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

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Authors' contributions

This work was carried out in collaboration among all authors. Authors AKS and RS conceived the presented idea about the topic selection for the review paper and wrote the paper. Authors AK and RS collection of data. Authors SM, ML, VS performed computer simulations and contributed to paper writing. Authors BK and PSD performed text mining analysis and reviewed the paper. Ethical and informed consent for data use: The information provided in the article related to the topic that helpful for readers. Data availability and access: The data available in the article is freely available. All authors read and approved the final manuscript.

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Review Article

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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, *Trichoderma harzianum* has gained attention due to its remarkable ability to combat various crop pathogens in sustainable form. Biocontrol agents 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. *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. As global agriculture seeks alternatives to chemical pesticides, leveraging *T. harzianum 's* potential offers a valuable avenue toward resilient and environmentally safe crop production.

Keywords: Trichoderma; biotic factors; fungi; nematode; antibiosis; mycoparasitism; management.

1. INTRODUCTION

Trichoderma spp. is 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. is frequently used as soil applications, seed treatments, and seedling root dips to manage various plant diseases, promote plant growth, and increase crop output [1-3]. 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 [4]. 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. There are more than 370 *Trichoderma spp*. including *T. harzianum*, *T. viride*, *T. asperellum*, *T. hamatum*, *T. atroviride*, *T. koningii*, *T. longibrachiatum*, and *T. aureoviride* are reported to date [5,6]. There are several species of *Trichoderma* has been used as biocontrol agent including *T. harzianum*, *T. hamatum*, *T. longibrachiatum*, *T. koningii*, *T. viride*, *T. polysporum*, *T. asperellum* [7]. It has been mentioned in several studies that most *Trichoderma spp*. can produce bioactive substances and have antagonistic effects on plant-pathogenic fungi and plant-pathogenic nematodes [8]. A number of bioactive substances, including secondary metabolites and cell wall-degrading enzymes, can effectively improve crop resistance, reduce plant diseases, and promote plant growth [9].

2. MECHANISMS OF TRICHODERMA ACTION

2.1 Competitive Interaction

A fundamental facet of biological control, competition transpires when multiple microorganisms for limited resources. The establishment of an introduced antagonist in the presence of native microflora can pose long-term challenges [10,11]. *Trichoderma* spp. possess enduring conidia and a wide range of substrate utilization, potent contenders for resources [12].

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 [13]. 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. Trichoderma is 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 [14,15]. Some studies have discovered that *Trichoderma* species can eliminate plant diseases and promote plant growth [16,17]. Besides, *Trichoderma* spp. has been proven able to detoxify toxic compounds and fasten the degradation of organic material [18,19]. *Trichoderma* to speeds up growth, takes up nutrients, and alters the rhizosphere under field conditions all contributing to their success in the soil ecosystem and their function as natural decomposers. Additionally, the potential to withstand adverse conditions and have tremendous effectiveness against plant pathogenic diseases [20,21]. According to Halifu et al. [22], *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.

2.3 Root Colonization

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 Trichoderma to solubilize various minerals including phytase, CuO, and metallic Zn. 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 Trichoderma cultures. Furthermore, *Trichoderma*-treated plants demonstrate significant increases in both plant biomass dry matter (92%) and copper uptake (42%) compared to untreated controls. Notably, specific Trichoderma isolates display an enhanced 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 Trichoderma contributes to soil acidification, promoting the solubilization of phosphates, micronutrients, and mineral components, including iron, magnesium, and manganese [23,20,24].

