Journal of Animal & Plant Sciences, 34(2): 2024, Page: 304-317
ISSN (print): 1018-7081; ISSN (online): 2309-8694
https://doi.org/10.36899/JAPS.2024.2.0718
Review Article

HARNESSING *TRICHODERMA* SPP. FOR SUSTAINABLE PLANT DISEASE MANAGEMENT: MECHANISMS, METABOLITES AND APPLICATION STRATEGIES-A REVIEW

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ABSTRACT

Trichoderma spp. has emerged as a potent biological control agent (BCA) for managing plant diseases, offering sustainable and eco-friendly alternatives to chemical fungicides. This review explores the multifaceted roles of *Trichoderma* spp. in plant disease suppression, growth promotion, and induced systemic resistance. The success of *Trichoderma* spp. as a BCA lies in its diverse mechanisms of action, including mycoparasitism, competition, antibiosis, and induction of systemic resistance. Notably, *Trichoderma* spp. produce a range of volatile compounds that inhibit plant pathogens while promoting plant growth. Furthermore, their ability to solubilize nutrients, such as iron and phosphate, and produce phytohormones like auxins, contributes to enhanced plant vitality. Molecular characterization has facilitated the identification of various *Trichoderma* species with distinct biocontrol properties. Application methods, including seed treatment, soil application, and foliar spray, have been developed to optimize the efficacy of Trichoderma-based biocontrol strategies. Overall, *Trichoderma* spp. exhibited the multiple mode of actions against the pathogens and which used as a versatile and effective biocontrol agent for integrated disease management and sustainable agriculture

Keywords: *Trichoderma* spp., Biological control agent, Plant diseases, Disease suppression, Growth promotion, Sustainable agriculture

Published first online February 06, 2024 Published final March 31, 2024

INTRODUCTION

Biological control of plant diseases involves the reduction of plant pathogen populations through the use of living organisms (Heimpel and Mills, 2017). The effectiveness of biocontrol agents (BCAs) hinges on their robust reproductive capacity, ability to thrive in challenging conditions, efficient nutrient utilization, rhizosphere revitalization, competitive prowess against phytopathogenic fungi and capacity to enhance plant growth and defense mechanisms. Pal and Gardener (2006) highlighted the efficacy of selective biocontrol agents in reducing soil-borne pathogens. Unlike costly and environmentally hazardous chemical fungicides, the combined use of biocontrol agents and organic amendments proves effective in mitigating soil-borne diseases (Dukare *et al*., 2011).

Trichoderma sp., a fungal genus comprising around 100 recognized species, is globally distributed due to its rapid growth (Druzhinina *et al*., 2006). This species is a prominent biocontrol agent within the fungal realm, displaying versatility by multiplying in various substrates and enduring diverse contaminants and environmental conditions (Hu *et al*., 2020). Renowned for its ability to colonize plant roots and suppress a broad spectrum of plant pathogens, *Trichoderma* sp. generates multiple propagules like mycelium, conidia, and quiescent resting spores (Martin *et al*., 1999). *Trichoderma* sp. employs controlled chemotropic growth; upon contact, its hyphae envelop pathogen hyphae and initiate the secretion of cell wall proteases (chitinases, β1,3-glucanases). This degradation of the fungal cell wall forms pores through which Trichoderma accesses nutrients from its target (Silva *et al*., 2019). Sood *et al*. (2020) differentiated nine Trichoderma species based on conidiophore branching patterns and conidium morphology: *T. aureoviride*, *T. pseudokoningii*, *T. harzianum*, *T. koningii*, *T. longibrachiatum*, *T. piluliferum*, *T. viride*, *T. hamatum*, and *T. polysporum*. Commercially successful as biofungicides, their antagonistic attributes including rhizosphere competition, mycoparasitism, enzyme and antibiotic production, and induced resistance, underpin their effectiveness (Dehariya *et al*., 2015).

Role of *Trichoderma* spp.

Volatile Compound Production by *Trichoderma* spp.: Volatile organic compounds (VOCs) represent complex mixtures of low-molecular-weight substances that facilitate communication between plants, antagonists and mutualistic symbionts both below and above ground. *Trichoderma* spp. produces the volatile compound 6-pentyl-2H-pyran-2-one (6PP), which inhibits the growth of plant pathogens like *Fusarium oxysporum* (Rubio *et al*., 2009). This compound is responsible for the distinctive yellow coloration and coconut-like aroma observed in certain *Trichoderma* strains. Furthermore, even at low concentrations, 6PP exhibits the potential to enhance plant growth both above and below ground, along with stimulating seed germination and seedling development (Sood *et al*., 2020). These effects suggest its role as an auxin compound or an inducer of auxin production (Rubio *et al*., 2009). *T. harzianum* releases volatile compounds, including alkyl pyrenes which demonstrate suppressive effects against *S. cepivorum* (Fravel, 1988). Among these, *T. harzianum* stands out as a potent antagonist, effectively emitting volatile compounds to control *S. rolfsii*, followed by *T. hamatum* and *T. viride*. Through the release of these volatile compounds, the antagonists succeed in suppressing soil-dwelling pathogens.

