

Review

Bio-Exploration of Plant Growth-Promoting Fungus *Trichoderma* as a Potent Candidate for Plant Disease Management: An Overview

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Abstract: Chemical pesticides are widely used to control plant diseases, but their widespread use can have a detrimental impact on the environment and human health. This has led researchers and growers to seek out alternative solutions. One promising approach is the use of the Plant Growth-Promoting Fungus (PGPF) *Trichoderma* spp. as a biological control agent. This method is effective, cost-efficient, and sustainable, reducing the incidence and severity of plant diseases while enhancing crop production. *Trichoderma* works in several ways to combat pathogens, including through mycoparasitism, antibiosis, competition, plant growth promotion, and stimulation of pathogen defenses. Various formulations of *Trichoderma* have shown potential as bio-fungicides and plant growth stimulants. Additionally, secondary metabolites from *Trichoderma* spp. have been found to have potent antimicrobial properties against various phytopathogens. This chapter provides an overview of the potential and mechanisms of action of *Trichoderma* in controlling plant diseases. It is intended to be a helpful resource for those seeking an alternative to chemical fungicides for managing plant diseases.

Keywords: *Trichoderma*, Plant Growth Promotion, Disease Suppression, Mechanisms, Metabolites and Formulation

Introduction

Plant diseases have a devastating impact on agriculture and society, leading to significant economic losses for farmers and agricultural industries (Sultana and Hossain, 2022). Crop losses reduce yields, threatening food security, causing shortages, and raising food prices. This limits access to essential nutrients, leading to malnutrition and hunger. Communities reliant on agriculture suffer social disruption, affecting livelihoods, employment, and food access. Historically, plant diseases have caused immense human suffering, including loss of livelihoods, poverty, hunger, displacement, and death. Notable examples include the Irish potato famine of the 19th century, which resulted in over two million deaths and mass emigration, the Bengal famine of 1943, and the wheat blast outbreaks in Bangladesh in 2016 (Agrios, 2005; Islam *et al.*, 2016; Savary *et al.*, 2020; Hossain, 2022a).

Effective plant disease management is crucial to reducing crop losses. Methods to prevent infection by plant pathogens include cultural, chemical, physical, and

biological approaches. Chemical methods are effective but costly, harmful to human health and the environment, and can lead to pesticide resistance. Additionally, they negatively impact beneficial soil microbes, increasing the host's susceptibility to plant pathogens (Heydari and Pessarakli, 2010). Therefore, researchers and growers are exploring non-chemical alternatives for plant disease management, such as using microbial agents in biological control to target specific pathogens (Hossain and Sultana, 2020; Hossain 2022b; Sultana and Hossain, 2022). *Trichoderma* is a Plant Growth-Promoting Fungus (PGPF) that stimulates plant growth and is one of the most widely used biocontrol fungal agents for treating a wide range of plant diseases (Fig. 1). Researchers have demonstrated that *Trichoderma* displays antagonistic activity against pathogens that are transmitted through seeds and soil (Arefin *et al.*, 2019; Begum *et al.*, 2010; Das *et al.*, 2019; Rahman *et al.*, 2020a-b; 2021; Rubayet and Bhuiyan, 2016; 2023; Bhuiyan and Rubayet, 2023; Hasan *et al.*, 2023; Rahman *et al.*, 2024). Inoculating seeds or seed materials and soil with *Trichoderma* has

shown the potential to manage the disease and boost crop productivity (Halifu *et al.*, 2019; Hossain and Sultana, 2024). Many studies indicate that *Trichoderma* can induce local and systemic resistance to pathogens (Hossain *et al.*, 2017). Employing *Trichoderma* for biological control is promoted as an environmentally friendly, cost-effective, and sustainable plant disease management strategy. This approach is feasible for managing diseases where other control methods are lacking or for products requiring organic certification without pesticide residues.

Researchers worldwide have screened *Trichoderma* strains for disease control efficacy, gaining insights into their mechanisms of action. Numerous formulations have been developed and field-tested to enhance the fungus's applicability (Mbarga *et al.*, 2012). This review consolidates current knowledge on the crucial role and mechanisms of *Trichoderma* in plant disease control, focusing on field application formulations.

Plant Growth-Promoting Fungus (PGPF)

PGPF stands for Plant Growth-Promoting Fungi, which is a broad group of nonpathogenic fungi found in the rhizosphere that create a mutually beneficial connection with host roots, hence increasing plant growth (Hossain *et al.*, 2008; Hossain and Sultana, 2020). This group of fungi plays a crucial role in the rhizosphere ecosystem without causing detrimental effects. Reported effects of PGPF include significant enhancements in germination rates, seedling vigor, biomass production, development of root hairs, photosynthetic efficiency, flowering and ultimately yield. Furthermore, certain strains have been shown to positively influence the biochemical composition of plants (Hossain *et al.*, 2017). The precise mechanism by which the PGPF promotes plant growth and development is still unknown. However, most of the PGPF are soil-borne saprophytes that mineralize nutrients from decomposing organic materials. Phytohormones produced by many PGPFs have a vital role in the growth enhancement of plants. Furthermore, these fungi are competitive in the rhizosphere and can acquire substrate, spaces, and resources more than other rhizosphere microorganisms. PGPF also helps plants grow well by reducing the negative impact of harmful pathogens on plants (Jahagirdar *et al.*, 2019; Muslim *et al.*, 2019). Some PGPF strains even improve plant resilience to abiotic stresses (Hossain and Sultana, 2020). Until now, many fungal strains have been reported to act as PGPF. *Trichoderma*, *Talaromyces*, *Aspergillus*, *Penicillium*, *Aureobasidium*, *Purpureocillium*, *Exophiala*, *Cladosporium*, *Phomopsis*, *Colletotrichum*, *Chaetomium*, *Fusarium*, *Phoma*, *Gliocladium* (Ascomycota), *Rhodotorula*, *Rhizoctonia*, *Limonomyces*, *sterile fungi* (Basidiomycota), *Rhizopus* and *Mucor* (Zygomycota) are the most common PGPF (Shimizu *et al.*, 2013; Hossain *et al.*, 2017).

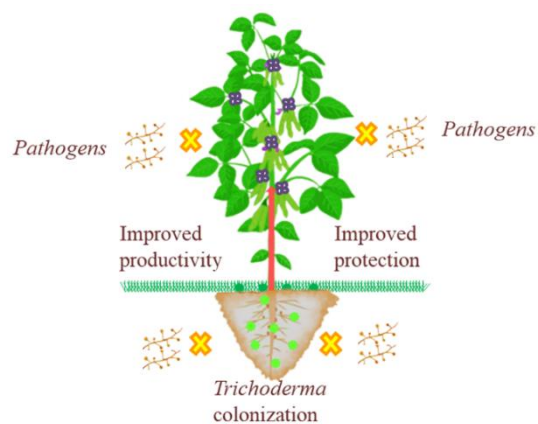


Fig. 1: Effect of root colonization by *Trichoderma* on plant growth and protection against pathogens

Trichoderma: Systematic, Reproduction and Diversity

Persoon (1994), a well-known mycologist, is credited with originally characterizing the fungus *Trichoderma* in 1794. *Trichoderma* is a filamentous fungus in the Hypocreaceae family that is widely dispersed, appearing in almost every soil. Recently, *Trichoderma* species have been found in water-damaged construction materials and indoor dust (Hossain and Sultana, 2020). While *Trichoderma* is typically classified as a free-living soil fungus, studies show that some species can function as opportunistic, nonpathogenic plant symbionts or fungal parasites. This beneficial microbe reproduces asexually by producing conidia and chlamydoconidia and sexually by producing ascospores (Shah and Afiya, 2019). Their growth and multiplication rate are very high (Rajesh *et al.*, 2016). *Trichoderma* typically starts its development as a white, cotton-like mycelium, which then transitions to yellowish-green and eventually forms dense, dark-green tufts, especially prominent in the center of a growth area on an agar surface (Islam *et al.*, 2018). The conidiophores are irregularly arranged, resembling flask-shaped or cylindrical clusters and sometimes almost spherical phialides. The conidia, which are usually green but can sometimes be hyaline, are ellipsoidal to nearly spherical and tend to cluster near the tips of the phialides (Zhu and Zhuang, 2015). *Trichoderma* is highly diverse with distinct physical and cultural characteristics (Fig. 2). On a rpb2-based phylogenetic tree, the most recent listing of nearly 200 (Atanasova *et al.* 2013) named species was displayed. Jaklitsch (2009) attributed the incredible genetic changes of many species to their mycoparasitic behavior.

An in-depth study that analyzed 143 species using multigene phylogenetic analysis, inherited trait restorations, and variation analysis supported this finding (Chaverri and Samuels, 2013). The genomes of two species identified as mycoparasites by Chaverri and Samuels (2013) contain mycoparasitism-specific genes, indicating genetic diversity after changing hosts.

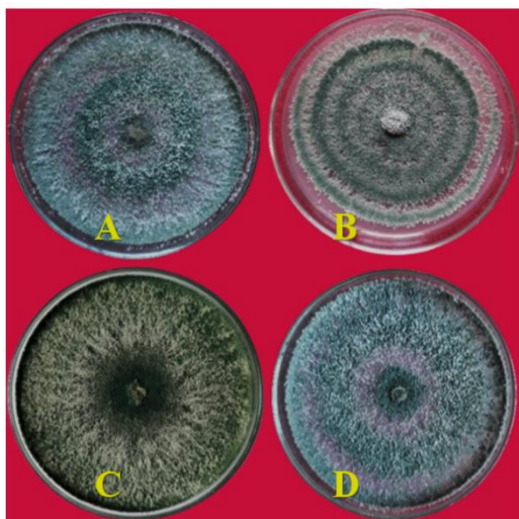


Fig. 2: *Trichoderma* strains with unique morphological and cultural characteristics on Potato Dextrose Agar (PDA) plates; (A) Isolate Pb-22; (B) Isolate Pb-24; (C) Isolate Com-70; and (D) Isolate BBUT-70

Conversely, the genome of a third species *T. reesei* previously believed to be saprobic, did not include these mycoparasitism genes (Kubicek *et al.* 2011). Previous research on the classification, variety, and evolutionary history of *Trichoderma* relied on random samples, as demonstrated by Overton *et al.* (2006a-b). Diversity studies have pondered on soil-dwelling species in limited geographical regions. For example, Hoyos-Carvajal *et al.* (2009) identified 29 species out of 183 isolates. Smith *et al.* (2013) discovered seven species out of 21 isolates in Colombia. Belayneh Mulaw *et al.* (2010) identified eight known species and potentially eight new species from 134 isolates obtained from Coffea plants. Wuczowski *et al.* (2003) found eight species in 46 samples in a limited area in the Donau-auen National Park near Vienna, Austria, while Migheli *et al.* (2009) found fifteen species in Sardinia in 482 isolates. Zachow *et al.* (2009) identified eight species from 42 isolates collected from the soil in Tenerife. Błaszczuk *et al.* (2011) broadened their soil research to encompass cereal grains, compost, and wood, identifying 14 species out of 170 isolates in Poland. Many researchers used ITS and identification methods on the ISTD website to demonstrate that some identified species were actually groups of species. Soil studies indicate that *T. harzianum* is the prime species group in that zone. Jaklitsch (2009; 2011) conducted an extensive review of *Trichoderma* species diversity, where they identified 75 distinct species from an examination of 620 *Hypocrea* specimens collected throughout central and northern Europe.

