplify Trichoderma's capacity to protect its ecological niche by competitively outmaneuvering microbial competitors, thereby positioning it as an effective adversary against pathogenic fungi and a promising biocontrol agent (Spiegel and Chet, 1998; Vinale*et al*., 2006; Navazio*et al*., 2007).

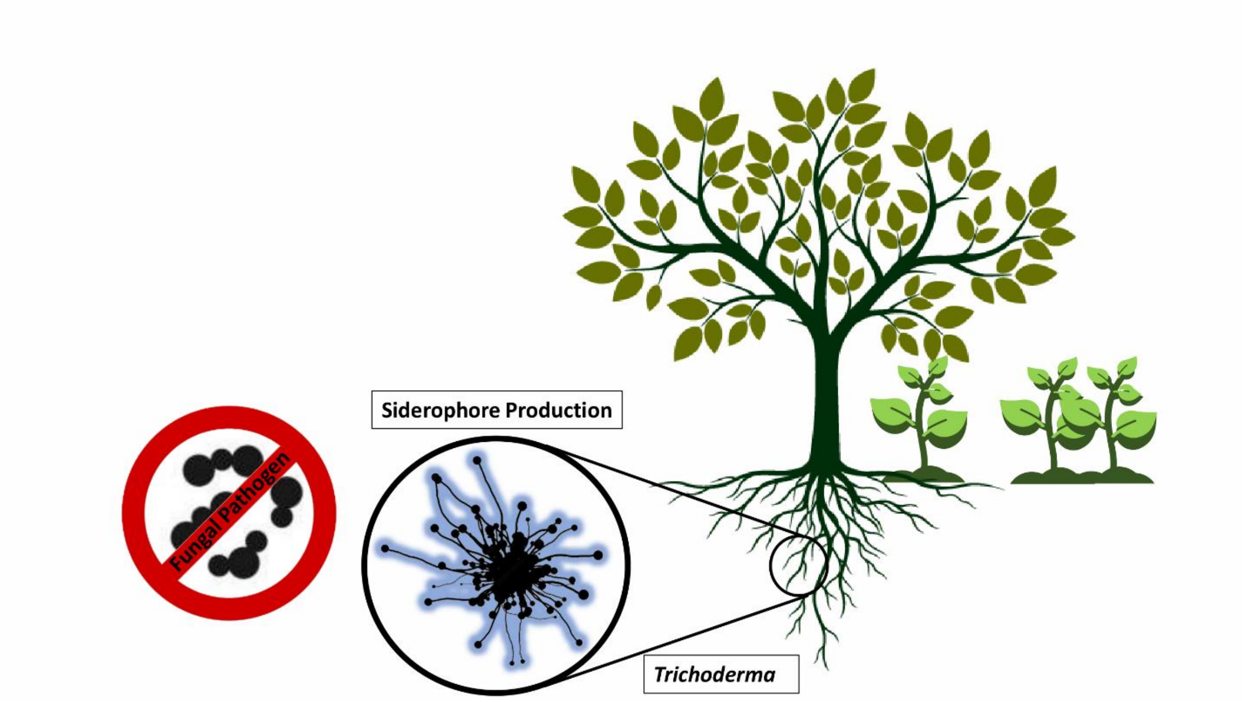

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Fig. 3.Induction of resistance by Trichoderma.

2.7.Trichoderma's Defense Activation through Gene Regulatory Mechanisms

Several strains of Trichodermahave displayed the ability to initiate defense responses in plants by activating various signaling pathways such as mitogen-activated protein kinase (MAPK) cascades, the cAMP pathway, and other pathways related to gene expression modulation that contribute to plant disease suppression and mycoparasitism inhibition (Mukhopadhyay and Kumar, 2020; Zeilinger and Omann, 2007). A key player in this process is the MAP-kinase TVK1, which has been identified in *T. virens* (Mendoza-Mendoza et al., 2003) as well as its counterparts in *T. asperellum* (Viterbo*et al*., 2005) and *T.atroviride* (Reithner*et al*., 2007). This kinase is pivotal in regulating signaling transduction pathways, thereby influencing output pathways that are vital for effective biocontrol. Interaction between *T. virens*, *T. asperellum*, and plant roots against *Rsolani* has been observed to increase the activity of genes linked to plant disease suppression (Helflish*et al*., 2021; Viterbo *et al*., 2005). Although deletion of these specific genes leads to reduced mycoparasitism efficiency, mutant strains exhibit enhanced biocontrol abilities. Additionally, the introduction of Trichoderma treatment followed by *Botrytis cinerea* injection into plants results in heightened systemic resistance to the pathogen. Notably, *Trichoderma* species possess genes such as TGA1 (*T. atroviride*), TGA A (*T. virens*), TGA3 (*T. atroviride*), and GNA3 (*T. reesei*) that have been extensively investigated for their involvement in biocontrol potential. TGA1 induces the production of antifungal compounds and facilitates coiling around host hyphae, contributing to effective antagonism; the absence of TGA1 leads to inhibited growth of host fungi (Rocha-Ramirez et al., 2002; Reithner*et al*., 2005). Another gene, Tga A, has been found to activate MAP-kinases, and its deletion results in the emergence of avirulent strains, highlighting its role in biocontrol (Mukherjee *et al*., 2004). Similarly, TGA3's presence is crucial for *Trichoderma's* biocontrol capacity (Zeilinger *et al*., 2005). GNA3's constitutive activation in *T. reesei* is associated with favorable effects on mycoparasitism, thus contributing to effective disease reduction.