Phytostimulation effects of *Trichoderma* spp.

Siderophore production: Trichoderma organisms release substances around root structures, enhancing the solubility of specific nutrients, thus facilitating their uptake by plants. One of these compounds, siderophores, plays a significant role in iron assimilation (López-Bucio *et al*., 2015). In an instance, a *T. asperellum* strain capable of producing siderophores augmented the availability of iron in sterilized soil, leading to improved nutrient absorption by cucumber plants (Zhao *et al*., 2014). This nutrient-boosting effect is attributed to the release of organic acids and iron-reducing enzymes which collaboratively convert insoluble iron (Fe (III)) to a soluble form (Fe (II)). Simultaneously, the synthesis of siderophores aids in enhancing the plant's ability to absorb iron, a process that inhibits the growth of plant pathogens by restricting their access to this essential element (López-Bucio *et al*., 2015). Notably, siderophores, being iron-chelating molecules, sequester insoluble iron and transform it into a soluble form, promoting its uptake by plants and curtailing the proliferation of plant pathogens through iron deprivation (Leong, 1986). This is achieved through the release of organic acids like lactic, citric, or tartaric acid as well as siderophores or iron-reducing agents (Li *et al*., 2015)

Phosphate solubilization and Ammonia generation: Antagonistic strains of Trichoderma exhibit the ability to convert unavailable phosphate in soil into an accessible form, even in soils contaminated with heavy metals (Rawat and Tewari, 2011). For instance, *T. harzianum* effectively enhanced the phosphorus and nutrient content of tomato seedlings resulting in improved stem girth, fruit yield, and fresh and dry weights (Azarmi *et al*., 2011). Upon interaction with Trichoderma, plants exhibited heightened expression of certain genes (López-Bucio *et al*., 2015). It has been discovered that certain strains of *T. harzianum* possess the capacity to solubilize various forms of phosphorus, such as phytate, Fe, copper, and zinc. Notably, field trials have shown that *Trichoderma* inoculation can reduce nitrogen supply by 30 to 50 percent without compromising crop yield (Shoresh *et al*., 2010). Many researchers evaluated the qualitative and quantitative ammonia production of *Trichoderma* sp. *Trichoderma* spp. exhibit a unique capability to produce ammonia through the enzymatic degradation of proteins and amino acids. These fungi secrete proteolytic enzymes that effectively break down complex nitrogen-containing compounds into simpler forms, including ammonia (NH_3) (Triveni *et al*., 2013). This ammonia production by *Trichoderma* holds significant implications in agriculture and biotechnology. Notably, it can exert a positive influence on plant growth. Ammonia serves as a vital source of nitrogen, an essential nutrient for plants. Trichoderma's ability to liberate ammonia from organic matter in the soil enhances the availability of nitrogen to plants. Consequently, these foster improved nutrient uptake and overall plant growth.

Indole-3-Acetic Acid (IAA) production: *Trichoderma virens* produces auxins like indole-3-acetic acid (IAA), indole-3-acetaldehyde (IAAld) and indole-3-ethanol (IEt), which contribute to plant enhancement and growth (Contreras-Cornejo *et al*., 2009). Research by Martínez-Medina *et al*. (2011) highlighted elevated levels of IAA and ACC deaminase in the aerial portions of *T. harzianum*-infected plants, underscoring the synergistic role of these hormones in stimulating growth. Furthermore, the application of *T. virens* or *T. atroviride* on Arabidopsis seedlings led to the synthesis of auxin-related substances like indole-3-acetic acid, indole-3-acetaldehyde, and indole-3-ethanol, resulting in enhanced biomass production (Contreras-Cornejo *et al*., 2014).

Mode of Action of *Trichoderma* spp.

Mycoparasitism and Competition: Pathogenic fungi release chemicals to attract antagonistic fungi, a phenomenon termed chemotropic growth, which is followed by the direct development of hyphae of the biocontrol agent towards the host during the initial interaction (Chet *et al*., 1981). In the process of antagonism, *Trichoderma* exhibits chemotropic growth, subsequently recognizing the host, coiling around it and forming appressoria on the target fungus. This is accompanied by the secretion of diverse hydrolytic enzymes, the penetration of hyphae and the disruption of the host's cellular machinery through the production of several enzymes that degrade cell walls, including glucanases, chitinases, and proteases (Harman and Petzoldt, 2004). An effective mechanism in *Trichoderma* as well as in a few other species like *Rhizoctonia solani* and *Fusarium oxysporum* strains involves competition for carbon sources (Sarrocco *et al*., 2009).