Common *Trichoderma* as PGPF

Trichoderma shows enormous potential as PGPF in many plant species, including tomato, chili, cucumber,

brinjal, bean, pea, radish, carrot and lettuce (Baker, 1988; Roy *et al.*, 2022; Simi *et al.*, 2019; Kleifeld and Chet, 1992; Liton *et al.* 2019; Lynch *et al.*, 1991; Ahmed *et al.*, 2019; Rubayet *et al.*, 2020 Ousley *et al.* 1993-1994). Among the 254 identified species (Bissett *et al.* 2015), 13 including *T. harzianum*, *T. viride*, *T. reesei*, *T. virens*, *T. atroviride*, *T. asperellum*, *T. longibrachiatum*, *T. citrinoviride*, *T. koningii*, *T. pseudokoningii*, *T. hamatum* and *T. polysporum* are important PGPF (Thakur, 2021). These *Trichoderma* strains induce short- and long-term improvement in plant growth (Doni *et al.* 2014; Hossain and Sultana 2020). According to Chang *et al.* (1986), treating vinca, chrysanthemum, pepper, tomato and cucumber seeds with a conidial suspension of *T. harzianum* T-203 enhanced the germination of pepper reduced the flowering time of vinca and increased the number of flowers in chrysanthemum. In the meantime, the plant height and biomass of the yield components remarkably increased. In addition, the interaction of *T. harzianum*, *T. virens*, and *Arabidopsis thaliana* resulted in the enhancement of lateral root number (Contreras-Cornejo *et al.*, 2014). Many other studies have shown that *Trichoderma* spp. may improve seed germination, root and shoot length, fresh and dry weight, plant height, number of leaflets, number of bulbs, pods, weight, diameter, branching, number of flowers, leaf area index, number of fruits and yield of various crops (Table 1).

Several mechanisms have been suggested to explain growth promotion, such as nutrient mineralization, improved nutrient uptake, increased photosynthesis, phytohormone production, and pathogen control. Most *Trichoderma* are involved in inorganic nutrient solubilization and sequestration (Mukhopadhyay and Kumar, 2020). They increase nutrient uptake by plants from the rhizosphere by secreting an organic biochemical compound that dissolves the mineral form of nutrients into available ions (Saravanakumar *et al.*, 2013). These fungi improve soil structure and texture (Halifu *et al.* 2019) and the associated microbial community (Zhou *et al.*, 2019). *Trichoderma* species are efficient colonizers, making root colonization with their mycelia by forming an appressorium for linking with the epidermis and the cortex of the plant cells (Yedia *et al.*, 1999). It enhances the rhizosphere by continuously colonizing roots, which augments extracellular organic compounds like urease, sucrase, phosphatase, and various organic acids within the root zone. This process stimulates nutrient recycling and boosts plant enzyme activity in the soil. (Halifu *et al.* 2019). Contreras-Cornejo *et al.* (2009) found that *Trichoderma* spp. enhance growth through an auxin-dependent mechanism. Through in vitro testing, they showed that *T. virens* Gv29.8 and *T. atroviride* IMI206040 have the ability to produce IAA

with derivatives and enhance the formation of lateral roots in Arabidopsis. However, the relationship between IAA synthesis and promoting plant growth in soil-based environments remains inconclusive. Hoyos-Carvajal *et al.* (2009) demonstrated that while many *Trichoderma* strains can synthesize IAA, only a few can stimulate plant growth. The other classes of microbial molecules identified as key players in promoting plant growth are the microbial Volatile Organic Compounds (mVOCs) (Hossain and Sultana 2024). mVOCs are low-molecular-weight, lipophilic compounds that readily evaporate at $\pm 25^{\circ}\text{C}$ and are known to play a role in long-distance communication among organisms (Hossain *et al.* 2017). mVOCs are diverse classes of chemicals, including mono and sesquiterpenes, alcohols, cyclohexanes,

esters, ketones, thioalcohols, thioesters, and lactones (Schenkel *et al.*, 2015). For example, 6-pentyl-2H-pyran-2-one (6-PP) has been identified in numerous *Trichoderma* species, such as *T. asperellum* (Kottb *et al.*, 2015), *T. atroviride* (Stoppacher *et al.* 2010), *T. citrinoviride* and *T. hamatum* (Jeleń *et al.*, 2014). In addition, it has been demonstrated that its production by *T. atroviride* induces lateral root formation in *A. thaliana* (Garnica-Vergara *et al.* 2016). Interestingly, not all *Trichoderma* species produce 6-PP (Atanasova *et al.* 2013). However, Kottb *et al.* (2015) found that most *Trichoderma* species can stimulate plant growth, suggesting that the correlation between 6-PP production and growth stimulation is less convincing, as observed by Lee *et al.* (2016).

Table 1: Effect of common *Trichoderma* spp. on growth and development of field crops

<i>Trichoderma</i> spp.	Crops	Consequences	References
<i>T. harzianum</i>	<i>Allium cepa</i>	↑ Root length, plant height, number of leaflets, and yield	Akter <i>et al.</i> (2016)
	<i>Capsicum frutescens</i>	↑ Plant height, fruiting, and yield	Simi <i>et al.</i> (2019)
	<i>Cicer arietinum</i>	↑ Plant height, pod, and yield	Talukdar <i>et al.</i> (2017)
	<i>Cucumis sativus</i>	↑ Cumulative root length, number of root tips	Yedia <i>et al.</i> (2001)
	<i>Daucus carota</i>	↑ Weight (fresh and dry), length (shoot and root), and yield	Ahmed <i>et al.</i> (2019); Hasan <i>et al.</i> (2021)
	<i>D. carota</i>	↑ yield	Rubayet <i>et al.</i> (2020)
	<i>Glycine max</i>	↑ Plant height, pod, and yield	Rahman <i>et al.</i> (2021)
	<i>Lens culinaris</i>	↑ Weight (fresh and dry), length (shoot and root), and yield	Das <i>et al.</i> (2019)
	<i>Phaseolus vulgaris</i>	↑ Yield	Liton <i>et al.</i> (2019)
	<i>Pisum sativum</i>	↑ Length and number of lateral roots	Naseby <i>et al.</i> (2001)
	<i>P. sativum</i>	↑ Yield	Akhter <i>et al.</i> (2015)
	<i>Raphanus sativus</i>	↑ Siliqua length and number, and yield	Arefin <i>et al.</i> (2019)
	<i>Solanum lycopersicum</i>	↑ Seeds germination of tomato and enhanced their seedling growth	Vinale <i>et al.</i> (2013)
	<i>S. lycopersicum</i>	↑ Root length and tips	Cai <i>et al.</i> (2013)
	<i>S. lycopersicum</i>	↑ Fruit and Yield	Nitu <i>et al.</i> (2016)
	<i>Solanum tuberosum</i>	↑ Yield	Rubayet and Bhuiyan (2016)
	<i>S. lycopersicum</i>	↑ Solubilization of PO_4^{3-} and micronutrient	Li <i>et al.</i> (2015)
	<i>Zea mays</i>	↑ Plant height and root length	Herrera-Jiménez <i>et al.</i> (2018)
<i>T. atroviride</i>	<i>Gossypium hirsutum</i>	↑ Protection against plant chitinases, induce expression of defense responses	Harman <i>et al.</i> (2004)
	<i>Z. Mays</i>	↑ Volatile compound and plant growth	Seidl <i>et al.</i> (2006)
	<i>A. thaliana</i>	↑ Hypersensitive response, defense response	Nieto-Jacobo <i>et al.</i> (2017)
<i>T. viride</i>	<i>Nicotiana tabacum</i>	↑ Phosphorus and Fe, defense response	Engelberth <i>et al.</i> (2001)
<i>T. asperellum</i>	<i>Cucumis sativus</i>	↑ Phosphorus and Fe, defense response	Segarra <i>et al.</i> (2007)
	<i>Arabidopsis</i>	↑ Volatile compound and plant growth	Yoshioka <i>et al.</i> (2012)
<i>T. koningii</i>	<i>A. thaliana</i>	↑ Volatile compound and plant growth	Nieto-Jacobo <i>et al.</i> (2017)
<i>T. saturnisporum</i>	<i>Lotus japonicus</i>	↓ Phenolic compounds	Chen <i>et al.</i> (2011)
	<i>S. lycopersicum</i>	↑ Phytochromes	Marín-Guirao <i>et al.</i> (2016)
<i>T. aggressivum</i>	<i>C. frutescens</i>	↑ Seedling growth	Sánchez-Montesinos <i>et al.</i> (2020)
	<i>C. frutescens</i>	↑ Seedling growth	Sánchez-Montesinos <i>et al.</i> (2020)
f. sp. <i>europaeum</i>	<i>S. lycopersicum</i>	↑ Tolerance to salt stress	Zhang <i>et al.</i> (2016)
<i>T. longibrachiatum</i>	<i>Triticum aestivum</i>	↑ Induce systemic resistance against foliar pathogens	Studholme <i>et al.</i> (2013)
<i>T. hamatum</i>	<i>A. thaliana</i>	↑ Induce systemic resistance against foliar pathogens	Studholme <i>et al.</i> (2013)
	<i>Oryza sativa</i>	↑ Production ammonia and salicylic acid	Rinu <i>et al.</i> (2014)
<i>T. gamsii</i>	<i>Z. mays</i>	↑ Production ammonia and salicylic acid	Rinu <i>et al.</i> (2014)
	<i>Glycine max</i>	↓ Siderophores	Rinu <i>et al.</i> (2014)
<i>T. phayaense</i>	<i>Cucumis melo</i>	↑ Plant vegetative growth	Nuangmek <i>et al.</i> (2021)
<i>T. tomentosum</i>	<i>Z. mays</i>	↑ Plant and root length	Herrera-Jiménez <i>et al.</i> (2018)
<i>T. reesei</i>	<i>T. aestivum</i>	↑ Nutrition status	Ikram <i>et al.</i> (2019)
<i>T. virens</i>	<i>A. thaliana</i>	↑ Volatile compound and plant growth	Nieto-Jacobo <i>et al.</i> (2017)

Biocontrol of Plant Diseases by *Trichoderma*

Biocontrol involves using living organisms to suppress, reduce, or eliminate pest populations. *Trichoderma* species display both biostimulation and biocontrol properties. They interact with plant roots through diffusible and volatile compounds, regulate the stress hormone ethylene, and produce phytohormones like auxins (indole-3-acetic acid). Their plant-protective mechanisms include parasitism, production of antibiotics and secondary metabolites, and activation of induced systemic resistance (ISR). *Trichoderma* stimulates growth and defense responses by activating Salicylic Acid (SA), Ethylene (ET), and Jasmonic Acid (JA) pathways, offering protection against various plant pathogens (Guzmán-Guzmán *et al.* 2023). This beneficial microorganism is a commonly used biocontrol agent against a wide range of diseases caused by fungi, bacteria, viruses, protists, and nematode species such as *T. harzianum*, *T. viride*, *T. atroviride*, *T. virens*, *T. citrinoviride*, *T. polysporum*, *T. stromaticum*, *T. hamatum*, *T. asperellum*, *T. saturnisporum* and *T. aggressivum* have been recognized as effective biological control agents against plant pathogens (Hossain *et al.*, 2017; Park *et al.*, 2019; Hossain and Sultana, 2024).