2.8. Secondary Metabolites

In addition to enzymatic strategies, fungi possess a potent chemical repertoire that aids their survival and competition within their ecological niches (Silva *et al*., 2019; Vinale*et al*., 2008). Numerous strains of *Trichoderma* spp. have been identified as producers of various secondary metabolites, including mycotoxins and potential antibiotics like peptaibols, along with over 100 metabolites exhibiting antibiotic activity such as polyketides, pyrones, terpenes, metabolites derived from amino acids, and polypeptides (Sivasithamparam and Ghisalberti, 1998). The peptide antibiotic paracelsin was the initial characterized secondary metabolite in *Trichoderma* spp. (Schuster and Schmoll, 2010). A novel class of peptaibols was subsequently discovered in Trichoderma (Degenkolb et al., 2008). Importantly, the presence of mycotoxin-producing Trichoderma species like *T. brevicompactum*, *T. arundinaceum*, *T. turrialbense*, and *T.protrudens* does not pose a risk to biocontrol efforts. These species are distantly related to those used in biocontrol, indicating that mycotoxins are not pivotal in defense mechanisms against pathogens. *Trichoderma* spp., like other fungi, areknown to emit a variety of volatile organic compounds, garnering increased attention recently (Raza and Shen, 2020; Elsherbiny *et al*., 2020). The biosynthesis of peptaibols in *Trichoderma* spp. is regulated by various factors, particularly environmental conditions such as light, pH, nutrient availability, starvation, and mechanical damage. The production of conidia is intertwined with effective peptaibol synthesis (de Sousa *et al*., 2021; Kubicek *et al*., 2007). Moreover, Trichoderma-treated plants have exhibited increased production of plant growth hormones, including cytokinin-related molecules like zeatin and gibberellin, fostering growth in terms of root and shoot length as well as biomass and leaf expansion (Howell, 2003).

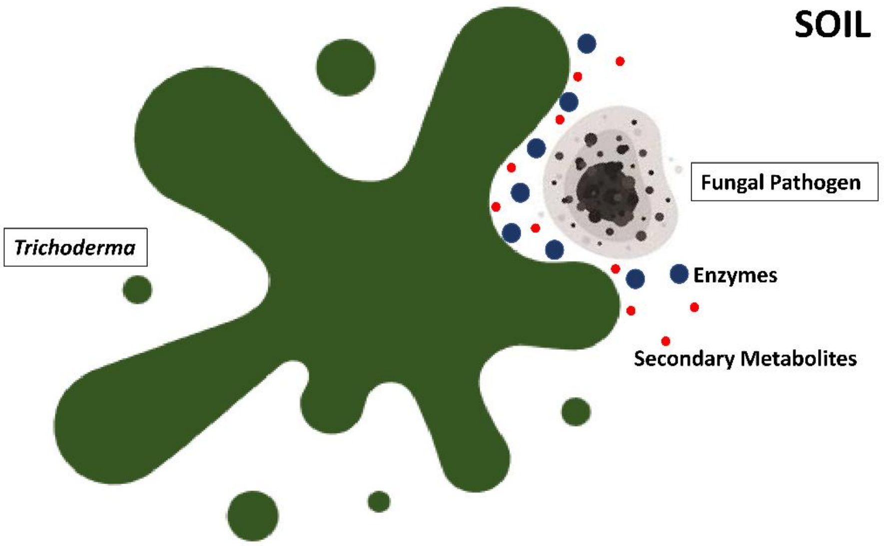

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Fig. 4 Mechanism of action by secondary metabolites.