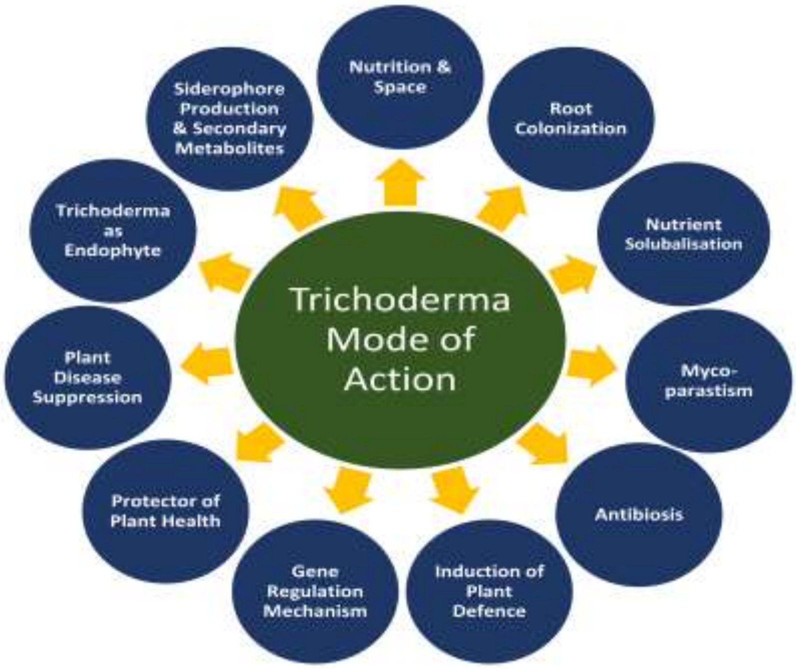

Fig. 1. Various modes of action used by Trichoderma

2.4 Mycoparasitism

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 [25], 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 *Sclerotium rolfsii* or *Rhizoctonia solani*. As indicated by studies by Ghasemi *et al*., [26], Abdel-Rahim and Abo-Elyousr [27], and Mukherjee *et al.*, [28] 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. Trichoderma has the ability to produce hundreds of antimicrobial secondary metabolites, including trichomycin, gelatinomycin, chlorotrichomycin, antibacterial peptides, and many more [29]. 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.

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 [30,31]. 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 [4]. 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 [30,32,33] 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 Trichoderma enhances plants' resilience against pathogenic assaults [21]. The rapid proliferation and spore production of Trichoderma, coupled with its strategic timing of invasion [34,35], facilitate effective disease management. By secreting antibiotics and possessing cell wall-degrading enzymes like cellulases, chitinases, and glucanases, *Trichoderma* spp. establish competitive dominance [26,11]. Furthermore, pretreatment of plants with *Trichoderma* species triggers a hypersensitive response, systemic acquired resistance (SAR), and induced systemic resistance (ISR) [36,20,24]. For instance, exposure to Trichoderma induced substantial physiological modifications in tomato plants, ultimately enhancing their resistance to diseases ([37]. Preconditioning cucumber plants with *Trichoderma* spp., as reported by Yedidia et al. [32], 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 [36,20,11]. 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 [38,11,39].

2.7 Trichoderma's Defense Activation through Gene Regulatory Mechanisms

Several strains of Trichoderma have 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 [40,41]. A key player in this process is the MAP-kinase TVK1, which has been identified in *T. virens* [42] as well as its counterparts in *T. asperellum* [43] and *T. atroviride* [44]. 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 *R solani* has been observed to increase the activity