Biocontrol of Fungal Diseases

Plant diseases contribute to approximately 10-15% of annual losses globally in main crops (Chatterjee *et al.*, 2016). Among plant diseases, 70-80% are caused by more than 19000 fungi (Peng *et al.* 2021). Managing these diverse groups of fungal pathogens without causing major ecological disruption is challenging. Using bioagents like *Trichoderma* could be beneficial in controlling these fungal diseases without upsetting the equilibrium of naturally occurring microorganisms.

Several studies have revealed that various strains of *Trichoderma* can inhibit common fungal pathogens such as *A. alternata* (Gveroska and Ziberoski, 2012), *A. tenuis* (Begum *et al.* 2010), *A. brassicae* (Arefin *et al.*, 2019), *Botrytis cinerea* (Mukesh *et al.*, 2016), *Cercospora moricola* (Mukesh *et al.*, 2016), *C. capsici* (Simi *et al.*, 2019), *F. culmorum* (Matarese *et al.*, 2012), *F. solani* (Rojo *et al.*, 2007), *M. phaseolina* (Rahman *et al.* 2021), *P. aphanidermatum* (Howell, 2002), *Phytophthora capsici* (Ezziyyani *et al.*, 2007), *Plasmopara viticola* (Banani *et al.*, 2013), *R. solani* (Amin *et al.*, 2010), *Rhizopus oryzae* (Howell, 2002), *Sclerotinia sclerotiorum* (Thakkar and Saraf, 2015), *Ustilago segetum var. tritici* (Mukesh *et al.*, 2016) (Table 2).

Table 2: Management of fungal diseases using *Trichoderma* spp. as a bioagent

Crops	Diseases	Pathogens	<i>Trichoderma</i> spp.	References
<i>Capsicum frutescens</i>	Anthraxnose	<i>Colletotrichum capsici</i>	<i>T. harzianum</i>	Simi <i>et al.</i> (2019)
<i>Rosa sp.</i>	Grey mold	<i>Botrytis cinerea</i>		Mukesh <i>et al.</i> (2016)
<i>Arachis hypogaea</i>	Brown root rot	<i>Fusarium solani</i>		Rojo <i>et al.</i> (2007)
<i>Nicotiana tabacum</i>	Brown spot	<i>A. alternata</i>		Gveroska and Ziberoski (2012)
<i>Glycine max</i>	Charcoal rot	<i>Macrophomina phaseolina</i>		Rahman <i>et al.</i> (2021)
<i>Solanum lycopersicum</i>	Collar rot	<i>Sclerotium rolfsii</i>		Amin <i>et al.</i> (2010)
<i>C. annuum</i>	Damping off	<i>Phytophthora capsici</i>		Ezziyyani <i>et al.</i> (2007)
<i>Gossypium hirsutum</i>	Damping off	<i>Rhizoctonia solani</i>		Howell (2002)
<i>Beta vulgaris</i>				
<i>C. annuum</i>	Fruit rot	<i>A. tenuis</i>		Begum <i>et al.</i> (2010)
<i>S. lycopersicum</i>	Fruit rot	<i>R. solani</i>		Amin <i>et al.</i> (2010)
<i>G. max</i>	Root rot disease	<i>R. solani</i>		Rahman <i>et al.</i> (2020c)
<i>Oryza sativa</i>	Sheath blight	<i>R. solani</i>		Naeimi <i>et al.</i> (2011)
<i>Daucus carota</i>	Southern blight	<i>S. rolfsii</i>		Ahmed <i>et al.</i> (2019); Rubayet <i>et al.</i> (2020)
<i>Solanum tuberosum</i>	Stem rot	<i>S. rolfsii</i>		Rubayet and Bhuiyan (2016)
<i>Cicer arietinum</i>	Dry root	<i>M. phaseolina</i>		Manjunatha <i>et al.</i> (2013)
<i>Zea mays</i>	Ear & kernel rot	<i>F. verticillioides</i>		Ferrigo <i>et al.</i> (2014)
<i>S. tuberosum</i>	Potato dry rot	<i>F. sambucinum</i>		Ru and Di (2012)
<i>Elettaria cardamomum</i>	Rot	<i>Phytophthora sp.</i>		Mukesh <i>et al.</i> (2016)
<i>Vitis vinifera</i>	Downy mildew	<i>Plasmopara viticola</i>		Banani <i>et al.</i> (2014)
<i>Z. Mays</i>	Ear & kernel rot	<i>F. verticillioides</i>		Ferrigo <i>et al.</i> (2014)
<i>Raphanus sativus</i>	Alternaria blight	<i>Alternaria brassicae</i>		Arefin <i>et al.</i> (2019)
<i>S. lycopersicum</i>	Fruit rot	<i>R. solani</i>	<i>T. viride</i>	Amin <i>et al.</i> (2010)
<i>Solanum melongena</i>	Root rot disease	<i>M. phaseolina</i>		Ramezani (2008)
<i>Zingiber officinale</i>	Rhizome rot	<i>Pythium sp.</i>		Mukesh <i>et al.</i> (2016)
<i>Phaseolus vulgaris</i>	Web blight	<i>Sclerotinia sclerotiorum</i>		Amin <i>et al.</i> (2010)
<i>Cajanus cajan</i>	Foot rot	<i>F. udum</i>		Mukesh <i>et al.</i> (2016)
<i>G. max</i>	Root rot	<i>F. oxysporum f. sp. adzuk</i>		John <i>et al.</i> (2010)
<i>Rosa sp.</i>	Grey mold	<i>Botrytis cinerea</i>		Mukesh <i>et al.</i> (2016)

Table 2: Count.

<i>Vigna radiata</i>	Dry root	<i>R. bataticola</i>	<i>T. virens</i>	Dubey <i>et al.</i> (2009)
<i>Z. officinale</i>	Rhizome rot	<i>Pythium sp.</i>		Mukesh <i>et al.</i> (2016)
<i>S. lycopersicum</i>	Fruit rot	<i>R. solani</i>		Amin <i>et al.</i> (2010)
<i>S. lycopersicum</i>	Wilt	<i>F. oxysporum</i> f. sp. <i>lycopersici</i> (FOL)	<i>T. asperellum</i>	El Komy <i>et al.</i> (2015)
<i>Zea mays</i>	Root rot disease	<i>F. oxysporum</i> f. sp. <i>adzuki</i>		Mbarga <i>et al.</i> (2012)
<i>Beta vulgaris</i>	Damping-off	<i>R. solani</i>		Kakvan <i>et al.</i> (2013)
<i>Medicago sativa</i>	Blossom blight	<i>S. sclerotiorum</i>	<i>T. atroviride</i>	Li <i>et al.</i> (2005)
<i>C. frutescens</i>	Grey mold	<i>B. cinerea</i>		Freeman <i>et al.</i> (2004)
<i>S. tuberosum</i>	Potato dry rot	<i>F. sambucinum</i>		Ru and Di (2012)
<i>S. tuberosum</i>	Potato dry rot	<i>F. sambucinum</i>	<i>T. longibrachiaum</i>	Ru and Di (2012)
<i>Arachis hypogaea</i>	Brown root	<i>F. solani</i>		Rojo <i>et al.</i> (2007)
<i>Z. officinale</i>	Rhizome rot	<i>Pythium sp.</i>		Mukesh <i>et al.</i> (2016)
<i>S. lycopersicum</i>	Root-knot	<i>M. incognita</i>	<i>T. citrinoviride</i>	Fan <i>et al.</i> (2020)
<i>G. max</i>	White mold	<i>S. sclerotiorum</i>		Thakkar and Saraf (2015)
	Charcoal rot	<i>M. phaseolina</i>		
<i>A. cepa</i>	Purple blotch	<i>A. porri</i>	<i>T. pseudokoningii</i>	Imtiaj and Lee (2008)
<i>Triticum aestivum</i>	Loose smut	<i>Ustilago segetum</i> var. <i>tritici</i>	<i>T. koningii</i>	Mukesh <i>et al.</i> (2016)
<i>B. vulgaris</i>	Damping-off	<i>S. rolfsii</i>		Paramasivan <i>et al.</i> (2014)
<i>Morus alba</i>	Leaf spot	<i>Cercospora moricola</i>	<i>Trichoderma</i> spp.	Mukesh <i>et al.</i> (2016)
<i>B. vulgaris</i>	Damping-off	<i>S. rolfsii</i>	<i>T. reesei</i>	Paramasivan <i>et al.</i> (2014)
<i>Fragaria ananassa</i>	Anthracnose	<i>C. acutatum</i>	<i>T. hamatum</i>	Freeman <i>et al.</i> (2004)
<i>C. annuum</i>	Root rot disease	<i>R. solani</i>	<i>T. polysporum</i>	Ramezani (2008)

Freeman *et al.* (2004) observed that *T. harzianum* isolate T-39 could efficiently manage the *C. acutatum* and *B. cinerea* in strawberries under controlled environmental conditions. *T. guizhouense* 9185 and *T. simmonsii* 8702 isolates significantly decreased the *R. solani* disease severity and incidences by 36.6 and 45.0%, respectively (Wang and Zhuang, 2019). *T. harzianum* IMI-392432, *T. pseudokoningii* IMI-392431, *T. harzianum* IMI-392433, *T. virens* IMI-392430 and *T. harzianum* IMI-392434 have shown significant biocontrol efficacy against *A. alternata* (Rahman *et al.*, 2020b). Sánchez-Montesinos *et al.* (2019) reported that *T. aggressivum* f. *europaeum* controlled the damping-off caused by *Pythium ultimum* in melon seedlings, reducing the severity of the disease by 63%. Rini and Sulochana (2007) achieved a 25% reduction in the incidence of *Rhizoctonia* root rot in chili by applying *T. pseudokoningii* or *T. harzianum*. Hafez *et al.* (2018) reported that *T. viride* and *T. harzianum* controlled powdery mildew caused by *Podosphaera xanthii* on cucumbers by approximately 40%. *T. harzianum* T22 and other *Trichoderma*-based formulations inhibited *Fusarium* crown and foot rot by less than 30% (Roberti *et al.*, 2012).