Antibiosis: *Trichoderma* spp. produce antibiotics that counter fungal phytopathogens, including gliovirin, gliotoxin, viridin, viridol, koninginins, pyrones, and peptaibols (Howell, 2003). Trichokonin VI, a peptaibol derived from *T. pseudokoningii* SMF2, exhibits antibacterial properties by inducing widespread apoptotic programmed cell death in fungal infections (Shi *et al*., 2012). *Trichoderma asperellum* produces two asperelines (A and E) and five trichotoxins (T5D2, T5E, T5F, T5G, 1717A), which are associated with antibiosis (Mukherjee *et al*., 2013). Harzianic acid obtained from *T. harzianum* strain exhibits *in-vitro* antibiotic activity against *Pythium irregulare*, *Sclerotinia sclerotiorum*, and *Rhizoctonia solani* (Vinale *et al*., 2009). *Trichoderma* strains are capable of producing both volatile and non-volatile antibiotics including 43 active antibiotic compounds (such as alkyl pyrones, isonitriles, polyketides, peptaibols, diketopiperazines, sesquiterpenes, and steroids), as well as a variety of enzymes like esterase, chitinase, and cellulase (Sivasithamparam and Ghisalberti, 1998). Antibiotics produced by *Trichoderma* spp., including gliotoxin, viridin, gliovirin, koninginins, pyrones, and viridol are effective against a wide range of fungal phytopathogens, such as *Rhizoctonia* sp., *Pythium*, and *S. rolfsii* (Harman and Petzoldt, 2004).

Induced Systemic Resistance (ISR): The colonization and penetration of plant root tissues lead to a series of morphological and biochemical changes in *Trichoderma* -treated plants, ultimately resulting in induced systemic resistance (ISR) within the treated plant (De Meyer *et al*., 1998). Trichoderma species can colonize various plant organs and produce chemicals that stimulate plant growth, inducing significant alterations in plant metabolism (Harman, Howell, *et al*., 2004). The *Trichoderma harzianum* species generate resistance inducers, xylanase, and other elicitors which are believed to play a significant role in biological control (Anderson *et al*., 1993). *Trichoderma* strains establish their presence within plant roots before inducing plant growth and defense mechanisms against diseases (Harman, 2006). The decrease in late blight incidence was positively correlated with an increase in the levels of defense-related enzymes such as phenylalanine ammonia lyase, peroxidase, polyphenol oxidase and β-1,3 glucanase in tomato seedlings treated with a microbial consortium of *T. harzianum* and *B. subtilis*, followed by a foliar spray of *Pseudomonas putida* (Mohankumar *et al*., 2015).

Growth Enhancement by *Trichoderma* sp.: Utilizing the roll towel method, cucumber seeds treated with the T-203 strain of *T. harzianum* within a hydroponic setup exhibited a remarkable 95 percent increase in root area and a 75 percent extension in root length. Consequently, there was a notable 25 percent augmentation in total plant biomass in terms of dry weight, as compared to cucumber plants that were not inoculated (Yedidia *et al*., 2001). *Trichoderma* spp. engage in a symbiotic relationship with plants, contributing to the production of auxins, which serve as plant growth regulators responsible for enhancing both flowering and root development (Gravel *et al*., 2007). When subjected to seed treatments using formulated *Trichoderma* isolates namely CRRIT-1, CRRIT-3, CRRIT-5, CRRIT-9, and CRRIT-13, among these, *Trichoderma erinaceum* (CRRIT-2) emerged as a significant enhancer of growth indices, influencing parameters such as root dry weight, shoot dry weight, root fresh weight, shoot fresh weight, leaf count, plant height, root length, shoot length, and tiller count (Swain *et al*., 2018).

Secondary Metabolites produced by *Trichoderma* sp.: Zhang *et al*. (2014) discovered that various phenolic compounds and auxiliary metabolites containing phytohormones, recognized as specific auxins are released by fungi, potentially contributing to improved seedling vigor. Likewise, several secondary metabolites produced by *Trichoderma* have been shown to impact plant growth, including koninginins, 6-pentyl-α-pyrone, trichocaranes A–D, harzianopyridone, cyclonerodiol, harzianolide, and harzianic acid, as exemplified by their effects (Vinale *et al*., 2014).