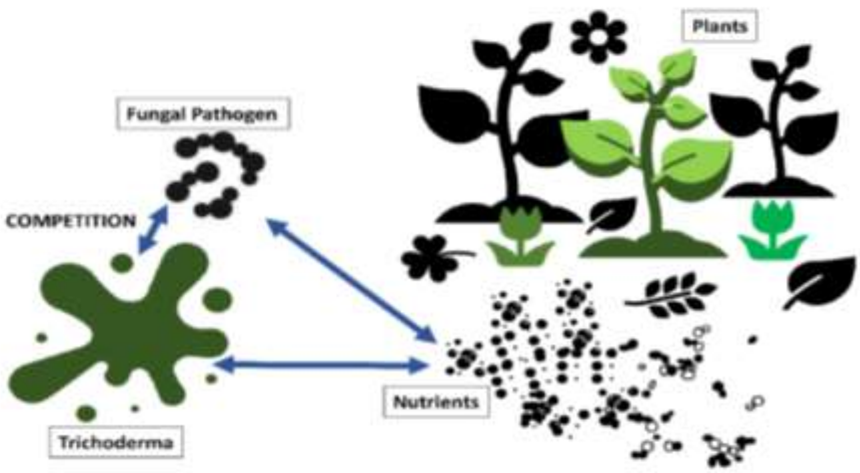

Fig. 2. Mechanism of action by competition

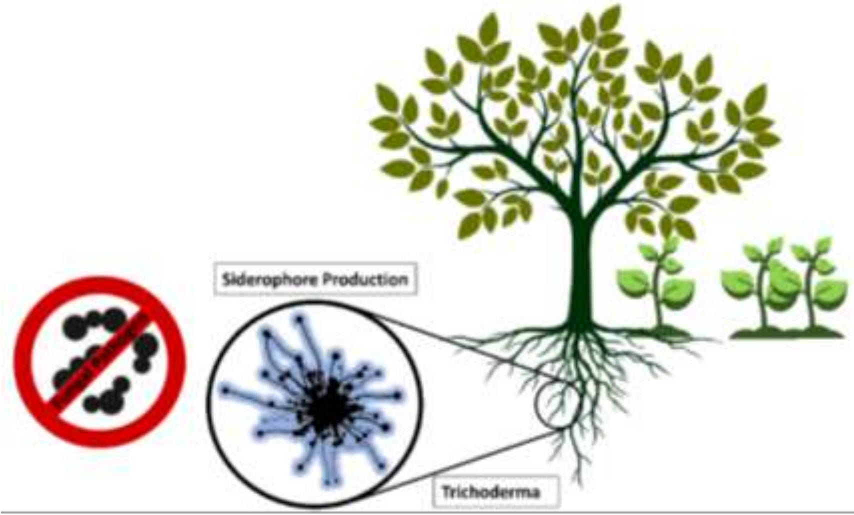

Fig. 3. Induction of resistance by Trichoderma

of genes linked to plant disease suppression [45,43]. Although deletion of these specific genes leads to reduced mycoparasitism efficiency, mutant strains exhibit enhanced biocontrol abilities. 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 [46]. 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 [47]. Similarly, TGA3's presence is crucial for *Trichoderma's* biocontrol capacity [48]. 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 [49,11]. 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 [50]. The peptide antibiotic paracelsin was the initial characterized secondary metabolite in *Trichoderma* spp. [51]. A novel class of peptaibols was subsequently discovered in Trichoderma [52]. 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, known to emit a variety of volatile organic compounds, garnering increased attention recently [53,54]. 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 [49,55]. 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 [56].

2.9 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

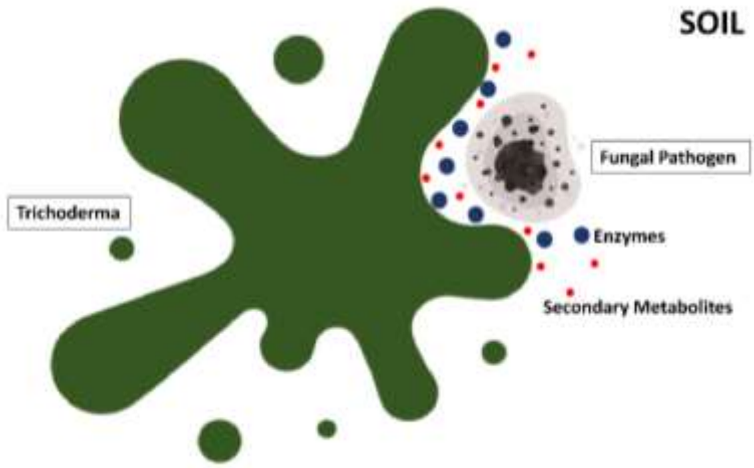

Fig. 4. Mechanism of action by secondary metabolites

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 a successful 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. Their impact on crops generally aligns, 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 *Pythium arrhenomanes*, *Rhizoctonia solani*, *Fusarium oxysporum*, *etc*. *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 *Fusarium oxysporum* f.sp. *cubense*. Trichoderma's potential in bacterial disease management merits exploration.

2.10 *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.

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 [71]. 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 *Xanthomonas euvesicatoria*, by influencing plant physiology and disease resistance through systemic gene expression adjustments related to stress and metabolism [37].

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

Fungal strains	Targeted disease	Target pathogen	Reference
Aspergillus fumigates	Cocoa/black pod	*Phytophthora Palmivora*	Adebola and Amadi [57]
Paecilomyces lilacinus	Tomato/Root-knot disease	*Meloidogyne javanica*	Hanawi [58]
Penicillium oxalicum	Tomato/Root-knot disease	*Fusarium oxysporum* f. sp. *Lycopersici*	Sabuquillo et al. [59]
Penicillium sp. EU0013	Tomato and cabbage/wilt	*Fusarium oxysporum*	Alam et al. [60]
Pochonia chlamydosporia	Carrot/Root knot disease	*Meloidogyne incognita*	Bontempo et al. [61]
Purpureocillium lilacinum	Vigna radiata/Root-knot disease	*Meloidogyne incognita*	Khan et al. [62]
Purpureocillium lilacinum	Pineapple/Root knot disease	*Meloidogyne javanica*	Kiriga et al. [63]
Trichoderema hamatum	Cabbage	*Sclerotinia sclerotiorum apothecia*	Jones et al. [64]
Trichoderma asperellum	Beans	*S.sclerotiorum apothecia*	Geraldine et al. [65]
Trichoderma asperellum	Onion	*Sclerotium cepivorum*	Rivera-Méndez et al. (2020)
Trichoderma atroviride	Beans	*Botrytis cinerea*	Brunner et al. [66]
Trichoderma harzianum	Rice/brown spot	*Bipolaris oryzae*	Khalili et al. [67]
Trichoderma harzianum T-22	Soya bean	Suppressive effect on *S. sclerotiorum*	Zeng et al. [68]
Trichoderma spp.	Tobacco/root rot	*Rhizoctonia solani*	Gveroska and Ziberoski [69]
Trichoderma virens	Okra/Root-knot disease	*Meloidogyne incognita*	Tariq et al. [70]

(Source-: Kumar et al. [2])

In an *in-vitro* dual culture technique, the effectiveness of five *Trichoderma* species *i.e., Trichoderma viride*, *T. hamatum, T. harzianum, T. lignorum,* and *T. koningii* against bacterial blight of cotton triggered by *Xanthomonas axonopodis* 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 [72]. 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 *Erwinia carotovora* (Rashid *et al*., 2013).