Recently, Sánchez-Montesinos *et al.* (2021) revealed that *T. aggressivum* f. *europaeum* TAET1 completely inhibited the growth of *Sclerotinia sclerotiorum*, *Mycosphaerella melonis*, and *B. cinerea* in detached leaf assays, as well as the germination of sclerotia of *S. sclerotiorum*. In plant assays for pathosystems, the disease incidence and severity ranged from 22% for *F. solani* to 80% for *M. melonis*. This isolate reduced the incidence of

Podosphaera xanthii by 66.78% in zucchini leaves. In a field trial, application of *T. harzianum* at a rate of 90 g/m² significantly reduced pre- and post-emergence mortality of carrots caused by *S. rolfsii* and enhanced the yield of healthy edible taproots relative to the control (Fig. 3). *Trichoderma*-treated plants were larger and yielded substantially more edible taproots than untreated plants. Therefore, applying *Trichoderma* to crops can be regarded as one of the most viable alternatives to chemical fungicides against fungal diseases.



Fig. 3: Effect of *Trichoderma harzianum* on seedling mortality and edible taproot infection caused by *Sclerotium rolfsii* in carrots; (A) plants grown in untreated plots; (B) Plants grown in *T. harzianum*-treated plots; (C) Infected edible taproot harvested from untreated plants; (D) healthy-looking edible taproot harvested from *Trichoderma*-treated plants

Biocontrol of Bacterial Diseases

Bacterial pathogens rank second only to fungi as significant plant pathogens globally. Six genera of bacteria for instance *Agrobacterium*, *Xanthomonas*, *Pseudomonas*, *Corynebacterium*, *Erwinia*, and *Streptomyces* are responsible for causing important plant diseases (Michalak *et al.*, 2022). The management of plant bacteria is complex due to the faster growth rate under favorable environmental conditions (Sundin *et al.*, 2016). Moreover, a few chemicals are effective against bacterial diseases. Hence, using bioagents such as *Trichoderma* spp. is preferable to controlling bacterial infections in crops. However, reports on using *Trichoderma* spp. for the biocontrol of bacterial diseases are limited. *Ralstonia solanacearum* (Bacterial wilt) is one of the most harmful bacteria that can cause wilt disease in crops such as tomatoes, potatoes, and brinjal. Other methods of controlling *R. solanacearum* have recently been investigated but achieving the desired level of disease control in a sustainable and environmentally friendly manner remains challenging. *Ralstonia solanacearum* infection in tomatoes was successfully controlled by applying *T. asperellum* in open conditions (Konappa *et al.*, 2018). The results showed that treating the soil with *T. asperellum* intensified tomato plant growth, and yield and declined wilt incidence. In this study, *T. asperellum* elicited bacterial wilt resistance in tomato plants.

In this study, *T. asperellum* elicited bacterial wilt resistance in tomato plants. In the recent investigations, the utilization of *Trichoderma* spp. Soil applications in the form of fungal suspension have been observed to effectively control *R. solanacearum* in potato cultivation,

as indicated by Mohamed *et al.* (2020). *Erwinia* is another notorious bacterial genus that can cause soft rot and die-back diseases in the potato and papaya. Sulaiman *et al.* (2020) investigated the effectiveness of *Trichoderma* spp. in inhibiting *Erwinia carotovora*, subsp. *carotovora* which causes the soft rot disease of potato tuber. *Trichoderma* isolates significantly slowed *Erwinia* growth. Disease incidence was reduced by 20.00% and 26.25% on potato slices treated with *T. harzianum* isolate 2 (TH2) and *Trichoderma* Viride isolate 3 (TV3), respectively compared to 94.25% in control. A considerable decrease in disease incidence was seen in tubers derived from tubers treated with TV3 and TH2, showing a disease severity of 20.27 and 16.47%, respectively, compared to 90.42% in control. Tamizi *et al.* (2022) also identified *Trichoderma* spp. as a potential component of *Erwinia* spp. Biocontrol program. According to Baazeem *et al.* (2021); and Papianni *et al.* (2020), the presence of *T. hamatum* and *T. atroviride*, hindered the growth and development of *Xanthomonas campestris* pv. *campestris*, *Acidovorax avenae*, and *Erutima carafavora*. During vegetable cultivation, the application of *T. harzianum*, *T. virens*, *T. parareesei*, *T. asperellum*, and *T. viride* suppressed the notorious bacteria such as *Ralstonia solanacearum*, *Acidovorax citrulli*, *Clavibacter michiganensis* subsp. *michiganensis*, *Erwinia carotovora*, subsp. *carotovora*, *E. mallotivora*, *Xanthomonas euvesicatoria*, *R. solanacearum*, *X. oryzae* pv. *oryzae*, *Pseudomonas syringae* pv. *lachrymans*, *X. campestris*, *Pectobacterium carotovorum* subsp. *carotovorum*, *P. syringae* pv. *Tomato* (Table 3). Globally, potato common scab causes substantial economic losses, and existing control measures are ineffectual.

Table 3: Management of bacterial diseases using *Trichoderma* spp. as a bioagent

Crops	Diseases	Pathogens	<i>Trichoderma</i> spp.	References
<i>Solanum lycopersicum</i>	Bacterial wilt	<i>Ralstonia solanacearum</i>	<i>T. harzianum</i>	Yan and Khan (2021)
<i>In vitro</i>	<i>in vitro</i>	<i>Acidovorax citrulli</i>		Smirnova <i>et al.</i> (2018)
<i>S. lycopersicum</i>	Bacterial wilt	<i>Clavibacter michiganensis</i> subsp. <i>Michiganensis</i>		Abo-Elyousr and Marei Almasaudi (2022)
<i>Solanum tuberosum</i>	Soft rot	<i>Erwinia carotovora</i> , subsp. <i>carryover</i>	<i>Trichoderma</i> spp.	Sulaiman <i>et al.</i> (2020)
<i>Carica papaya</i>	Dieback	<i>E. mallotivora</i>		Tamizi <i>et al.</i> (2022)
<i>S. lycopersicum</i>	Bacterial spot	<i>Xanthomonas euvesicatoria</i>		Fontenelle <i>et al.</i> (2011)
<i>S. lycopersicum</i>	Bacterial wilt	<i>R. solanacearum</i>	<i>T. asperellum</i>	Konappa <i>et al.</i> (2018)
<i>Nicotiana tabacum</i>	<i>In vitro</i>	<i>X. oryzae</i> pv. <i>oryzae</i>		Singh <i>et al.</i> (2019)
<i>Cucumis sativus</i>	<i>In vitro</i>	<i>Pseudomonas syringae</i> pv. <i>lachrymans</i>		Yedidia <i>et al.</i> (2003)
<i>In vitro</i>	<i>In vitro</i>	<i>X. campestris</i>	<i>T. hamatum</i>	Baazeem <i>et al.</i> (2021)
<i>In vitro</i>	<i>In vitro</i>	<i>X. campestris</i> pv. <i>campestris</i>	<i>T. atroviride</i>	Papianni <i>et al.</i> (2020)
Vegetables	Bacterial soft rot	<i>Pectobacterium carotovorum</i> subsp. <i>carotovorum</i>	<i>T. viride</i> <i>T. virens</i>	Abd-El-Khair <i>et al.</i> (2021)
<i>S. lycopersicum</i>	Bacterial blight	<i>P. syringae</i> pv. <i>tomato</i>	<i>T. parareesei</i> <i>T. harzianum</i>	Morán-Diez <i>et al.</i> (2020)

However, biological control approaches have proven efficient against phytopathogens in various crops. Simultaneous field tests were conducted to compare the efficacy of *T. asperellum* and *T. longibrachiatum* in preventing potato scabs (Porto *et al.*, 2022). Based on yield losses caused by potato scab, the *T. asperellum* and *T. longibrachiatum* reduced disease severity from 80% in control to 34% and from 56% in control to 5%, respectively. In the second experiment, TA lowered disease severity by 61% compared to the control group (98%). These results indicate that *Trichoderma* spp. may be a feasible alternative for the control of bacterial plant diseases.

Biocontrol of Viral Diseases

Globally, plant viral diseases pose a serious threat to sustainable and productive agriculture and are responsible for several billion dollars in annual losses (Mumford *et al.*, 2016). Plant viruses are obligate hyperparasites that can cause devastating plant diseases during crop cultivation. It's responsible for partial or complete losses of the standing crops. The management strategies are different due to their unique characteristics. The virus is an infectious nucleoprotein particle that can replicate in a living cell. It can also remain the primary source in the living cell, such as a viable seed. Moreover, monocropping with low genetic diversity and high plant density also exaggerates the virus diseases in the crop field. After secondary infection, viruses rapidly transmit the entire crop field through the vector likely, polyphagous arthropods, nematodes, and plant-parasitic fungi organisms (Walkey, 1991).

On the contrary, it has no appropriate chemical substance for directly controlling viruses. In the running era, developing an effective virus management strategy is a burning issue. Among the different methods, the biological control methods are still the most efficient and practical tactic for controlling plant viruses across the globe. Although little is known about the impact of *Trichoderma* spp. on the induction of plant defenses against viruses, this fungus is effective against several mosaic viruses such as Tobacco Mosaic Virus (TMV), Cucumber Mosaic Virus (CMV), and Cucumber green mosaic virus (Table 4). *Trichoderma* spp. that colonizes plant roots can modulate the induction of systemic resistance against the Cucumber green mosaic virus (Lo *et al.*, 2000). A study evaluated *T. asperellum* SKT-1 for its ability to induce resistance against the yellow strain of Cucumber mosaic virus in Arabidopsis plants. Arabidopsis plants treated with barley grain inoculum and culture filtrate of SKT-1 showed a significant reduction in disease severity and CMV compared to control plants (Elsharkawy *et al.*, 2013). Additionally, all Arabidopsis plants treated with SKT-1 exhibited significantly reduced disease severity and CMV compared to untreated control plants. Vitti *et al.* (2015) investigated the T22 strain of *T. harzianum* as a novel strategy for managing viruses, demonstrating its ability to enhance tomato defense responses against CMV. The mechanism of action of T22 involves modulation of viral symptoms, inhibition of the RNA-dependent RNA polymerase gene, and the participation of Reactive Oxygen Species (ROS) as secondary messengers in the defense response against the virus. Similarly, Abdelkhalek *et al.* (2022) reported that the application of *T. hamatum* effectively controlled TMV.