3. The Role of Trichoderma in Managing Plant Diseases

The utilization of living organisms to curtail pest populations is referred to as biocontrol. *Trichoderma* spp., as highlighted by Hajek and Eilenberg in 2018, stands out as the most widely employed biocontrol agent against various root, shoot, and post-harvest diseases, earning them recognition for their eco-friendliness. According to Siemering *et al*.'s findings in 2016, Trichoderma primarily establishes itself along root surfaces and within the upper layers of root cells, with roots serving as their primary habitat. The introduction of Trichoderma involves asuccessful application to plant roots during seeding, as demonstrated by Gava and Pinto in 2016 and Siddaiah*et al.* in 2017. Several researchers assert that treating seeds has proven effective in ensuring the colonization of Trichoderma spp. on roots, facilitating plant benefits.At present, *Trichoderma* species adopt three primary mechanisms for biological control against pathogens: (i)recognizing and infiltrating plant pathogenic fungi-like species by disrupting their cell walls and absorbing released nutrients, a strategy known as mycoparasitism; (ii) promoting plant disease resistance by altering root architecture during interactions with pathogens; and (iii) combating root-knot and cyst nematodes.While, their impact on crops generally aligns,where there are instances of species-specific and strain-specific relationships. Commercially available products typically contain one or more *Trichoderma* species, such as *T. viride*, *T. virens*, and *T. harzianum*. The effectiveness of products containing different species or strains can vary under similar field and climatic conditions. The prevalent forms of *Trichoderma* spp. products are wettable powders or granules. Approximately ninety percent of various *Trichoderma* strains are applied to crops to counter plant diseases due to their antagonistic properties against phytopathogens.

The evaluation of their performance as biocontrol agents (BCAs) considers input costs within the field and crop productivity. Comparatively, the input costs and applications related to BCA and crop productivity demonstrate cost-effectiveness when pitted against synthetic inputs. Despite their cost advantage, excessive use of synthetic inputs like fertilizers and pesticides can lead to reduced profitability for farmers, if the balance between input costs and crop productivity is skewed. *Trichoderma* species not only minimize crop losses but also increase yields, bolstering profitability. Imran et al.'s observations in 2020 underscore how the judicious application of *Trichoderma*, along with compost, can offer an economical alternative to pricey chemical fertilizers. The utilization of *Trichoderma* is an effective sustainable approach to maintaining soil health. Research indicates that *Trichoderma* species effectively suppress plant pathogenic organisms like *Pythiumarrhenomanes*, *Rhizoctoniasolani*, *Fusariumoxysporum*, *Alternariatenuis*, and *Botrytis cinerea*. *T. harzianum*, widely distributed worldwide and found across various substrates, features prominently in agricultural practices for its natural disease-suppressing abilities. Table 1 shows various bicontrol agents and their use in disease management.

In the *T. harzianum* species complex, consisting of closely linked members with minimal morphological differences, substrate, and origin play a pivotal role in defining ecological notions of species. Variations in functional goals, such as the secretion of secondary metabolites, growth conditions, target phytopathogens, host ranges, and geographic distribution, arise within this complex. Ahluwalia et al.'s 2015 study revealed distinct variations in secondary metabolites and antifungal activity between two *T. harzianum* strains (T-4 and T-5) from different geographical regions in the Himalayas, reflecting the impact of environmental conditions.Moreover, studies by Napitupulu*et al.*, in 2019 demonstrated differences in antagonistic efficacy among ten *T. harzianum* strains isolated from diverse sources across Java, Indonesia. These strains exhibited varying degrees of antagonism against *Fusariumoxysporum*f.sp.*cubense*. Trichoderma's potential in bacterial disease management merits exploration.

Table 1. Fungal strains as biocontrol agents against various plant pathogens.