Molecular Characterization of *Trichoderma* spp.: In the study conducted by Maymon *et al*. (2004), molecular methodologies were employed to identify various biocontrol properties among *Trichoderma* isolates, leading to their classification into three primary clades through sequence analysis. Consequently, a valid phylogenetic tree encompassing isolates from the *T. harziunum* clade was constructed. Thilagavathi *et al*. (2012) collected 20 isolates of *Trichoderma* species from rhizosphere soils associated with diverse host plants in

Tamil Nadu, India. The highly effective TTH1 isolate underwent molecular characterization utilizing ITS1 to ITS2 PCR amplification. The resultant amplified product was sequenced and subsequently compared with nucleotide sequences present in the GenBank database. A UPGMA tree was constructed using CULSTAL X 1.81 for similarity assessment, ultimately leading to the identification of *T. asperellum*. By analyzing the ITS region of rRNA sequences, *Trichoderma* species were identified, confirming the species-level variations of *T. reesi*, *T. harzianum*, and *T. asperellum* (Asis and Siddiquee, 2016).

Delivery systems of *Trichoderma* sp.: The application methods for *Trichoderma* antagonists are based on the survival of pathogen resting structures and the mechanisms of pathogen infection. Examples of application methods include seed treatment (Peer and Schippers, 1989), soil application (Nandakumar *et al*., 2001), seedling root dip and foliar application (Rosales and Mew, 1997).

Improving seed quality attributes through Seed Treatment: Radish and pea seeds treated with *T. hamatum* effectively controlled *Sclerotium rolfsii* and *Pythium* spp., leading to improved seedling emergence and enhanced characteristics such as seedling length, seedling root length, leaf count and seedling fresh weight in onion seeds treated with *T. harzianum* (Harman *et al*., 1980; Dabiré *et al*., 2016). Employing seed biopriming and *Trichoderma* spp. seed treatment accelerated germination and seedling vigor by triggering the release of phytohormones in various plants like okra, maize, beans, mustard, chilli, soybean, chickpea and tomato, thereby augmenting germination percentage (Babychan and Simon, 2017). *Trichoderma* spp. treatment of tomato seeds not only increased seed germination percentage through enzyme and phytohormone activation but also indirectly influenced soil microflora, nutrient availability and growth promotion, subsequently reducing *S. rolfsii* incidence (Tsahouridou and Thanassoulopoulos, 2001). Rajput *et al*. (2020) demonstrated that biopriming tomato seeds with four *Trichoderma* strains, specifically *T. pseudokonigii* BHUR2, *T. harzianum* BHUP4, *T. asperellum BHUV2*/ and *T. longibrachiatum* BHUR5, effectively prevented *S. rolfsii* infection and enhanced antioxidative enzyme activity on 25 days after sowing (DAS).

Improving seed quality attributes through Soil Application: *T. viride* and *T. harzianum* seed and soil treatments exhibited notable efficacy in reducing mortality rates of groundnut and cotton seedlings due to disease (Kulkarni and Kulkarni, 1994). In beans, *T. harzianum* combined with wheat bran rapidly colonized soil, resulting in reduced infestations of *R. solani* and *S. rolfsii* (Elad *et al*., 1980). *T. viride* and *T. harzianum* were effective in mitigating onion white rot caused by *S. rolfsii* when incorporated as a soil additive along with 0.1 percent wheat bran/gram of dry soil (Kay and Stewart, 1994). Srivastava *et al*. (2010) found that applying *T. asperellum* to the soil at 7, 15, and 30 DAS significantly reduced seedling blight, collar rot, stem rot, and root rot diseases in jute, yielding the lowest disease incidence. A talc-formulated *T. asperellum* applied to soil efficiently reduced carnation wilt, leading to improved plant growth, increased shoot count, stalk length, and flower production (Vinodkumar *et al*., 2017). When introduced into conventional soil cultivation, *Trichoderma* spp. elevated secondary metabolism in root systems acting as a chemical defense against pathogens, enhancing plant biomass, disease control and rooting systems (López-Bucio *et al*., 2015).

Combination of Delivery Systems: Jeyalakshmi *et al*. (2013) highlighted a combined approach involving neem cake soil application (250 kg/ha) and *T. viride* seed treatment and soil application (2.5 kg/ha), followed by azadirachtin foliar spray @ 3 ml/liter of water on 30 and 45 DAS. This strategy resulted in minimal *S. rolfsii* disease incidence and maximum sesame seed yield. Vasumathi *et al*. (2017) identified an effective combination comprising powdered formulations of *T. virens* (TRI 37), *T. harzianum* (TRI 35 and TRI 36) and *T. asperellum* (TRI 9) with talc, applied at 10^8 cfu/g for seed sensitization (10g/kg seed) and soil application (2.5 kg/ha) achieving a substantial 76.82% reduction in cucumber damping-off caused by *Pythium aphanidermatum* compared to the control group.