Table 4: Management of viral, protist, and nematode diseases using *Trichoderma* spp. as a bioagent

Crops	Diseases	Pathogens	<i>Trichoderma</i> spp.	References
<i>S. lycopersicum</i>	Mosaic	<i>Tobacco mosaic virus</i>	<i>T. hamatum</i>	Abdelkhalek <i>et al.</i> (2022)
<i>S. lycopersicum</i>	Mosaic	<i>Cucumber mosaic virus</i>	<i>T. harzianum</i>	Vitti <i>et al.</i> (2016)
<i>Nicotiana tabacum</i>	Mosaic	<i>Tobacco mosaic virus</i>	<i>T. koningii</i>	Taha <i>et al.</i> (2021)
<i>Cucumis sativus</i>	Mosaic	<i>Cucumber green mosaic virus</i>	<i>Trichoderma</i> spp	Lo <i>et al.</i> (2000)
<i>Brassica oleracea</i>	Clubroot	<i>Plasmodiophora brassicae</i>	<i>T. viride</i>	Adhikari <i>et al.</i> (2020)
Crucifers	Clubroot	<i>P. brassicae</i>	<i>T. harzianum</i>	Yu <i>et al.</i> (2015)
<i>Brassica rapa</i>	Clubroot	<i>P. brassicae</i>	<i>T. harzianum</i>	Li <i>et al.</i> (2020)
			<i>Trichoderma</i> spp.	Suada <i>et al.</i> (2019)
<i>S. lycopersicum</i>	Root-knot	<i>Meloidogyne incognita</i>	<i>T. harzianum</i>	Khan <i>et al.</i> (2018)
Field crops	Root-knot	<i>M. javanica</i>		Sahebani and Hadavi (2008)
<i>Cicer arietinum</i>	Root-knot	<i>M. incognita</i>		Rizvi <i>et al.</i> (2018)
<i>Helianthus annuus</i>	Root-knot	<i>M. incognita</i>		Haggag and Amin (2001)
<i>S. lycopersicum</i>	Root-knot	<i>M. incognita</i>	<i>T. viride</i>	Sahebani and Hadavi (2008)
<i>H. annuus</i>	Root-knot	<i>M. incognita</i>		Haggag and Amin (2001)
<i>Solanum tuberosum</i>	Cyst-forming	<i>Globodera rostochiensis</i>		Bairwa <i>et al.</i> (2017)
		<i>G. pallida</i>		Lima <i>et al.</i> (2018)
Field crops	Cyst-forming	<i>Heterodera avenae</i>	<i>T. longibrachiatum</i>	Zhang <i>et al.</i> (2014)
<i>S. lycopersicum</i>	Root-knot	<i>M. incognita</i>	<i>T. citrinoviride</i>	Fan <i>et al.</i> (2020)
<i>Saccharum officinarum</i>	Root-knot	<i>M. incognita</i>	<i>Trichoderma</i> spp.	Freitas <i>et al.</i> (2012)
<i>G. max</i>	Root-knot	<i>Meloidogyne</i> spp.		Elhady <i>et al.</i> (2018)
<i>Arabidopsis</i>	Yellow strain	<i>Cucumber mosaic virus</i>	<i>T. asperellum</i>	Elsharkawy <i>et al.</i> (2013)

Biocontrol of Protist Diseases

Protista is a unicellular eukaryotic microorganism. They also cause severe diseases in the plant and animal communities. *Plasmodiophora brassicae* of Protista is one of the most important examples, which can cause clubroot disease in the Cruciferae family, resulting in significant economic yield loss (Howard *et al.*, 2010). Controlling clubroot has long been a primary concern all over the world. The spread of *P. brassicae* spores is rapid and facilitated by contaminated soil, farm equipment, infected plant materials, and surface water. The resilient resting spores can persist in the soil for extended periods. In the absence of effective control measures against *P. brassicae*, there is a pressing need to explore novel management approaches. The biological control method has proven highly effective in reducing soil-borne diseases like clubroot. *Trichoderma* species have been extensively studied as bio-agents against protists, such as *P. brassicae* (Table 4). In greenhouse pot trials, the application of the *T. harzianum* strain T4 reduced *P. brassicae* incidence in Chinese cabbage by 79% (Yu *et al.*, 2015). Another study demonstrated the biocontrol efficacy of *T. harzianum* strain LTR-2 against *P. brassicae* in field conditions, reducing disease incidence from 96.7-51.3% in Chinese cabbage (Li *et al.*, 2020). Zhao *et al.* (2022) identified two strains, *Trichoderma guizhouense* Hz36 and *T. koningiopsis* Hk37 from clubroot-infected rapeseed fields with biocontrol potential against clubroot. The biocontrol efficiency of Hz36 strain on clubroot in rapeseed and *A. thaliana* was 44.29 and 52.18%, respectively. Strain Hk37 exhibited similar effects, with biocontrol efficiencies of 57.30% in rapeseed and 68.01% in *A. thaliana*. *T. viride* also showed effectiveness as a bio-fungicide against cauliflower clubroot (Adhikari *et al.*, 2020). When mixed with organic fertilizer containing actinomycetes, *Trichoderma* application prevented clubroot disease (Joo *et al.*, 2004). *Trichoderma* spp. has the potential to effectively control protist diseases. These findings focus on the promising potential of *Trichoderma* strains for clubroot biocontrol.

Biocontrol of Nematode Diseases

Phytonematode represents a serious threat to the agricultural production system, causing a 12.3% loss in global yield (Singh *et al.*, 2015). Even though chemical nematicides have a residual effect, growers use them to combat nematodes during crop cultivation. Numerous studies have explored the effectiveness of *Trichoderma* as a bio-agent against plant parasitic nematodes such as root-knot, and cyst-forming (Table 4). In greenhouse experiments, the inoculation of tomato seeds with *T. harzianum* significantly diminished the impact of *Meloidogyne javanica*, influencing its establishment, development, and reproductive capacity. This was evident

through various parameters including the reduction in the number of galls and egg masses per plant and the number of eggs within each mass (Sahebani and Hadavi, 2008). Additionally, a remarkable decrease in egg hatching was observed, indicating that this particular *Trichoderma* sp. holds promise as a bio-agent against plant parasite nematode. Similarly, *T. harzianum*'s presence in tomato roots hindered nematode performance at various stages of parasitism, including invasion, production of gall, and reproduction of the nematodes (Martínez-Medina *et al.* 2017). The impact of suspension culture and exudates from five *Trichoderma* species such as *T. harzianum*, *T. viride*, *T. virens*, *T. hamatum*, and *T. koningii* on controlling *M. incognita* on tomato plants was investigated. Fungus metabolites from liquid culture significantly affected the production of egg hatching and increased the juvenile mortality rate of *M. incognita*. Soil application of culture suspension containing fungus spores had a greater detrimental effect on juvenile populations while enhancing plant growth more effectively than fungus exudates (Khan and Mohiddin, 2018). *T. harzianum* exhibited the most effective nematode control performance. In open-field conditions, *T. harzianum* inhibited *M. javanica* egg hatching (Naserinasab *et al.*, 2011). Under in vitro conditions *T. harzianum*, *T. koningii*, and *T. viride* caused over 50% mortality in *M. javanica* juveniles (Qureshi *et al.*, 2012). *T. asperellum* M2RT4 decreased gall formation, egg mass, and egg production in pineapple roots in Kenya (Kiriga *et al.*, 2018). Other *Trichoderma* species such as *T. asperelloides*, *T. harzianum*, *T. viride*, and *T. hamatum* exhibited chitinase activity and antagonistic effects against *M. incognita* in tomatoes. *T. asperelloides* significantly reduced root gall formation and total nematode population (Sayed *et al.*, 2019).

Trichoderma demonstrates significant potential as a biocontrol agent against not only root-knot nematodes but also cyst nematodes through direct parasitism of eggs and larvae. *T. longibrachiatum* has a strong inhibitory effect on *Heterodera avenae* cyst hatching due to complete spore coverage, leading to cyst destruction (Zhang *et al.*, 2014). *T. longibrachiatum* also affects female development and *H. avenae* egg and juvenile stages (Zhang *et al.*, 2017). Contina *et al.* (2017) utilized a GFP-labeled strain of *T. harzianum* to demonstrate reduced infection and reproduction of *Globodera pallida*. The fungus negatively impacted both cysts and juveniles of *G. pallida* but did not affect eggs. Additionally, *T. harzianum* established hyphal colonization in potato rhizoplane and rhizosphere, potentially providing long-term protection against infection. Numerous studies highlight the potential of the genus *Trichoderma* to efficiently suppress plant-parasitic nematodes through direct interaction.

Biocontrol Mechanisms of *Trichoderma* Strain

The management of diseases with the assistance of *Trichoderma* arises from the interactions between the bio-agent and plant pathogenic populations. *Trichoderma* species have been extensively researched and commercially utilized as agents for biological control, soil enhancement, and biofertilization owing to their capability to protect plants and regulate pathogen populations across diverse soil conditions. Generally, the mechanisms underlying biocontrol can be divided into two main categories (Fig. 4). The first involves a direct process where *Trichoderma* antagonizes, lyses, kills, or parasitizes the pathogen. Antibiosis, mycoparasitism, and competition are the primary strategies employed by *Trichoderma* in directly combating fungal pathogens. The other mechanism is an indirect approach in which *Trichoderma* creates an unfavorable infection environment. Induced resistance represents the primary indirect mechanism employed by *Trichoderma* (Hossain, 2024).

Antibiosis

Antibiosis is the process through which a microbe inhibits the growth of other microbes by secreting a low-molecular-weight, diffusible chemical. Antibiosis focuses primarily on generating secondary metabolites with an inhibiting or lethal effect on a parasitic fungus (Fig. 5). More than one hundred eighty 2° metabolites representing diverse chemical product classes have been identified from *Trichoderma* (Reino *et al.*, 2007; Masi *et al.*, 2018). These compounds can be categorized based on their metabolic origins as peptaibol, polyketide, or terpene. *Trichoderma* spp. are recognized producers of peptaibols, which are polypeptide antibiotics characterized by a molecular weight ranging from 500-2200 Da and comprised of non-proteinogenic amino acids, notably α -aminoisobutyric acid (Turaga *et al.*, 2020). These molecules feature an acetylated N-terminus and amino alcohols at the C-terminus, rendering them amphipathic in nature and capable of forming voltage-gated ion channels in membranes. Peptaibols are synthesized by Non-Ribosomal Peptide Synthetases (NRPSs).