Fungal strains	Targeted disease	Target pathogen	Reference
Aspergillus fumigates	Cocoa/black pod	*PhytophthoraPalmivora*	Adebola and Amadi (2010)
Paecilomyceslilacinus	Tomato/Root-knot disease	*Meloidogynejavanica*	Hanawi (2016)
Penicilliumoxalicum	Tomato/Root-knot disease	*Fusariumoxysporum*f. sp.*Lycopersici*	Sabuquillo et al. (2006)
Penicillium sp. EU0013	Tomato and cabbage/wilt	*Fusariumoxysporum*	Alam et al. (2010)
Pochoniachlamydosporia	Carrot/Root knot disease	*Meloidogyne incognita*	Bontempo et al. (2017)
Purpureocilliumlilacinum	Vigna radiata/Root-knot disease	*Meloidogyne incognita*	Khan et al. (2019)
Purpureocilliumlilacinum	Pineapple/Root knot disease	*Meloidogynejavanica*	Kiriga et al. (2018)
Trichoderemahamatum	Cabbage	*Sclerotiniasclerotiorum apothecia*	Jones et al. (2014)
Trichodermaasperellum	Beans	*S. sclerotiorum apothecia*	Geraldine et al. (2013)
Trichodermaasperellum	Onion	*Sclerotiumcepivorum*	Rivera-Méndez et al. (2020)
Trichodermaatroviride	Beans	*Botrytis cinerea*	Brunner et al. (2005)
Trichodermaharzianum	Rice/brown spot	*Bipolarisoryzae*	Khalili et al. (2012)
Trichodermaharzianum T-22	Soya bean	Suppressive effect on *S. sclerotiorum*	Zeng et al. (2012)
Trichoderma spp.	Tobacco/root rot	*Rhizoctoniasolani*	Gveroska and Ziberoski (2011)

Trichoderma virens	Okra/Root-knot disease	*Meloidogyne incognita*	Tariq et al. (2018)

(Source-: Kumar *et al.* 2022)

3.2.*Trichoderma*spp. for Bacterial Disease Management

Trichoderma spp.'s inhibitory effects on various plant pathogens, encompassing fungi and plant parasitic nematodes, are well-documented. Evidence substantiates their effectiveness against plant pathogenic bacteria, both in laboratory settings and in mitigating bacterial disease severity in controlled environments and fields. Though limited literature exists on the antagonistic potential of *Trichoderma* spp. against bacterial plant pathogens, their ability to produce diverse secondary metabolites and volatile chemicals that inhibit phytopathogenic bacteria through antibiosis is recognized. Additionally, *Trichoderma* spp. are acknowledged for inducing plant defense mechanisms, thereby reducing bacterial pathogen infections by triggering systemic acquired resistance.Under field conditions, different *T.asperellum* isolates have demonstrated effectiveness in reducing the incidence of diseases, such as *Ralstoniasolanacearum*-induced bacterial wilt symptoms in tomatoes. The application of *T. asperellum* was found to increase enzyme activity and induce systemic acquired resistance in tomato plants, ultimately lowering disease severity. In the case of cucumber, *T.asperellum* applied to the root system induced systemic acquired resistance to angular leaf spot caused by *Pseudomonas syringae*pv.*lachrymans*, resulting in reduced disease severity. *Trichoderma hamatum* consistently safeguards tomato plants against bacterial leaf spots caused by *Xanthomonaseuvesicatoria* through the modulation of plant physiology and disease resistance. In vitro tests revealed that multiple *Trichoderma* species inhibit the growth of *Xanthomonasaxonopodis*pv.*malvacearum*, the pathogen responsible for bacterial blight in cotton, with the exception of *T. viride* and *T. lignorum*. *Trichodermaharzianum* effectively suppressed the bacteria causing soft rot in vegetable and tuber crops due to *Erwiniacarotovora*when tested through diffusion and post-harvest storage methods.In conclusion, *Trichoderma*'s significant role in plant disease management extends to both fungal and bacterial pathogens. Its multifaceted strategies, encompassing direct antagonism, the induction of systemic resistance, and the production of inhibitory metabolites, underscore its potential as a valuable biocontrol agent in sustainable agriculture practices.The suppressive capabilities of *Trichoderma* spp. against a range of plant pathogens, including numerous fungal pathogens and plant parasitic nematodes, are well recognized. It's clear that *Trichoderma* spp. are effective against bacterial plant pathogens, based on both in vitro evidence and their ability to lessen bacterial disease severity in greenhouse and field experiments, even though there is limited literature on their antagonistic capabilities against these bacteria.Various secondary compounds and volatile substances generated by *Trichoderma spp.* are identified to counteract multiple phytopathogenic bacteria through the antibiosis method. Furthermore, these compounds trigger plant defense systems, reducing bacterial pathogen infections by eliciting systemic acquired resistance in plants.