Formulation of Biocontrol Agents: To effectively combat plant diseases, various formulations of biocontrol agents have been employed. The use of large quantities of cell suspensions for biocontrol agent application is impractical due to storage, transportation and handling constraints. Consequently, researchers have developed powdered formulations of biocontrol agents with extended shelf lives. Tewari *et al*. (2012) investigated diverse delivery strategies for *T. harzianum* and determined that a combination of soil treatment, root dip and foliar spray significantly reduced sheath blight disease severity in rice (29.07%) compared to the control. *Gliocladium virens* formulations were tested against chickpea wilt complex induced by *S. rolfsii* by Tewari and Mukhopadhyay (2001), demonstrating that these formulations remained viable for up to three months when refrigerated at 5°C, with the *G. virens* and carboxymethyl cellulose mixture showing the longest spore lifespan. Jayaraj *et al*. (2006) developed multiple formulations of *T. harzianum* for seed treatment against soilborne diseases including talc, lignite, lignite + fly ash-based powder, wettable powder, bentonite paste, polyethylene glycol-paste and gelatin-glycerin-gel.

***Trichoderma* sp. against fungal, nematode viral and bacterial plant diseases:** *Trichoderma* species have proven to be invaluable assets in the realm of plant disease management due to their multifaceted roles in combating various plant pathogens (Fig. 1). Their mycoparasitic abilities demonstrated by actively parasitizing and disrupting the growth of fungal pathogens have been well-documented (Harman *et al.*, 2004). Additionally, *Trichoderma* species exhibit competition with pathogenic organisms, both fungi and bacteria for essential nutrients and space, reducing the resources available to the pathogens (Lorito *et al.*, 2010). Furthermore, they contribute to disease suppression through the production of antimicrobial metabolites and lytic enzymes (Vinale *et al.*, 2008). *Trichoderma* also plays a pivotal role in nematode management either through direct parasitism or by inducing systemic resistance in plants against nematodes (Mukherjee *et al.*, 2013). However, it's important to note that *Trichoderma* spp. are not typically employed for direct viral disease management but rather excel in controlling fungal and nematode pathogens (Harman *et al.*, 2004).

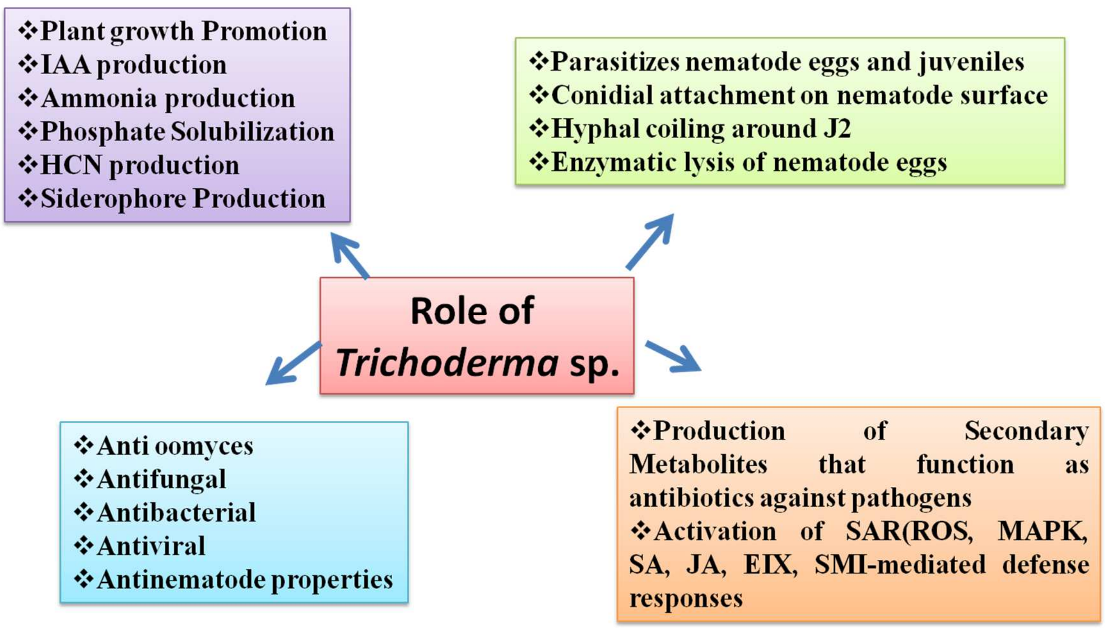

Fig .1: Multifaceted role of *Trichoderma* sp.