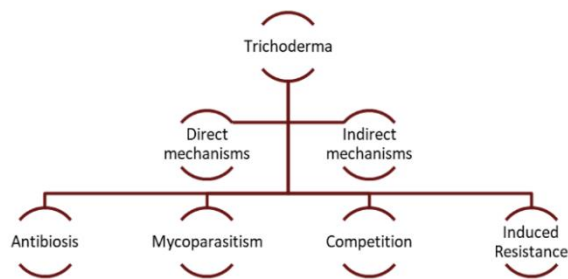


Fig. 4: Biocontrol mechanisms of *Trichoderma* against plant pathogens

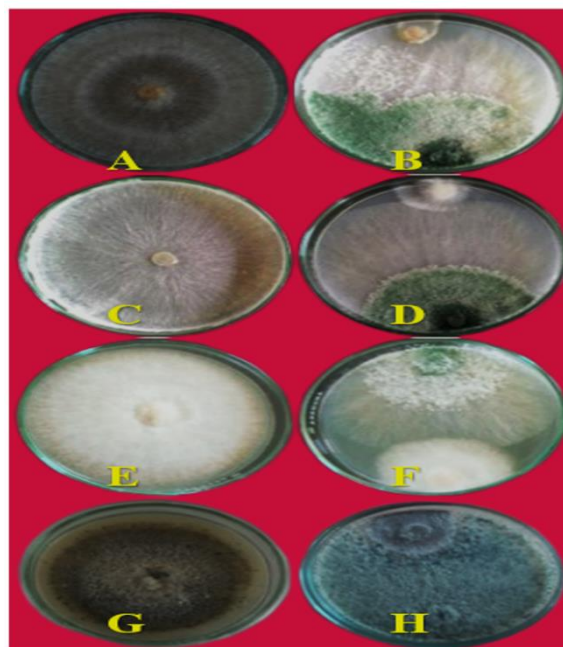


Fig. 5: Antagonism of *Trichoderma* against plant pathogens. (A), (C), (E) and (G) *Rhizoctonia solani*, *Sclerotium rolfsii*, *Fusarium oxysporum* and *Colletotrichum capsici* culture without *Trichoderma*, respectively. (B), (D), (F) and (H) *R. solani*, *S. rolfsii*, *F. oxysporum* and *C. capsici* culture with *Trichoderma* isolate Pb-22, respectively

Trichoderma spp. can also synthesize the secondary types of defensive metabolite, known as polyketides, through sequential actions catalyzed by a complex of enzymes known as polyketide synthases. *T. viride* produces trichotoxins A and B, trichocellins, trichodecenins, and trichorovins whereas other *Trichoderma* strains produce a vast array of antibiotics (Reino *et al.*, 2007). Trichorzianins A and B, HA, MA and trichorzins were also recovered from *T. harzianum* culture filtrate. Interestingly, *T. longibrachiatum* can produce tricholongins BI and BII, while *T. koningii* yields trichokonins and longibrachins; *T. atroviride* cultures yield neoatroviridins A-D and atroviridins A-C. In addition, *T. aureoviride*, *T. viride*, *T. hamatum*, *T. koningii*, *T. harzianum*, *T. virens*, and *T. lignorum* cultures yielded additional antibacterial and fungicidal compounds, such as trichoviridin, koningins, dermadin, koningic acid and lignoren, viridin, (Reino *et al.*, 2007). Gliovirin and gliotoxin are two of the most important 2° metabolites produced by *Trichoderma* strains belonging to the P and Q groups, respectively. *T. virens* P group strains negatively impact *Pythium ultimum*, but not *R. solani*. However, the Q group is more aggressive against *R. solani* (Howell *et al.*, 2000). *T. virens* gene veA ortholog vel1 encodes the VELVET protein, which regulates the production and biocontrol action of gliotoxin and other genes involved in 2° metabolism (Mukherjee *et al.*, 2012).

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In the presence of Koninginin D, the growth of soil-borne pathogens such as *R. solani*, *Fusarium oxysporum*, *Pythium middletonii*, *Bipolaris sorokiniana*, and *Phytophthora cinnamomic* was reported to be inhibited (Dunlop *et al.*, 1989). Viridins derived from *Trichoderma* spp. Such as *T. viride*, *T. virens*, and *T. koningii* inhibited the germination of *Botrytis allii*, *Aspergillus Niger*, *Fusarium caeruleum*, *Penicillium expansum* *Stachybotrys atra* and *Colletotrichum lini* spores (Singh *et al.*, 2005). Harzianic acid produced from *T. harzianum* exhibited antibacterial activity against *Sclerotinia sclerotiorum*, *Pythium irregulare*, and *R. solani in vitro* (Manganiello *et al.*, 2018). *T. asperellum* strain generated two asperelines (A and E) and five trichotoxins called T5G, T5D2, 1717A, T5E, and T5F with antibiotic properties (Brito *et al.*, 2014). In many cases, the antibiotic effect is combined with lytic enzymes, resulting in enhanced antagonistic activity compared to antibiotics or enzymes acting independently (Monte, 2001). According to Howell (2003), the initial breakdown of cell walls by lytic enzymes, as observed in *F. oxysporum* and *B. cinerea* facilitates improved penetration of antibiotics into the target hyphae.

Mycoparasitism

Parasitism delineates a symbiotic relationship between two organisms where one benefits while the other is adversely affected. Mycoparasitism refers to a form of association wherein a parasitic fungus, known as a hyperparasite, thrives as a parasite on another fungus, termed a hypoparasite. It is also referred to as hyperparasitism when biocontrol fungi, acting as

hyperparasites, parasitize pathogenic fungi, the hypoparasites, to utilize them as a source of nutrients. Hyperparasites generate parasitizing hyphae to acquire nutrients from the host. The bio-agent ensnares the pathogen by coiling around its hyphae. *Trichoderma* demonstrates the ability to hyperparasitize and secrete hydrolytic enzymes, such as chitinases, cellulases, xylanases, glucanases, and proteinases, which degrade the host's cell wall. It identifies the host fungus and initiates attack through hyphal diffusion preceding cell lysis. The interaction between the parasitic fungus and the host (pathogen) involves coiling, haustoria formation, secretion of various hydrolytic enzymes aiding hyphal penetration, production of antimicrobial metabolites, host demise, and subsequent nutrient extraction from the decomposed organic matter (Omann *et al.*, 2012). Several studies demonstrate that numerous *Trichoderma* strains attack and destroy plant-pathogenic fungi, such as *Fusarium* spp., *Pythium* spp., *R. solani*, *Ustilago maydis*, *Alternaria alternata*, *S. rolfisii*, *Botrytis cinerea* and *Meloidogyne javanica* through mycoparasitism (Harman *et al.*, 2004; Druzhinina *et al.*, 2011). During parasitism, *T. harzianum* isolates 203 parasitizes *S. rolfisii* and generates hydrolytic enzymes, chitinase, and (1,3) glucanase inside the attacked sclerotia. (Elad *et al.*, 1984). *T. harzianum*-248 parasitized the *Meloidogyne javanica* and declined reproduction such as eggs (Sharon *et al.*, 2009). *Trichoderma* interacted with *R. solani* and coiled around the host cells, penetrating, plasmolysis, and destroying the hyphae (Tzavella-Klonari and Deligianni-Mappa, 1991). *T. atroviride* and *T. harzianum* parasitized the seed and soil-borne *Fusarium* fungus (Sharma, 2011). It has been demonstrated that about 20-30 known genes, proteins, or metabolites are engaged in this activity (Lorito *et al.*, 1998).

Competition

The inadequate supply and contest for nutrients result in the natural control of phytopathogen populations. Competition for micro- and macronutrients, such as carbon, nitrogen, and iron, plays a crucial role in interactions between beneficial and harmful fungi. *Trichoderma* species struggle with pathogens for resources, colonization niches, and infection sites in the rhizosphere. *Trichoderma* is superior to other rhizospheric microorganisms in its ability to mobilize resources and occupy niches. *Trichoderma* outperforms other soil microbes in competent mobilization and utilization of immobilized nutrients. *Trichoderma* achieves this by lowering soil pH through biosynthesis and releasing organic acids such as gluconic, and fumaric. Furthermore, these organic acids aid in the solubilization of micronutrients and mineral cations such as phosphates, magnesium, iron, and manganese, (Vinale *et al.*, 2008). Additionally, Fe ions act as cofactors for various enzymes and are essential nutrients for plant growth and

development (Miethke, 2013). In the presence of oxygen with pH 7 iron exists primarily as Fe³⁺. In an aerobic environment, Fe tends to form an insoluble ferric oxide, rendering it unavailable for root absorption (Miethke, 2013). *Trichoderma* spp. Secretes an iron-chelating compound known as a siderophore. This complex binds to insoluble Fe³⁺ and converts it to the easily absorbable soluble form Fe²⁺. Siderophore increases the availability of Fe to plants while simultaneously depleting soil Fe sources, inhibiting the growth of target fungi (Srivastava *et al.*, 2018). Fungal siderophores identified to date are commonly classified as hydroxamates and are categorized into three families for instance, fusarinines, coprogens, and ferrichromes. *Trichoderma* produces various types of siderophores, which play a crucial role in enabling fungi to withstand unfavorable soil conditions. Siderophores synthesized by antagonistic fungi can potentially hinder the growth and progression of plant pathogens by sequestering iron nutrients, thereby limiting their availability (Mukherjee *et al.*, 2012).

Induced Plant Resistance

Trichoderma and other microbial biocontrol agents are commonly employed in sustainable agriculture to manage crop diseases and boost plant productivity. *Trichoderma* can colonize plants and induce systemic and local resistance to various plant diseases (Harman *et al.*, 2004; Shores *et al.*, 2010). Induce Systemic Resistant

(ISR) is one of several biocontrol techniques of *Trichoderma* for evading plant diseases by triggering a defensive reaction. ISR mediated by *Trichoderma* species in plants involves the activation of augmented defense responses against invading pathogens. Induction of Pathogenesis-Related (PR) proteins such as glucanases and chitinases and the mechanical strengthening of cell walls via lignification are also observed in *Trichoderma*-induced plants (Table 5). Other significant plant defense enzymes synthesizing phenolic antimicrobial chemicals include phenylalanine-ammonia-lyase, polyphenol oxidase, and peroxidase (Patel and Saraf, 2017). The 2° metabolites 6-pentylpyrone and harzianalide produced by *T. atroviride* and *T. harzianum* can also induce systemic defensive responses in tomato and oilseed rape seedlings against *Leptosphaeria maculans* and *B. cinerea* (Vinale *et al.* 2008). *T. virens* produces peptaibols of fourteen and eighteen amino acids, each with a range of isoforms that elicit systemic resistance (Viterbo *et al.*, 2007). *Trichoderma* spp., in fact, interacts with a plant's defense system during root colonization by releasing antimicrobial compounds (e.g., phytoalexins). The interaction with plants in the early stages of root colonization may trigger cell detoxification and plant defense mechanisms (Ruocco *et al.*, 2009). Inducing terpenoid phytoalexins toxic by *T. virens* protects *Gossypium hirsutum* from *R. solani* (Kumar and Palakshappa, 2009).