In field conditions, different isolates of *T.asperellum* demonstrated their effectiveness in reducing disease occurrence, delaying bacterial wilt symptoms in tomatoes caused by *R.solanacearum*. The application of *T. asperellum* was observed to amplify activities like peroxidase (POX), phenylalanine ammonia-lyase (PAL), polyphenol oxidase (PPO), -1,3-glucanase, and total phenol after the pathogen was introduced in the field, consequently fortifying systemic acquired resistance in tomato plants (Konappa*et al*., 2018). Additionally, when *T. asperellum* was applied to the root system, it exhibited systemic resistance against angular leaf spot (*Pseudomonas syringae*pv.*lachrymans*) in cucumbers, leading to a decrease in disease intensity.*T.hamatum*has consistently demonstrated protection against the bacterial leaf spot of tomatoes induced by *Xanthomonaseuvesicatoria*, by influencing plant physiology and disease resistance through systemic gene expression adjustments related to stress and metabolism (Alfano *et al*., 2007).

In an *in-vitro* dual culture technique, the effectiveness of five *Trichoderma* species *i.e.,Trichodermaviride*, *T. hamatum*, *T. harzianum*, *T. lignorum*, and *T. koningii* against bacterial blight of cotton triggered by *Xanthomonasaxonopodis*pv.*malvacearum* was assessed. Except for *T. viride* and *T. lignorum*, all *Trichoderma*species were found to hinder the growth of *X. axonopodis*pv.*malvacearum* after a three-day incubation. Interestingly, T. harzianum demonstrated strong antagonistic activity against the plant pathogen Xanthomonas *in-vitro*, sourced from ten varied agro-climatic regions in Karnataka, restricting its growth (Tallapragada and Gudimi, 2011).Utilizing the well diffusion method and post-harvest storage tests, *T.harzianum* was determined to counteract the bacteria leading to soft rot in vegetable and tuber crops, notably those triggered by *Erwiniacarotovora* (Rashid *et al*., 2013).

3.3 Utilizing *Trichoderma*spp. in the Control of Nematode Diseases

Plant parasitic nematodes pose a major threat to a variety of crops, both within greenhouses and in the fields. They can either directly cause diseases in plants through parasitism or act as carriers for other harmful pathogens like fungi, bacteria, or viruses. Their subterranean feeding habits make controlling them a formidable challenge. Many nematicides have been banned due to their high residual toxicity, posing significant health and environmental risks. Moreover, these chemicals often fail to penetrate deep enough into the soil to effectively control nematode populations, leading to increased resistance.Using biological means like *Trichoderma*spp. is becoming increasingly relevant for managing these pests. This fungus stands out among biocontrol agents for its antagonistic properties against a wide range of plant pathogens. Trichoderma not only coils around nematodes, restricting their movement but also produces spores that attach to nematodes. Additionally, *Trichoderma*releases secondary metabolites, including toxins and antibiotics, which can incapacitate these pests. Studies have revealed that applying specific strains of Trichoderma, like *T. harzianum* and *T. viride*, can reduce nematode-related damage in crops such as tomatoes.Various experiments have shown that different *Trichoderma* strains can inhibit the growth and activities of several nematodes. For example, *Trichodermalongibrachiatum*showed potential in controlling nematodes like *Scutellonema* sp. and *Helicotylenchus*. Some strains even produce enzymes that help in breaking down the nematode body cuticle*Trichoderma* also parasitizes nematodes by conidia which are attached to nematodes. The gelatinous matrix of nematodes plays an important role in the attachment of conidia and the parasitization process by forming carbohydrate-lectin-like interactions. Trichoderma also produces many secondary metabolites like toxins and antibiotics like malformin, gliotoxin, viridian, and penicillin, which might contribute to the toxicity along with inactivity and immobility of plant parasitic nematodes.The root-knot nematode, *M. incognita*, was found to have significantly fewer galls, egg masses, eggs per egg mass, and reproductive factors after *T. harzianum* and *T. viride* were applied to tomato crops (Mukhtar, 2018). The hatching of *M. javanica* eggs was shown to be inhibited by *T. harzianum* culture filtrates when they were tested at various concentrations, and this inhibition grew stronger with increasing culture filtrate concentration. *T. harzianum* showed direct parasitism of *M. javanica* eggs and decreased nematode pathogenicity by reducing the number of galls, egg masses, eggs, and gall width under field conditions (Naserinasab*et al*., 2011).Culture filtrates derived from various *Trichoderma* species, including *T. harzianum*, *T. viride*, *T. koningii*, *T. reesei*, and *T. hamatum*, demonstrated the ability to impede the reproductive and developmental processes of reniform nematodes (*Rotylenchusreniformis*) and root-knot nematodes in laboratory settings. This effect was attributed to the presence of harmful metabolites. Moreover, under greenhouse conditions, these filtrates suppressed the mobility and activity of nematodes from both genera by thwarting their infiltration and growth, as observed by their inhibited penetration and development stages (Bokhari, 2009).