2.11 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, *Trichoderma longibrachiatum* 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 [73]. 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 [74]. 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 [75].

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 [76]. *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 (*Globoderarosto chinensis*) in soil [77,78].

3. 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. Whereas unscientific and unusual use of chemical pesticides has caused serious hazards to the environment and enhanced pathogens' resistance unscientific and unusual use of chemical pesticides has caused serious hazards to the environment and enhanced pathogens' resistance. to chemical pesticides. Several experiments have proven that *Trichoderma* has good biological control effects and can reduce the use of chemical pesticides [79-85].

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 [86-90]. These innovative formulations are deemed more effective than their predecessors and exhibit efficacy against a broader spectrum of pathogens. 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 [91-96]. 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.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Bahadur A, Dutta P. *Trchoderma spp.:* Their impact in crops diseases management. In Trichoderma-Technology and Uses. Intech Open; 2022.
2. Kumar A, Sheoran N, Saini R, Kumari P, Singh A. Biological control: concept, Mechanism and their role in Sustainable Management of Plant Diseases, Sustainable Production through Crop Management and Improvement. 2022;201-22.
3. Harman GE. Overview of mechanisms and uses of Trichoderma spp. Phytopathology. 2006;96(2):190-4.

4. Singh R, Anbazhagan P, Viswanath HS, Tomer A. Trichoderma species: A Blessing for Crop Production. In Trichoderma: agricultural applications and beyond. Cham: Springer. 2020;127-58.
5. Sánchez-Montesinos B, Santos M, Moreno-Gavíra A, Marín-Rodulfo T, Gea FJ, Diánez F. Biological control of fungal diseases by Trichoderma aggressivum f. europaeum and its compatibility with fungicides. J Fungi (Basel). 2021;7(8):598.
6. Sun J, Karuppiah V, Li Y, Pandian S, Kumaran S, Chen J. Role of cytochrome P450 genes of Trichoderma atroviride T23 on the resistance and degradation of dichlorvos. Chemosphere. 2022;290:133173.
7. Di Marco S, Metruccio EG, Moretti S, Nocentini M, Carella G, Pacetti A et al. Activity of Trichoderma asperellum strain ICC 012 and Trichoderma gamsii strain ICC 080 toward diseases of esca complex and associated pathogens. Front Microbiol. 2021;12:813410.
8. Druzhinina IS, Chenthamara K, Zhang J, Atanasova L, Yang D, Miao Y et al. Massive lateral transfer of genes encoding plant cell wall-degrading enzymes to the mycoparasitic fungus Trichoderma from its plant-associated hosts. PLOS Genet. 2018;14(4):e1007322.
9. Kubicek CP, Komoń-Zelazowska M, Sándor E, Druzhinina IS. Facts and challenges in the understanding of the biosynthesis of peptaibols by Trichoderma. Chem Biodivers. 2007;4(6): 1068-82.
10. Papavizas GC, Dunn MT, Lewis JA, Beagle-Ristaino JE. Liquid fermentation technology for experimental production of biocontrol fungi. Phytopathology. 1984;74(10):1171.
11. Vinale F, Marra R, Scala F, Ghisalberti EL, Lorito M, Sivasithamparam K. Major secondary metabolites produced by two commercial Trichoderma strains active against different phytopathogens. Lett Appl Microbiol. 2006;43(2):143-8.
12. Sood M, Kapoor D, Kumar V, Sheteiwy MS, Ramakrishnan M, Landi M et al. Trichoderma: The ”secrets” of a multitalented biocontrol agent. Plants (Basel). 2020;9(6):762.
13. Tyśkiewicz R, Nowak A, Ozimek E, Jaroszuk-Ściseł J. Trichoderma: the current status of its application in agriculture for the biocontrol of fungal phytopathogens and stimulation of plant growth. Int J Mol Sci. 2022;23(4):2329.
14. Naher L, Yusuf UK, Ismail A, Hossain K. *Trichoderma spp*.: A biocontrol agent for sustainable management of plant diseases. Pak J Bot. 2014;46(4):1489-93.
15. Sundaramoorthy S, Balabaskar P. Biocontrol efficacy of Trichoderma spp. against wilt of tomato caused by Fusarium oxysporum f. sp. lycopersici. J Appl Biol Biotechnol. 2013;1(3):036-40.
16. Ibrahim DS, Elderiny MM, Ansari RA, Rizvi R, Sumbul A, Mahmood I. Role of Trichoderma spp. in the management of plant-parasitic nematodes infesting important crops. In: Management of phytonematodes: recent advances and future challenges. Singapore: Springer. 2020;259-78.
17. Garnica-Vergara A, Barrera-Ortiz S, Muñoz-Parra E, Raya-González J, Méndez-Bravo A, Macías-Rodríguez L et al. The volatile 6-pentyl-2H-pyran-2-one from Trichoderma atroviride regulates Arabidopsis thaliana root morphogenesis via auxin signaling and ethylene INSENSITIVE 2 functioning. New Phytol. 2016;209(4):1496-512.
18. Yadav AN. Recent trends in mycological research. Springer International Publishing; 2021.
19. Sharma P, Jha AB, Dubey RS, Pessarakli M. Reactive oxygen species, oxidative damage, and antioxidative defense mechanism in plants under stressful conditions. J Bot. 2012;2012:1-26.
20. Benítez T, Rincón AM, Limón MC, Codón AC. Biocontrol mechanisms of Trichoderma strains. Int Microbiol. 2004 Dec 7;7(4):249-60.
21. Harman GE, Howell CR, Viterbo A, Chet I, Lorito M. Trichoderma species opportunistic, avirulent plant symbionts. Nat Rev Microbiol. 2004;2(1):43-56.
22. Halifu S, Deng X, Song X, Song R. Effects of two Trichoderma strains on plant growth, rhizosphere soil nutrients, and fungal community of Pinus sylvestris var. mongolica annual seedlings Forests. 2019;10(9):758.
23. Ghazanfar MU, Raza M, Raza W, Qamar MI. Trichoderma as potential biocontrol agent, its exploitation in agriculture: a review. Plant Prot. 2018;2(3).
24. Vinale F, Sivasithamparam K, Ghisalberti EL, Marra R, Woo SL, Lorito M.