Table 5: *Trichoderma* spp. elicit Induced Systemic Resistance (ISR) chemical compounds

<i>Trichoderma</i> spp.	Crops	Pathogens	Products	References
<i>T. virens</i>	<i>Gossypium hirsutum</i>	<i>Rhizoctonia solani</i>	Inducing terpenoid phytoalexins toxic for protecting plants against fungi	Kumar and Palakshappa (2009)
	<i>Solanum lycopersicum</i>	<i>Pseudomonas syringae</i>	Producing proteins-Sm1 and Ep11 to induces systemic resistance in plants	Salas-Marina <i>et al.</i> (2015)
<i>Trichoderma</i> spp.	<i>Musa sapientum</i>	<i>F. oxysporum</i> f. sp. <i>ubense</i>	ISR-based induction of PAL, POs, and surge in total phenolic compound	Bubici <i>et al.</i> (2019)
<i>T. koningii</i>	<i>M. sapientum</i>	<i>F. oxysporum</i> f. sp. <i>ubense</i>	ISR-based induction of PAL, POs, and surge in total phenolic compound	Thangavelu and Mustafa (2010)
<i>T. pseudokoningii</i>	<i>M. sapientum</i>	<i>F. oxysporum</i> f. sp. <i>ubense</i>	ISR-based induction of PAL, POs, and surge in total phenolic compound	Thangavelu and Gopi (2015)
<i>T. hamatum</i>	<i>M. sapientum</i>	<i>F. oxysporum</i> f. sp. <i>ubense</i>	ISR-based induction of PAL, POs, and surge in total phenolic compound	Thangavelu and Gopi (2015)
<i>T. harzianum</i>	<i>Nicotiana tabacum</i>	<i>Ralstonia solanacearum</i>	ISR-based intensification in POX, PPO, and PAL actions	Yuan <i>et al.</i> (2016)
	<i>Piper nigrum</i>	<i>Phytophthora capsici</i>	Producing of the phytoalexins capsidiol toxic for protecting plants against fungi	Ahamed and Vermette (2009)
	<i>Cicer arietinum</i> <i>P. vulgaris</i>	<i>S. rolfsii</i> <i>F. solani</i>	Induced phenolic compounds Producing of PPO, PO, and chitinase.	Singh <i>et al.</i> (2013) Abd-El-Khair <i>et al.</i> (2019)
<i>T. atroviride</i>	<i>Arabidopsis thaliana</i>	<i>B. cinerea</i>	Phyostimulation, salicylic acid, Jasmonic acid, and camalexin	Contreras-Cornejo <i>et al.</i> (2011)
<i>Trichoderma</i>	<i>Solanum melongena</i>	<i>Sclerotium rolfsii</i>	Rise in phenolic content, predominantly gallic, shikimic, t-chlorogenic, and syringic acid	Bisen <i>et al.</i> (2019)
<i>T. viride</i>	<i>P. vulgaris</i>	<i>F. oxysporum</i> f. sp. <i>phaseoli</i>	Involvement of volatile metabolites in reducing fox	Carvalho <i>et al.</i> (2014)
	<i>M. sapientum</i>	<i>F. oxysporum</i> f. sp. <i>ubense</i>	ISR-based induction of PAL, POs, and phenolic compound	Thangavelu <i>et al.</i> (2004)

T. virens helps to stimulate defense responses, JA, salicylic acid, and camalexin production in *Arabidopsis* for controlling the infestation from *B. cinerea* (Contreras-Cornejo *et al.*, 2011). ISR elicited by *Trichoderma* spp., *T. pseudokoningii*, *T. koningii*, *T. hamatum*, *T. harzianum*, against *F. oxysporum* f. sp. *cubense* and *Ralstonia solanacearum* was associated with induction of POs, PAL and surge in total phenolic compound (Maketon *et al.* 2008; Thangavelu and Mustafa, 2010; Thangavelu and Gopi, 2015; Thangavelu and Gopi, 2015; Yuan *et al.*, 2016; Bubici *et al.*, 2019) (Table 5).

Bulk Production of *Trichoderma* Formulation

Developing a functioning product, formulation and delivery system is the core of successful biological control methods for effective plant disease management practice. Bulk production, quality control, delivery, and its scope in commercialization are essential for developing any *Trichoderma* formulation. Cost-effective mass propagation of *Trichoderma* could only support an ample supply of the agent. According to Nakkeeran *et al.* (2006), an ideal inoculant formulation should meet shelf life, non-phytotoxicity, solubility in water and quickly release the microbial inoculants, tolerance to an adverse environment, cost-effective, capability of controlling plant diseases and availability of the raw materials. *Trichoderma*'s mass

production systems should be compatible with industrial and commercial expansion processes and field applications. There are two basic ways for mass production of *Trichoderma* inoculum, where one is solid and another is liquid state fermentation. Considering the cost of the substrates, solid fermentation appears to be more suitable and economical for large-scale production of *Trichoderma*. A variety of low-cost organic materials can be employed as substrates (Jeyarajan, 2006; Rubayet and Bhuiyan, 2012, Faruk *et al.*, 2015). Many researchers found that rice bran, wheat bran, grass pea bran, mustard oilcake, corn, chickpea meal, tea waste, millets, rice straw, sugar beet pulp, sorghum grain, corn bagasse, sugarcane bagasse, and fortified compost such as poultry refuse as suitable ingredients for bulk production of *Trichoderma* spp. (Rubayet and Bhuiyan, 2012; Boblina *et al.*, 2019; Naeimi *et al.*, 2020; Simon and Anamika, 2011; Pandya *et al.*, 2012; Rini and Sulochana, 2007; Singh *et al.*, 2014; Kumar and Palakshappa, 2009; Tewari and Bhanu, 2004; Mulatu *et al.*, 2021; Kumar and Sahu, 2014; Rahman *et al.*, 2024; Chowdhury *et al.* 2024) (Table 6). These substrates can be prepared singly or as a mixture of different substrates in varying proportions. Despite its many advantages, it has some disadvantages, notably the time and space required for inoculum preparation.

Table 6: Different substrates are used for the production of *Trichoderma* spp.

<i>Trichoderma</i> spp.	Suitable substrates	References
<i>T. polysporum</i>	Sorghum grains	Rajput and Shahzad (2015)
<i>T. harzianum</i>	Wheat grain	Rubayet and Bhuiyan (2012)
	Vermicompost	Boblina <i>et al.</i> (2019)
	Rice straw and husk, pulp of sugar beet, broom sorghum grain, and cow dung	Naeimi <i>et al.</i> (2020)
	Wastes of spinach, banana, papaya, tealeaves guava, brinjal, pea husk, and sugarcane	Simon and Anamika (2011)
	Sorghum grain	Pandya <i>et al.</i> (2012)
	Coir pith + neem cake (1:1)	Rini and Sulochana (2007)
	Mushroom compost	Singh <i>et al.</i> (2014)
	Maize grain	Kumar and Palakshappa (2009)
	Wheat bran and paddy straw	Tewari and Bhanu (2004)
	Poultry Refuse	Rahman <i>et al.</i> (2024); Chowdhury <i>et al.</i> (2024)
<i>T. viride</i>	Wastes of spinach, banana, papaya, tealeaves guava, brinjal, pea husk, and sugarcane	Simon and Anamika (2011)
	Coir pith + neem cake (1:1)	Rini and Sulochana (2007)
	Dried lima bean shell	Yparraguirre and Galliani-Pinillos (2020)
<i>T. longibrachiatum</i>	Wheat bran and white rice and (2:1 w/w)	Mulatu <i>et al.</i> (2021)
<i>T. asperellum</i>	Wheat bran and white rice and (2:1 w/w)	Mulatu <i>et al.</i> (2021)
<i>Trichoderma</i> spp.	Cotton husks	Ramos <i>et al.</i> (2008)
	Compost and paddy husk	Irfeey <i>et al.</i> (2018)
	Millet	Kumar and Sahu (2014)

On the other hand, liquid-state fermentation is used to plenty production of *Trichoderma* inoculum in a fluid medium before applying it in the field (Rajesh *et al.*, 2016). This technique is so easy and efficient for maximum *Trichoderma* biomass and inoculum production. Molasses yeast medium, Potato Dextrose Broth (PDB), and V8 juice are commonly used as the liquid-based substrate for large-scale production of *T. harzianum* Rifai (Hassan, 2014). Commercial uses of *Trichoderma* spp. for promoting crop health and managing plant diseases rely on developing commercial formulations with suitable carriers that enable *Trichoderma* spp. to endure indeterminately. Formulations such as talc, vermiculite-wheat bran, pasta granules, alginate prills, press mud, coffee husk and oil, and banana waste-based formulations are commonly used for enhancing the *Trichoderma* shelf life (Jeyarajan *et al.*, 1994; Lewis and Papavizas, 1991; Connick *et al.*, 1991; Prasad and Rangeswaran, 1998; Jeyarajan, 2006; Sawant and Sawant, 1996) (Table 7). As a carrier material, several types of organic well-decomposed composts such as a farmyard, vermicompost, poultry refuse, and cow dung are occasionally used. Using such *Trichoderma* formulations reduces plant disease and increases soil fertility. Because the shelf life of a bio-agent is critical to its successful commercialization. In general, antagonists formulated in an organic food base have an extended shelf life than those formulated in an inorganic or inert food base. The shelf life of *Trichoderma* formulation in coffee husk is >18 months, whereas talc, peat, lignite, and kaolin shelf life of 3-4 months. *Trichoderma* propagules in talc formulation lost 50% of their viability after 120 days of storage (Sankar and Jeyarajan, 1996). However, Bhat *et al.* (2009) reported that talc-based formulations stored at room temperature had a shelf life of up to 180 days.