T.longibrachiatum (TL6) exhibited inhibition of eggs and second-stage juveniles (J2s) of *Heteroderaavenae* in wheat crops. This was achieved through the parasitization of nematode eggs, characterized by the formation of dense mycelium coverings, breakdown of egg contents, and penetration by numerous hyphae that led to deformities in the J2s. Consequently, greenhouse trials involving wheat seedlings treated with TL6 resulted in reduced *H. avenae* infestations and enhanced plant growth due to the suppression of nematode cysts and juveniles in the soil (Zhang *et al*., 2017).*T.longibrachiatum* displayed the ability to inhibit *Scutellonema*sp. and *Helicotylenchus* by creating an appressorium-like structure that made direct contact with the nematode. This structure produced penetration holes in the nematode's cuticle, causing the cuticle to disintegrate and leading to the collapse of the nematode due to loss of turgor. In contrast, *T.viride* and *T.harzianum* induced excessive coiling of their mycelium around the anterior and head regions of the nematodes, likely related to the extraction of the nematode's bodily contents and suppression of its cuticle. *T.koningii* utilized endo and exochitinases to facilitate hyphal penetration through the nematode's cuticle. Strains of *T. virens*, *T. atroviride*, and *T. rossicum* displayed remarkable efficiency in reducing the population of *Xiphenema index*, and the application of *T. viride* led to a decline in the population of the Potato cyst nematode (*Globoderarostochinensis*) in soil (Daragó*et al*., 2013; Umamaheswari*et al*., 2012).

Conclusion:

Trichoderma species exhibit numerous characteristics that hold significant potential for their utilization in agriculture. These qualities encompass the mitigation of abiotic stresses, enhancement of physiological stress responses, facilitation of nutrient uptake in plants, improvement of nitrogen utilization efficiency in diverse crops, and contribution to heightened photosynthetic efficiency. The global utilization of this genus has expanded, encompassing roles as general plant protectants and growth promoters, in addition to industrial applications. The genomes of *Trichoderma* species encompass a plethora of valuable genes, enabling these fungi to adapt to challenging environments such as soil, water, decaying matter, and within plants themselves. The metabolic pathways within *Trichoderma* species are exceptionally intricate, particularly in the context of secondary metabolite production. Nonetheless, the integration of advanced molecular and proteomic techniques offers the possibility of uncovering novel pathways with extensive agricultural applications.The mapping of *Trichoderma*species proteomes and their interactions has enabled the development of novel products founded on synergistic combinations of the living fungus and its secreted metabolites. These innovative formulations are deemed more effective than their predecessors and exhibit efficacy against a broader spectrum of pathogens. It is worth noting that certain strains of Trichoderma do not induce resistance or growth enhancement. The application of Trichoderma to maize cultivation, for instance, results in an average yield increase of approximately 5%. However, the responses vary significantly among different maize varieties, with some displaying neutral or even negative growth responses.Furthermore, the identification of specific pivotal gene products associated with favorable outcomes facilitates swift assessments of critical protein or gene expression, even on a field scale. This presents a valuable management tool for reliable evaluation of interactions. The dual capacity of these fungi to induce resistance against biotic stresses such as diseases and abiotic stresses like drought and salinity, coupled with their ability to enhance nutrient utilization efficiency, positions them as immensely valuable tools. Through their application, plant productivity can be notably elevated, contributing to food security and environmental preservation.Importantly, the ability of these fungi to curb the production of compounds from surplus fertilizers can reduce the application of nitrogen fertilizers, thereby mitigating nitrate pollution in soil and water bodies, as well as curtailing air pollution. With their antagonistic properties, *Trichoderma* species have proven successful in managing onion diseases such as white rot, pink rot, Fusarium basal rot, onion smudge, and damping off. Their introduction to the root zones of crops like cucumber, bell pepper, and strawberry has led to significant yield increases. Additionally, *Trichoderma* species exhibit resilience against an array of stubborn pollutants including heavy metals, pesticides, and polyaromatic hydrocarbons. This versatility positions *Trichoderma* as a potent biological tool for disease management in plants while concurrently fostering agricultural and environmental sustainability.

1. **Ethical and informed consent for data use:** The information provided in the article related to the topic that helpful for readers.
2. **Data availability and access:** The data available in the article is freely available.

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