Trichoderma–plant-pathogen interactions. Soil Biol Biochem. 2008;40(1):1-10.
25. Weindling R. Trichoderma lignorum as a parasite of other soil fungi. Phytopathology. 1932;22(8):837-45.
26. Ghasemi S, Safaie N, Shahbazi S, Shams-Bakhsh M, Askari H. Enhancement of lytic enzymes activity and antagonistic traits of Trichoderma harzianum using γ-radiation induced mutation. J Agric Sci Technol. 2019;21(4):1035-48.
27. Abdel-Rahim IR, Abo-Elyousr KAM. Talaromyces pinophilus strain AUN-1 as a novel mycoparasite of Botrytis cinerea, the pathogen of onion scape and umbel blights. Microbiol Res. 2018;212-213:1-9.
28. Mukherjee PK, Latha J, Hadar R, Horwitz BA. Role of two G-protein alpha subunits, TgaA and TgaB, in the antagonism of plant pathogens by Trichoderma virens. Appl Environ Microbiol. 2004 Jan;70(1):542-9.
29. Maruyama CR, Bilesky-José N, de Lima R, Fraceto LF. Encapsulation of Trichoderma harzianum preserves enzymatic activity and enhances the potential for biological control. Front Bioeng Biotechnol. 2020;8:225.
30. Adnan M, Islam W, Shabbir A, Khan KA, Ghramh HA, Huang Z et al. Plant defense against fungal pathogens by antagonistic fungi with Trichoderma in focus. Microb Pathog. 2019;129:7-18.
31. Demain AL, Fang A. The natural functions of secondary metabolites. Adv Biochem Eng Biotechnol. 2000;69:1-39.
32. Yedidia I, Shoresh M, Kerem Z, Benhamou N, Kapulnik Y, Chet I. Concomitant induction of systemic resistance to Pseudomonas syringae pv. lachrymans in cucumber by Trichoderma asperellum (T-203) and accumulation of phytoalexins. Appl Environ Microbiol. 2003;69(12):7343-53.
33. Hanson LE, Howell CR. Elicitors of plant defence responses from biocontrol strains of Trichoderma virens. Phytopathology. 2004;94(2):171-6.
34. Kumar M, Choudhary S, Chaurasiya DK. Mechanism of Trichoderma spp. and their role in biological management of plant diseases. Biotica Res Today. 2020; 2(8):722-6.
35. Kumar N, Khurana SP. Trichoderma-plant-pathogen interactions for the benefit of agriculture and environment. In: Biocontrol agents and secondary metabolites. Woodhead Publishing. 2021;41-63.
36. Gupta R, Bar M. Plant immunity, priming, and systemic resistance as mechanisms for Trichoderma spp. biocontrol. In Trichoderma. Singapore: Springer. 2020;81-110.
37. Alfano G, Ivey LML, Cakir C, Bos JIB, Miller SA, Madden Kamoun VL et al. Systemic modulation of gene S. expression in tomato by Trichoderma hamatum 382. Biol Control. 2007;97:429-37.
38. Spiegel Y, Chet I. Evaluation of Trichoderma spp. as a biocontrol agent against soilborne fungi and plant–parasitic nematodes in Israel. Integr Pest Manag Rev. 1998;3(3):169-75.
39. Navazio L, Baldan B, Moscatiello R, Zuppini A, Woo SL, Mariani P et al. Calcium-mediated perception and defense responses activated in plant cells by metabolite mixtures secreted by the biocontrol fungus Trichoderma atroviride. BMC Plant Biol. 2007;7:41.
40. Mukhopadhyay R, Kumar D. Trichoderma: a beneficial antifungal agent and insights into its mechanism of biocontrol potential. Egypt J Biol Pest Control. 2020;30(1):1-8.
41. Zeilinger S, Omann M. Trichoderma biocontrol: signal transduction pathways involved in host sensing and mycoparasitism. Gene Regul Syst Biol. 2007 Nov 8;1:227-34.
42. Mendoza-Mendoza A, Pozo MJ, Grzegorski D, Martínez P, García JM, Olmedo-Monfil V et al. Enhanced biocontrol activity of Trichoderma through inactivation of a mitogen-activated protein kinase. Proc Natl Acad Sci U S A. 2003 Dec 23;100(26):15965-70.
43. Viterbo A, Harel M, Horwitz BA, Chet I, Mukherjee PK. Trichoderma mitogen-activated protein kinase signaling is involved ininduction of plant systemic resistance. Appl Environ Microbiol. 2005 Oct;71(10):6241-6.
44. Reithner B, Schuhmacher R, Stoppacher N, Pucher M, Brunner K, Zeilinger S. Signaling via the Trichoderma atroviride mitogen-activated protein kinase Tmk 1 differentially affects mycoparasitism and plant protection. Fungal Genet Biol. 2007 Nov;44(11):1123-33.
45. Heflish AA, Abdelkhalek A, Al-Askar AA, Behiry SI. Protective and Curative Effects of Trichoderma asperelloides Ta41 on Tomato Root Rot Caused by Rhizoctonia solani Rs33. Agronomy. 2021;11(6):1162.

