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


1Department of Plant Pathology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai – 625 104, Tamil Nadu, India
2Department of Plant Pathology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Killikulam – 628 252, Tamil Nadu, India
3Horticulture Research Station (TNAU), Thadiyankudisai, Dindugal-624 212, Tamil Nadu, India
4Department of Plant Breeding and Genetics, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai – 625 104, Tamil Nadu, India
5Department of Crop Physiology & Biochemistry, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Killikulam – 628 252, Tamil Nadu, India
*Corresponding author’s E-mail: ayyanduraipatho9793@gmail.com

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

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

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 include 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* spp. *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 (NH₃) (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 antibiotic (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, isonitiriles, polyeptides, 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 spp.:** 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-a-pyrene, 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. harzianum* 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 t alc, applied at 10⁸ cfu/g for seed sensitzation (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 t alc, 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.](image)

**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.

<table>
<thead>
<tr>
<th>S. No</th>
<th><em>Trichoderma</em> Species</th>
<th>Morphology</th>
<th>Characteristics</th>
<th>Metabolites Produced</th>
<th>Specific Diseases</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><em>Trichoderma harzianum</em></td>
<td>White to green mycelium</td>
<td>Common biocontrol agent; saprophytic</td>
<td>Trichodermin, Trichodermin derivatives, Cellulases</td>
<td>Various plant pathogens</td>
<td>Harman et al., 1998 Lorito et al., 1998 Vinale et al., 2008</td>
</tr>
<tr>
<td>2</td>
<td><em>Trichoderma viride</em></td>
<td>Green mycelium</td>
<td>Green mold fungus; versatile fungicide</td>
<td>Viridin, Viridiol, Volatile Organic Compounds</td>
<td>Botrytis, Sclerotinia,</td>
<td>Howell et al., 2003 Druzhinina et al., 2011 Vinale et al., 2008</td>
</tr>
<tr>
<td>3</td>
<td><em>Trichoderma reesei</em></td>
<td>Green mycelium</td>
<td>Cellulolytic fungus; industrial</td>
<td>Cellulases, Xylanases, β-glucosidases</td>
<td>Various plant pathogens</td>
<td>Paloheimo et al., 2018 Teeri et al., 2003 Foreman et al., 2003</td>
</tr>
<tr>
<td>4</td>
<td><em>Trichoderma atroviride</em></td>
<td>Green mycelium</td>
<td>Mycoparasite; plant protector</td>
<td>Atroviridin, Trichodermin, Chitinases</td>
<td>Botrytis, Rhizoctonia,</td>
<td>Mukherjee et al., 2013 Djonovic et al., 2006</td>
</tr>
<tr>
<td>5</td>
<td><em>Trichoderma virens</em></td>
<td>Green mycelium</td>
<td>Rhizosphere colonizer; plant symbiont</td>
<td>Viridiol, Volatile Organic Compounds</td>
<td>Rhizoctonia solani</td>
<td>Vinale et al., 2006 Harman et al., 1998 Su et al., 2016</td>
</tr>
<tr>
<td>6</td>
<td><em>Trichoderma koningii</em></td>
<td>White mycelium</td>
<td>Mycoparasite; cellulolytic</td>
<td>Koningsins, Chitinases, Glucanases</td>
<td>Various fungal plan</td>
<td>Seidl et al., 2010 Druzhinina et al., 2011 Sing et al., 2010 Chet et al., 1980 Cai et al., 2009</td>
</tr>
<tr>
<td>7</td>
<td><em>Trichoderma hamatum</em></td>
<td>White mycelium</td>
<td>Soilborne; biocontrol and root colonizer</td>
<td>Hamatins, Cellulases, β-1,3-glucanases</td>
<td>Rhizoctonia, Pythium</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><em>Trichoderma longibrachiatum</em></td>
<td>White mycelium</td>
<td>Saprophytic; cellulolytic</td>
<td>Longibrachins, Chitinases, Glucanases</td>
<td>Various plant pathogens</td>
<td>Migheli et al., 2008 Elad et al., 2004</td>
</tr>
<tr>
<td>9</td>
<td><em>Trichoderma asperellum</em></td>
<td>White mycelium</td>
<td>Plant growth-promoting; mycoparasite</td>
<td>Asperellic acid, Indole-3-acetic acid, Chitinases</td>
<td>Various plant pathogens</td>
<td>López-Bucio et al., 2015</td>
</tr>
<tr>
<td>10</td>
<td><em>Trichoderma koningiopsis</em></td>
<td>White mycelium</td>
<td>Biological control agent; mycoparasite</td>
<td>Koninginins, Chitinases, Glucanases</td>
<td>Various plant pathogens</td>
<td>Mathys et al., 2019 Woo et al., 2006 Grondona et al., 1997</td>
</tr>
</tbody>
</table>
been observed to enhance the plant’s defense mechanisms against plant-parasitic nematodes, particularly root-knot nematode eggs and J2 activities (Zhang et al., 2019). 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 Heteroderda 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).

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

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

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 Gignardia citricarpa in citiculture, 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 Heteroderda 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 SM2F, 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 (Karthiskeyan 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.

**REFERENCES**


Harman, and Petzoldt (2004). Interactions between *Trichoderma harzianum* strain T22 and maize inbred line Mo17 and effects of these interactions on diseases caused by *Pythium ultimum* and *Colletotrichum graminicola*. Phytopathology. 94 (2):147-153. DOI: https://doi.org/10.1094/PHYTO.2004.94.2.147.


Migheli, Q., & Balmas, V (2008). The green mould disease of citrus: a challenge for research and
Ayyandurai et al.,  J. Anim. Plant Sci., 34 (2) 2024


Tewari, Lakshmi, Singh, and Rajbir (2012). Biological control of sheath blight of rice by Trichoderma harzianum using different delivery systems. Indian Phytopathology.


Vinodkumar, S., T. Indumathi, and S. Nakkeeran (2017). Trichoderma asperellum (NVTA2) as a potential antagonist for the management of stem rot in...


Zhao, L., F. Wang, Y. Zhang, and J. Zhang (2014). Involvement of *Trichoderma asperellum* strain T6 in regulating iron acquisition in plants. J. Basic Microbial. 54 (S1): S115-S124. DOI: https://doi.org/10.1002/jobm.201400148.