***Trichoderma* spp. vs. Plant fungal Pathogens:** Padmaja *et al*. (2013) assessed the impact of 10 native *Trichoderma* isolates and a commercial formulation on *S. rolfsii*-induced groundnut stem rot. Among these isolates, two exhibited superior growth inhibition of 80% to 70%. Madhavi and Bhattiprolu (2011) evaluated five biocontrol agents and found that *T. harzianum* displayed the highest mycelial inhibition (57.5%) against *S. rolfsii,* surpassing *T. viride* I (55.8%), *T. viride* II (53.63%), and *T. hamatum* (44.46%). Ramamoorthy *et al*. (2000) observed that *T. harzianum* application was particularly effective in controlling *S. rolfsii* wilt in jasmine, reducing disease incidence to 21.8% and 25% on 60 and 120 days after planting (DAP) respectively followed by *T. viride*, which achieved 83% and 92.19% disease reduction on 60 and 120 DAP respectively. Suryawanshi *et al*. (2015) found that *T. viride*, *T. harzianum*, *T. hamatum* and *T. virens* suppressed *S. rolfsii* growth by 87.85%, 85.22%, 79.88%, and 82.33%, respectively. Banakar Sahana *et al*. (2017) tested five bioagents and observed the highest inhibition in *Trichoderma virens* (67%) on 4 days after inoculation (DAI), while *T. harzianum* and *T. viride* exhibited 44% and 61% inhibition respectively. On 8 DAI, *T. virens* achieved the greatest inhibition (70%), followed by *T. viride* (63%). Upamanya and Dutta (2019) assessed six indigenous biocontrol agents against soil-borne diseases and found that *T. harzianum* inhibited the mycelial growth of *R. solani* and *S. sclerotiorum* by 74.44% and 69.15%, respectively. Additionally, three T. viride isolates and *Pseudomonas fluorescens* effectively inhibited *S. rolfsii* mycelial growth, with TV1 achieving 69.4% inhibition and *Pseudomonas fluorescens* achieving 64.40% inhibition (Karthikeyan *et al*., 2006). The different genus of *Trichoderma* sp. characteristics and their specific metabolite production, commercially available product and *Trichoderma* sp. against the specific diseases are shown in Table 1 and Table 2.

Table 1. Different genus of *Trichoderma* species characteristics, specific role, metabolites production and against the specific diseases.

S. No	***Trichoderma* Species**	**Morphology**	**Characteristics**	**Metabolites Produced**	**Specific Diseases**	**References**
1	*Trichoderma harzianum*	White to green mycelium	Common biocontrol agent; saprophytic	Trichodermin, Trichodermin derivatives, Cellulases	Various plant pathogens	Harman *et al*., 1998 Lorito *et al*., 1998 Vinale *et al*., 2008
2	*Trichoderma viride*	Green mycelium	Green mold fungus; versatile	Viridin, Viridiol, Volatile Organic Compounds	*Botrytis*, *Sclerotinia*,	Howell *et al*., 2003 Druzhinina *et al*., 2011 Vinale *et al*., 2008
3	*Trichoderma reesei*	Green mycelium	Cellulolytic fungus; industrial	Cellulases, Xylanases, β-glucosidases	Various plant pathogens	Paloheimo *et al*., 2018 Teeri *et al*., 2003 Foreman *et al*., 2003
3	*Trichoderma atroviride*	Green mycelium	Mycoparasite; plant protector	Atroviridin, Trichodermin, Chitinases	*Botrytis*, *Rhizoctonia*,	Mukherjee *et al*., 2013 Djonovic *et al*., 2006
4	*Trichoderma virens*	Green mycelium	Rhizosphere colonizer; plant symbiont	Viridiol, Volatile Organic Compounds	*Rhizoctonia solani*	Vinale *et al*., 2006 Harman *et al*., 1998 Su *et al*., 2016
5	*Trichoderma koningii*	White mycelium	Mycoparasite; cellulolytic	Koningsins, Chitinases, Glucanases	Various fungal plan	Seidl *et al*., 2010 Druzhinina *et al*., 2011 Sing *et al*., 2010
6	*Trichoderma hamatum*	White mycelium	Soilborne; biocontrol and root colonizer	Hamatins, Cellulases, β-1,3-glucanases	*Rhizoctonia*, *Pythium*	Chet *et al*., 1980 Cai *et al*., 2009
7	*Trichoderma longibrachiatum*	White mycelium	Saprophytic; cellulolytic	Longibrachins, Chitinases, Glucanases	Various plant pathogens	Migheli *et al*., 2008 Elad *et al*., 2004
8	*Trichoderma asperellum*	White mycelium	Plant growth-promoting; mycoparasite	Asperellic acid, Indole-3-acetic acid, Chitinases	Various plant pathogens	López-Bucio *et al*., 2015
9	*Trichoderma koningiopsis*	White mycelium	Biological control agent; mycoparasite	Koninginins, Chitinases, Glucanases	Various plant pathogens	Mathys *et al*., 2019 Woo *et al*., 2006 Grondona *et al*., 1997

Table 2. Commercially available some important *Trichoderma* sp.