46. Rocha-Ramirez V, Omero C, Chet I, Horwitz BA. Herrera-Estrella Trichoderma atroviride G-protein alpha-subunit gene tga1 is involved in mycoparasitic coiling and condition. A Eukaryot Cell. 2002 Aug;1(4):594-605.
47. Mukherjee KP, Nautiyal CS, Mukhopadhyay AN. Molecular mechanisms of plant and microbe coexistence. Heidelberg: Springer; 2008.
48. Zeilinger S, Reithner B, Scala V, Peissl I, Lorito M, Mach RL. Signal transduction by Tga3, a novel G protein alpha subunit of Trichoderma atroviride. Appl Environ Microbiol. 2005 Mar;71(3):1591-7.
49. de Sousa TP, Chaibub AA, Cortes MVCB, Batista TFC, Bezerra GA, da Silva GB et al. Molecular identification of Trichoderma sp. isolates and biochemical characterization of antagonistic interaction against rice blast. Arch Microbiol. 2021; 203(6):3257-68.
50. Sivasithamparam K, Ghisalberti EL. Secondary metabolism in Trichoderma and Gliocladium. In: Harman GE, Kubicek CP, editors. Trichoderma and Gliocladium. London: Taylor & Francis; 1998;139-92.
51. Schuster A, Schmoll M. Biology and biotechnology of Trichoderma. Appl Microbiol Biotechnol. 2010;87(3):787-99.
52. Degenkolb T, von Döhren H, Nielsen KF, Samuels GJ, Brückner H. Recent advances and future prospects in peptaibiotics, hydrophobin, and mycotoxin research, and their importance for chemotaxonomy of Trichoderma and Hypocrea. Chem Biodivers. 2008;5(5):671-80.
53. Raza W, Shen Q. Volatile organic compounds mediated plant-microbe interactions in soil. In: Molecular aspects of plant beneficial microbes in agriculture. Academic Press. 2020;209-19.
54. Elsherbiny EA, Amin BH, Aleem B, Kingsley KL, Bennett JW. Trichoderma volatile organic compounds as a biofumigation tool against late blight pathogen Phytophthora infestans in postharvest potato tubers. J Agric Food Chem. 2020;68(31):8163-71.
55. Kubicek CP, Steindorff AS, Chenthamara K, Manganiello G, Henrissat B, Zhang J et al. Evolution and comparative genomics of the most common Trichoderma species. BMC Genomics. 2019;20(1):485.
56. Howell CR. Mechanisms employed by Trichoderma species in the biological control of plant diseases: the history and evolution of current concepts. Plant Dis. 2003;87(1):4-10.
57. Adebola MO, Amadi JE. Screening three Aspergillus species for antagonistic activities against the cocoa black pod organism (*Phytophthora palmivora*). Agric Biol J North Am. 2010; 1(3):362-5.
58. Hanawi MJ. Tagetes erecta with native isolates of *Paecilomyces lilacinus* and *Trichoderma hamatum* in controlling root-knot nematode *Meloidogyne javanica* on tomato. International Journal of Application or Innovation in Engineering & Management. 2016;5(1):81-8.
59. Sabuquillo P, De Cal AD, Melgarejo P. Biocontrol of tomato wilt by Penicillium oxalicum formulations in different crop conditions. Biol Control. 2006;37(3):256-65.
60. Alam SS, Sakamoto K, Amemiya Y, Inubushi K. Biocontrol of soil-borne Fusarium wilts of tomato and cabbage with a root-colonizing fungus, Penicillium sp. EU0013. In: 19th World Congress of Soil Science, Soil Solutions for a Changing World. 2010;1-6.
61. Bontempo AF, Lopes EA, Fernandes RH, Freitas LGD, Dallemole-Giaretta R. Dose-response effect of Pochonia chlamydosporia against meloidogyne incognita on carrot under field conditions. Rev Caatinga. 2017;30(1):258-62.
62. Khan A, Tariq M, Asif M, Khan F, Ansari T, Siddiqui MA. Integrated management of meloidogyne incognita infecting Vigna radiata L. using biocontrol agent Purpureocillium lilacinum. Trends Appl Sci Res. 2019;14(2):119-24.
63. Kiriga AW, Haukeland S, Kariuki GM, Coyne DL, Beek NV. Effect of Trichoderma spp. and Purpureocillium lilacinum on meloidogyne javanica in commercial pineapple production in Kenya. Biol Control. 2018;119:27-32.
64. Jones EE, Rabeendran N, Stewart A. Biocontrol of Sclerotinia sclerotiorum infection of cabbage by Coniothyrium minitans and Trichoderma spp. Biocontrol Sci Technol. 2014;24(12):1363-82.
65. Geraldine AM, Lopes FAC, Carvalho DDC, Barbosa ET, Rodrigues AR, Brandão RS et al. Cell wall-degrading enzymes and parasitism of sclerotia are key factors on field biocontrol of white mold by