Trichoderma Metabolites as Potent Biopesticides

Secondary Metabolites (SMs) play a significant role in the complicated interactions among bio-agents, plants, and pathogens. The SMs biosynthesized by microbes are natural chemicals of low molecular weight (usually 3 kDa) and are typically unique to genera, species, or strains (Vinale *et al.*, 2009). These chemicals have been shown to reduce the proliferation and destructive actions of pathogens directly and augment disease resistance by triggering the plant defensive system. *Trichoderma* species secrete a multitude of metabolites while having minimal nutritional requirements. These metabolites can be used for agricultural, industrial, and medical purposes, making them essential to humans. Several *Trichoderma* spp. Show antifungal activities against phytopathogenic fungi, which may involve various classes of SMs such as gliovirin, terpenes, gliotoxin, pyrones, and peptaibols (Vinale *et al.*, 2008) (Table 8). Gliotoxin plays a crucial role in the biocontrol activity of *Trichoderma* virens against specific plant pathogenic fungi (Vey *et al.* 2001). *T. virens* biocontrol strains also generate gliotoxin, which was effective against *R. bataticola*, *Macrophomina phaseolina*, *Pythium deharyanum*, and *Pythium aphanidermatum* (Khan *et al.*, 2020). Gliovirin, an additional member of this class of toxins is primarily produced by a strain of *Trichoderma longibrachiatum* and *T. virens*. Gliovirin and its analogs were antifungal against *R. solani* and *Pythium ultimum* (Nakano *et al.*, 1990). Peptaibols are linear peptides composed of α , α -dialkylated amino acids, isovaline, amino isobutyric acid (Aib), an acetylated N-terminus, and a C-terminal amino alcohol. Peptaibols are primarily produced by *Trichoderma* species. Three peptaibols derived from *Trichoderma koningii*, trichokonins VI, VII, and VIII, exhibited broad-spectrum antimicrobial activity against a broad range of plant pathogens, including *Verticillium dahliae*, *Fusarium oxysporum*, *R. solani* and *Botrytis cinerea* (Khan *et al.*, 2020).

Table 7: List of different formulations developed using *Trichoderma* spp.

Types	Ingredients	References
Formulation based on talc	Liquid medium + talc powder (1:2)	Jeyarajan <i>et al.</i> (1994)
Vermiculite-wheat bran	Vermiculite = 100 g Wheat bran = 33 g Wet fermentor biomass = 20 g and 0.05N HCL = 175 mL	Lewis and Papavizas (1991) Connick <i>et al.</i> (1991)
Pesta granules	Wheat flour (WF) = 100 g Fermentor Biomass (FB) = 52 mL Sufficient sterile water up to form a dough	Prasad and Rangeswaran (1998)
Wheat flour- kaolin	WF = 80 gm; Kaolin = 20 gm FB = 52 mL	Fravel <i>et al.</i> (1995)
Alginate prills	Sodium Alginate = 25 gm WF = 50 gm; FB = 200 mL	Jeyarajan (2006)
Press mud	A mixture of mud and organic manure	Sawant and Sawant (1996)
Coffee husk	Main component of coffee husk	Batta (2007)
Formulation based on oil-	Vegetable or mineral oils in stable emulsion formulation	Doni <i>et al.</i> (2014)
Agro-product-based formulation	Suspension mixed with corn and sugarcane bagasse	

Table 8: List of *Trichoderma* 2° metabolites as potent biopesticides against plant pathogens

<i>Trichoderma</i> spp.	2° metabolites	References
<i>T. virens</i>	Glitoxin	Hua <i>et al.</i> (2021)
<i>T. koningii</i>	Cell wall-degrading biochemical materials such as β -1,3-glucanase & chitinase Secretion defense enzymes, β -glucanase, and chitinase produced by IAA and Gibberellic	Hirpara <i>et al.</i> (2017) Kamel <i>et al.</i> (2020)
<i>Trichoderma</i> spp. <i>T. viride</i>	Phenylalanine ammonia-lyase, chitinase, glucanase, and peroxidase Secretion defense enzymes and growth hormones such as chitinase and Gibberellic Inorganic phosphate, IAA, and siderophore Steroids and alkaloids Volatile metabolites 6-Pentyl pyron Caryophyllene oxide	Maddu and Ravuri (2021) Kamel <i>et al.</i> (2020) Kotasthane <i>et al.</i> (2015) Muhibbudin <i>et al.</i> (2021) Amin <i>et al.</i> (2010) Kotasthane <i>et al.</i> (2015) Awad <i>et al.</i> (2018)
<i>T. harzianum</i>	Secretion defense enzyme, chitinase, and β -glucanase produced IAA and Gibberellic Induce defense enzymes (2-3 folds) and phenolic content (3 folds) Volatile metabolites Dermin, gliotoxin, glioviridin, trichodermin, and viridin β -glucanase, β -glucosidase, gliotoxin, hydrazinopyridine, harzianolide, peptaibols, trichodermin, and viridin Volatile (toxic) and nonvolatile metabolites Cellulase Cell Wall Degrading Enzymes (CWDE)	Kamel <i>et al.</i> (2020) Muthukumar and Venkatesh (2014) Shaigan <i>et al.</i> (2008) Eziashi <i>et al.</i> (2007) Vinale <i>et al.</i> (2008) Swathi <i>et al.</i> (2015) Rashmi <i>et al.</i> (2016) John <i>et al.</i> (2015)
<i>T. longibrachiatum</i>	1-butanol 2-methyl, cedrene, caryophyllene, cuprenene, and longifolene Volatile Organic Compounds (VOC)	Sridharan <i>et al.</i> (2020-2021) Sridharan <i>et al.</i> (2020)
<i>T. asperellum</i>	CWDE Butenolides, cyclonerodiol, ferulic acid, gliovirin massoilactone, harzianolides, viridifungin A, viridin, and viridiol	John <i>et al.</i> (2015) Srinivasa <i>et al.</i> (2017)
<i>T. hamatum</i>	Volatile metabolites	Shaigan <i>et al.</i> (2008)
<i>T. atroviride</i>	Glucanase	Rashmi <i>et al.</i> (2016)

Isolated from *Trichoderma pseudokoningii*, Trichokonin VI induced extensive apoptotic programmed cell death in *Phytophthora parasitica*, *B. cinerea*, *Ascochyta citrullina*, *F. oxysporum*, and *V. dahlia* (Shi *et al.*, 2012). Trichokonins were also highly active for *Clavibacter* spp., a pathogen that infects economically significant crops such as maize, potato, and tomato (Meletzus and Eichenlaub, 1991). The peptaibols trichorzianine A1 and B1 from *T. harzianum* could inhibit the spore germination and hyphal elongation of plant pathogenic fungi (Lee *et al.*, 1999). The volatile organic compound Pyrone 6-PP was reported to be produced by *T. koningii*, *T. viride*, and *T. harzianum*. At a concentration of 0.3 mg/mL, it inhibited the growth of *F. oxysporum* by 31.7% and *R. solani* by 69.6%, respectively (Khan *et al.*, 2020). It was discovered that *T. harzianum* produces three bioactive analogs of pyrone 6-PP (Parker *et al.*, 1997). Another pyrone analog, viridepyronone, was made by a strain of *T. viride* and inhibited the growth of *S. rolfisii* by 90% at a minimum inhibitory concentration of 196 mg/ml (Evidente *et al.*, 2003). Harzianolide and T39 butenolide are antifungal butenolide compounds, which were isolated from strains of *T. harzianum*. These compounds were all antifungal against *P. ultimum*, *Gaeumannomyces graminis* var. *tritici*, and *R. solani* (Vinale *et al.*, 2006). The antifungal harzianopyridone was isolated from *T. harzianum*, which

contains a 2,3-dimethoxy-4-pyridinol-patterned pyridine ring system (Vinale *et al.*, 2006). The racemic form of harzianopyridone exhibited potent antifungal activity against plant-pathogenic fungi, including *R. solani*, *P. ultimum*, *G. graminis* var. *tritici*, *Botrytis cinerea*, *Phytophthora cinnamomi* and *Leptosphaeria maculans* (Vinale *et al.*, 2009). The azaphilones, such as harziphilone, fleophilone, and T22 azaphilone produced by *T. harzianum*, exposed substantial antifungal activity counter to *B. cinerea*, *P. ultimum*, *G. graminis* var. *tritici*, *P. cinnamomi*, *R. solani* and *L. maculans* (Vinale *et al.*, 2006; 2009). *T. koningii* and *T. harzianum* produced stigmaterol, which exhibited antifungal activity against *M. phaseolina*, *S. rolfisii*, *F. oxysporum*, and *R. solan* (Ahluwalia *et al.*, 2015). Two other steroids isolated from *Trichoderma* sp. YM 311505, ergosterol, and 3,5,9-trihydroxyergosta-7,22-dien-6-one exhibited potent antifungal activity against *Aspergillus niger*, *Pyricularia oryzae*, *Alternaria alternata*, and *Candida albicans* with MIC values of 32 g/mL (Xuan *et al.*, 2014). Three anthraquinones including 1,8-dihydroxy-3-methylantraquinone, 1-hydroxy-3-methylantraquinone (34), and 6-methyl-1,3,8-trihydroxyanthraquinone were identified in *T. harzianum* strains and found effective against *M. phaseolina*, *R. solani*, *F. oxysporum* and *S. rolfisii* (Ahluwalia *et al.*, 2015).

Conclusion and Future Perspectives

Organic agriculture necessitates prioritizing organic fertilizers and biopesticides to promote sustainable farming practices. Among microbial agents, *Trichoderma* has demonstrated exceptional potential as both a biofertilizer and biocontrol agent. Its enhanced competitive ability against harmful organisms has increased its application in managing a wide range of plant diseases, including those caused by fungi, nematodes, viruses, and bacteria. The effectiveness of *Trichoderma* as a bio-agent for various seed- and soil-borne diseases underscores its potential in achieving sustainable agriculture goals. Despite its advantages, *Trichoderma* is not as widely used as chemical fertilizers and pesticides. Several obstacles hinder its widespread acceptance, including its slower action compared to chemical alternatives, which limits its immediate effectiveness. *Trichoderma* does not completely eradicate plant pathogens, leading to residual disease presence and its performance can be inconsistent under different environmental conditions, affecting its reliability. Additionally, *Trichoderma* often struggles to establish itself effectively in the rhizosphere and the diverse and unpredictable field conditions pose challenges to its consistent application and efficacy. To address these challenges, future efforts should focus on improving the field performance of current biocontrol agents. Coordinated application strategies should be developed. Investment in advanced formulations that enhance the stability and activity of *Trichoderma* strains is necessary. Strengthening the inherent biocontrol properties of *Trichoderma* through biotechnological innovations is also crucial. A deeper understanding of the *Trichoderma* genome can facilitate the production of genetically modified strains with superior commercial and field potential, creating genetically enhanced strains that exhibit improved biocontrol properties and better adaptability to varying environmental conditions. The implementation of comprehensive policy frameworks at national and international levels is critical for promoting the use of *Trichoderma* in agriculture. Supporting initiatives that encourage the large-scale production and commercialization of *Trichoderma*-based products and developing policies that facilitate their efficient distribution and utilization among farmers are essential. Such measures are anticipated to support the sustainable management of plant diseases and significantly impact agricultural practices, promoting a shift towards more eco-friendly and sustainable farming systems.

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Author's Contributions

Md. Tanbir Rubayet: Research planning, data collection, drafted and data analysis.

Md. Motaher Hossain: Conceptions, fund acquisition, research designed and drafted reviewed.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that other authors have read and approved the manuscript and no ethical issues involved.

Conflict of Interest

The authors have no conflict of interest.

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