S. No	Commercial Product name	*Trichoderma* species	Target disease	Manufacturer or distributor
1	Root Pro	*T. harzianum*	Root rot	Efal Agri, Israel
2	Biospark Trichoderma	*T. pseudokoningii*	Wilt	Biospark Corporation, Phillipines
3	GlioGard and SoilGard	*T. virens*	Root rot	Grace-Sierra Co. Maryland
4	Tricho-X	*T. viride*	Root rot	Excel Industries Ltd.,, India
5	Plant helper	*T. atroviride*	Root rot	Ampac, California
6	Ecoderma	*T. viride + T. harzianum R*	Root rot and wilt	Morgo Biocontrol Pvt. Ltd., India
7	Trichodowe	*T. harzianum + T. viride*	Wilt	Agrimm, Technologies Ltd., New Zealand

T. koningii MTCC 796 and *T. harzianum* T12 have demonstrated their ability to parasitize the mycelia of *Macrophomina phaseolina* while also increasing the activities of Cell Wall-Degrading Enzymes (CWDEs) (Gajera *et al*. 2012; Khalili *et al*. 2016). Saravanakumar *et al*. (2016) discovered that the *T. asperellum* CCTCC-RW0014 strain displayed mycoparasitic activity against *F. oxysporum* f. sp. *cucumerinum* by producing various CWDEs like chitinase, cellulase, protease and β (1–3) glucanase. The growth of *F. solani* was impeded when *T. hamatum* URM 6656 was applied, likely due to the production of chitinase enzymes (da Silva *et al*. 2016). In the case of *T. harzianum* species (THSC), it attacked the fungal pathogen *Ceratocystis radicicola* of date palm, leading to the lysis of hyphal and phialoconidia structures (Al-Naemi *et al*. 2016). de Lima *et al*. (2016) reported that *T. atroviride* T17 exhibited strong antagonistic activity against *Guignardia citricarpa* in citriculture, attributed to the secretion of proteins, including chitinase, mutanase, α-1,3-glucanase, α-1,2-mannosidase, carboxylic hydrolase ester, carbohydrate-binding module family 13, glucan 1,3-β-glucosidase, α-galactosidase, and neutral protease.

***Trichoderma* sp. against plant parasitic nematode:** Scientists are showing an increasing interest in utilizing *Trichoderma* species as biological agents to control phytoparasitic nematodes, particularly root-knot nematodes (*Meloidogyne* spp.). *Trichoderma* has exhibited its potential in managing *M. javanica* and *M. incognita* across different crops and experimental conditions (El-Nagdi *et al*., 2019; Medeiros *et al*., 2017). Various components of *Trichoderma* including its fungal spores, hyphae and metabolites have proven effective against root-knot nematodes (Al-Hazmi and Tariq Javeed, 2016). Specifically, *T. harzianum* (T-79) has been observed to enhance the plant's defense mechanisms and inhibit the growth and reproduction of nematodes in tomato plants (Martinez-Medina *et al*., 2017).
The *T. longibrachiatum* has also demonstrated its ability to combat *Heterodera avenae* by directly affecting nematode eggs and J2 activities (Zhang *et al*., 2017). Khan *et al*. (2020) reported that *Trichoderma* spp., such as *T. viridae* and *T. pseudoharzianum* (T113), inhibited egg hatching and cause mortality in *M. incognita* J2s, through secondary metabolites (SMs) production. Recent research has also indicated that *T. harzianum* T22 and *T. asperellum* T-34 strains can induce resistance in tomato plants against *M. incognita*, although this effect was not observed in cucumbers. Furthermore, the identification of the Mi-1.2 gene has revealed its role in enhancing resistance in tomatoes against virulent root-knot nematodes, underscoring the potential of new *Trichoderma strains* in bolstering plant resistance (Pocurull *et al*., 2020). Overall, *Trichoderma* species and their metabolites present promising prospects for the biological control of phytopathogenic nematodes and other parasitic organisms (Li *et al*., 2019).

***Trichoderma* sp. against plant viruses:** Plant viruses are a widespread menace to plants, posing significant challenges to sustainable agriculture. Some of these viruses rely on various vectors including nematodes, insects, and fungi, for their transmission. Effective strategies to curb virus dissemination encompass Integrated Pest Management (IPM), enhancing host resistance and promoting plant growth. *Trichoderma,* a beneficial fungus has proven its ability to trigger plant defense mechanisms and bolster resistance, including Induced Systemic Resistance (ISR) and Systemic Acquired Resistance (SAR). This is achieved through the production of secondary metabolites, culture filters, and enzymes known as Cell Wall-Degrading Enzymes (CWDEs) (Luo *et al*. 2010). For example, Trichokonin, a type of antimicrobial peptaibols derived from *T. pseudokoningii* SMF2, has demonstrated its capacity to induce ISR and defense responses against the tobacco mosaic virus in tobacco plants (*Nicotiana tabacum* var. *Samsun* NN). Application of Trichokonin resulted in heightened levels of reactive oxygen species (ROS) and phenolic compounds in tobacco, increased the activities of pathogenesis-related enzymes such as PAL and POD and triggered the upregulation of various plant defense genes (Luo *et al*. 2010).