Trichoderma spp. Biol Control. 2013; 67(3):308-16.

66. Brunner K, Zeilinger S, Ciliento R, Woo SL, Lorito M, Kubicek CP et al. Improvement of the fungal biocontrol agent Trichoderma atroviride to enhance both antagonism and induction of plant systemic disease resistance. Appl Environ Microbiol. 2005;71(7):3959-65.
67. Khalili E, Sadravi M, Naeimi S, Khosravi V. Biological control of rice brown spot with native isolates of three Trichoderma species. Braz J Microbiol. 2012;43(1):297-305.
68. Zeng W, Kirk W, Hao J. Field management of Sclerotinia stem rot of soybean using biological control agents. Biol Control. 2012;60(2):141-7.
69. Gveroska B, Ziberoski J. The influence of Trichoderma harzianum on reducing root rot disease in tobacco seedlings caused by Rhizoctonia solani. Int J Pure Appl Sci Technol. 2011;2(2):1-11.
70. Tariq M, Khan A, Asif M, Khan F, Ansari T, Shariq M et al. Biological control: A sustainable and practical approach for plant disease management. Soil Plant Sci. 2020;70(6):507-24.
71. Konappa N, Krishnamurthy S, Siddaiah CN, Ramachandrappa NS, Chowdappa S. Evaluation of biological efficacy of Trichoderma asperellum against tomato bacterial wilt caused by Ralstonia solanacearum. Egypt J Biol Pest Control. 2018;28:1-11.
72. Tallapragada P, Gudimi M. Phosphate solubility and biocontrol activity of Trichoderma harzianum. Turk J Biol. 2011;35(5):593-600.
73. Mukhtar T, Jabbar A, Raja MU, Javed H. Management of root-knot nematode, meloidogyne incognita, in tomato with two Trichoderma species. Pak J Zool. 2018;50(4):1589-92.
74. Naserinasab F, Sahebani N, Etebarian HR. Biological control of meloidogyne javanica by Trichoderma harzianum BI and salicylic acid on tomato. Afr J Food Sci. 2011; 5(3):276-80.
75. Bokhari FM. Efficacy of some Trichoderma species in the control of Rotylenchulus reniformis and *Meloidogyne javanica*. Arch Phytopathol Plant Prot. 2009;42(4):361-9.
76. Zhang S, Gan Y, Ji W, Xu B, Hou B, Liu J. Mechanisms and characterization of Trichoderma longibrachiatum T6 in suppressing nematodes (*Heterodera avenae*) in wheat. Front Plant Sci. 2017;8:1491. doi: 10.3389/fpls.2017.01491, PMID 28966623.
77. Daragó Á, Szabó M, Hrács K, Takács A, Nagy PI. In vitro investigations on the biological control of Xiphinema index with Trichoderma species. Helminthologia. 2013;50(2):132-7.
78. Umamaheswari R, Somasekhar N, Manorama K, Joseph TA. Eco-friendly management of potato cyst nematodes in the Nilgiris of Tamil Nadu. Potato J. 2012;39(2).
79. Fiorentino M, Spillane SM, Beausoleil RG, Roberts TD, Battle P, Munro MW. Spontaneous parametric down-conversion in periodically poled KTP waveguides and bulk crystals. Optics express. 2007 Jun 11;15(12):7479-88.
80. Abdelkhalek A, Al-Askar AA, Arishi AA, Behiry SI. Trichoderma hamatum strain Th23 promotes tomato growth and induces systemic resistance against tobacco mosaic virus. J Fungi (Basel). 2022; 8(3):228.
81. Ahluwalia V, Kumar J, Rana VS, Sati OP, Walia S. Comparative evaluation of two Trichoderma harzianum strains for major secondary metabolite production and antifungal activity. Nat Prod Res. 2015;29(10):914-20.
82. Baazeem A, Almanea A, Manikandan P, Alorabi M, Vijayaraghavan P, Abdel-Hadi A. In vitro antibacterial, antifungal, nematocidal and growth promoting activities of Trichoderma hamatum FB10 and its secondary metabolites. J Fungi (Basel). 2021;7(5):331.
83. Chaverri P, Branco-Rocha F, Jaklitsch W, Gazis R, Degenkolb T, Samuels GJ. Systematics of the Trichoderma harzianum species complex and the re-identification of commercial biocontrol strains. Mycologia. 2015;107(3):558-90.
84. Chet I, Inbar J, Hadar Y. Fungal antagonists and mycoparasites. In: Wicklow DT, Soderstrom B, editors. The Mycota, environmental and microbial relationships. Vol. 4. Berlin, Germany: Springer-Verlag. 1997;165-84.
85. El Enshasy HA, Ambehabati KK, El Baz AF, Ramchuran S, Sayyed RZ, Amalin D et al. Trichoderma: biocontrol agents for promoting plant growth and soil health. Agriculturally important fungi for sustainable agriculture. Funct Annot Crop Prot. 2020;2:239-59.

86. Gava CAT, Pinto JM. Biocontrol of melon wilt caused by Fusarium oxysporum Schlect f. sp. melonis using seed treatment with *Trichoderma spp.* and liquid compost. Biol Control. 2016;97:13-20.
87. Hajek AE, Eilenberg J. Natural enemies: An introduction to biological control. Cambridge University Press; 2018.
88. Imran A, Arif M, Shah Z, Bari A. Soil application of Trichoderma and peach (*Prunus persica* L.) residues possesses biocontrol potential for weeds and enhances the growth and profitability of soybean (Glycine max). Sarhad J Agric. 2020;36(1):10-20.
89. Irshad MN, Anwar Z, But HI, Afroz A, Ikram N, Rashid U. The industrial applicability of purified cellulase complex indigenously produced by Trichoderma viride through solid-state bio-processing of agro-industrial and municipal paper wastes. BioResources. 2013;8(1):145-57.
90. Li N, Alfiky A, Wang W, Islam M, Nourollahi K, Liu X et al. Volatile compound-mediated recognition and inhibition between Trichoderma biocontrol agents and Fusarium oxysporum. Front Microbiol. 2018;9:2614.
91. Rivera-Méndez W, Obregón M, Morán-Diez ME, Hermosa R, Monte E. Trichoderma asperellum biocontrol activity and induction of systemic defenses against Sclerotium cepivorum in onion plants under tropical climate conditions. Biol Control. 2020;141:104145.
92. Napitupulu TP, Kanti A, Sudiana IM. Evaluation of the environmental factors modulating indole-3-acetic acid (IAA) production by Trichoderma harzianum InaCC. In IOP conference series: earth and environmental science. IOP Publishing; 2019;308(1):
93. Rey M, Delgado-Jarana J, Benítez T. Improved antifungal activity of a mutant of Trichoderma harzianum CECT 2413 which produces more extracellular proteins. Appl Microbiol Biotechnol. 2001;55(5):604-8.
94. Siddaiah CN, Satyanarayana NR, Mudili V, Kumar Gupta V, Gurunathan S, Rangappa S et al. Elicitation of resistance and associated defense responses in Trichoderma hamatum induced protection against pearl millet downy mildew pathogen. Sci Rep. 2017;7(1):43991.
95. Siemering G, Ruark M, Geven A. The value of Trichoderma for crop production. University of Wisconsin—extension, cooperative extension; 2016.
96. Silva RN, Monteiro VN, Steindorff AS, Gomes EV, Noronha EF, Ulhoa CJ. Trichoderma/pathogen/plant interaction in pre-harvest food security. Fungal Biol. 2019;123(8):565-83.

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