In a different study, *T. asperellum* SKT-1 was found to induce resistance in Arabidopsis plants against the cucumber mosaic virus (CMV). This induction was achieved by boosting the expression of genes that respond to salicylic acid (SA) and jasmonic acid/ethylene (JA/ET) in leaves. Moreover, pretreating Arabidopsis roots with the culture filter of *T. asperellum* SKT-1 activated defense mechanisms against CMV (Elsharkawy *et al*. 2013). Additionally, *T. harzianum* T-22 (T22) was shown to prompt defense responses in tomato plants against CMV. This was evidenced by an increase in hydrogen peroxide and superoxide anion levels, implying the involvement of reactive oxygen species (ROS) in plant defense (Vitti *et al*. 2015).

***Trichoderma* sp. against plant bacterial diseases:** Plant bacteria can inhabit various plant parts and serve important roles, but some strains can be harmful pathogens causing diseases. Control methods include using disease-free seeds, preventing bacterial transmission, sterilizing tools, employing chemical, physical, and biological controls. Among these, chemical methods are most effective, followed by plant breeding and biological approaches, which are more environmentally friendly. For example, *T. asperellum* T203 has demonstrated its ability to induce systemic resistance against the cucumber leaf pathogen *Pseudomonas syringae* pv. *lachrymans* by engaging the JA/ET signaling pathways associated with Induced Systemic Resistance (ISR) in cucumber plants. Meanwhile, *T. pseudokoningii* SMF2 has exhibited antimicrobial properties against a wide spectrum of bacteria, encompassing both Gram-positive and Gram-negative types. This strain has effectively managed *Pectobacterium carotovorum* sub sp. *carotovorum* (Pcc), responsible for causing soft rot disease in Chinese cabbage. The production of Trichokonins by this strain inhibited Pcc growth and induced resistance in cabbage plants, resulting in an increased production of reactive oxygen species (ROS), the activation of pathogenesis-related protein gene acidic PR-1a, and the induction of salicylic acid (SA)-mediated defense responses (Li *et al*., 2014).

Management of Groundnut Stem Rot by Biocontrol Agents in Pot Culture and Field Conditions: In both pot culture and field settings, antagonistic microorganisms have been employed to manage groundnut stem rot (Karthikeyan *et al*., 2006; Ganesan *et al*., 2007). Employing diverse biocontrol agents with multiple control mechanisms aligns well with integrated disease management strategies, which involve employing multiple disease suppression methods concurrently. Sharma *et al*. (2012) investigated the biological control of groundnut root rot and found that treating groundnut crops with *T. harzianum* (Th3) resulted in the lowest root rot incidence compared to control plots. Thangavelu and Gopi (2015) reported that combining two *Trichoderma* spp., namely rhizospheric *Trichoderma* sp. NRCB3 and endophytic *T. asperellum* Prr2, led to 100% reduction in fusarium wilt disease in banana and a substantial 250% increase in plant growth parameters compared to individual isolate application in pot and field conditions. This indicates that the combined application of two *Trichoderma* spp. with multiple functions effectively suppresses stem rot incidence while significantly enhancing plant growth promotion and pod yield parameters.

Conclusion: *Trichoderma* spp. emerges as a versatile biocontrol agent, showcasing its prowess in disease management and plant growth promotion. Its multifaceted mechanisms, including mycoparasitism, volatile compound production and nutrient solubilization offer a holistic approach to sustainable agriculture. Through tailored application and molecular characterization, *Trichoderma* spp. integrates seamlessly into disease management strategies. As we harness the multifaceted mode of actions of *Trichoderma* sp., we move towards resilient agriculture reducing chemical dependency and fostering environmental balance. While challenges remain, the promise of *Trichoderma* spp. as a cornerstone of integrated pest management is evident, promising greener, healthier crops and a more sustainable future.

Acknowledgements: The authors acknowledge the Department of Plant Pathology and Centre of Excellence for Innovations, Department of Biotechnology, Agricultural College & Research Institute, Madurai, Tamil Nadu Agricultural University, Tamil Nadu, India

Conflict of Interest: Authors state that there is no conflict of interest.

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