Chapter 15
Role of *Trichoderma* in Agriculture and Disease Management

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Contents

1 Introduction

Trichoderma spp., free-living saprophytic fungi, is found commonly in the soil where plant roots sustain especially in intercellular spaces. This fungus is known to be highly interactive in three different environments, viz., soil, root, and foliar (Singh et al. 2006). The first description of this fungus was recorded in Germany in the year 1791. In 1927, four species of this fungus is identified based on color, conidial shape, and colony appearance by Gilman and Abbott. There are two major species, i.e., *T. lignorum* (due to conidial globose structure) and *T. koningii* (due to conidial oblong structure), which are mostly known. In 1932, Weindling has shown its capability as an effective biocontrol agent toward pathogen, *Rhizoctonia solani*. Harman et al. (2004) had revealed this fungus to be opportunistic and avirulent symbiont, and at times, it also possesses parasitic capability. Several *Trichoderma* species such as *T. harzianum*, *T. viride*, *T. hamatum*, *T. koningii*, and *T.*

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longibrachiatum have phytopathogenic property against a number of fungi like *Pythium ultimum*, *Fusarium oxysporum*, *Sclerotinia sclerotiorum*, etc. (Manczinger et al. 2002).

Trichoderma is one recognized fungus which is being used as a biocontrol agent since 1920 (Samuels 1996). They are known to improve plant health along with their natural capability to degrade the toxic compounds produced by the plants. It is important for the overall growth of the plant, and its function is not limited to disease control particularly to soil-borne diseases (Zaidi et al. 2014). *Trichoderma* is a ubiquitous genus which grows in wider habitats and at high population densities (Chaverri et al. 2011). This could be proved through its diverse applications and role. The fungus have increase reproductive ability. It is known to survive under abiotic stress conditions and compete with other pathogens for the uptake of nutrients for their survival, augmenting the plant defense system (Tripathi et al. 2013; Daguerre et al. 2014; Keswani et al. 2014). Certain species of this fungus also have multiple interactions with crop plants, for example, *Trichoderma harzianum* strain T22 and *Trichoderma atroviride* strain P1 (Woo et al. 2006). This chapter focuses on the role of *Trichoderma* in agriculture and disease management.

2 Characteristic Features of *Trichoderma*

Increased growth rate, bright green conidia in major strains of this fungus, and repetitively branched structure of conidiophore are the main characteristics of this fungus (Gams and Bissett 1998). This fungus is known to be a flourishing colonizer of their habitat. It can be indicated by the way it utilizes the substrate and secretes enzymes and antibiotic compounds irrespective of the environmental condition, whether the condition is like that of tropical rainforest or of biotechnological fermentor (Schuster and Schmoll 2010). In *Trichoderma* colonization, the fungus identifies and adheres to root via hydrophobins or expansin-like proteins through which it penetrates in the tissues of the plant. Hydrophobins are small proteins which are hydrophobic, and it coats the cell wall of the fungus, whereas swollenin is also protein molecule that is known to break the cell wall of the plant (composed of crystalline cellulose structure) due to the carrier of cellulose-binding molecule which assists in the expansion of cell wall of root cells and root hairs (Brotman et al. 2008). For instance, *T. asperellum* produces TasHyd 1 (belonging to class I hydrophobin) and swollenin TasSwo (belonging to expansin-like proteins) that helps in protecting its hyphal tips and root colonization (Viterbo and Chet 2006; Brotman et al. 2008). Druzhinina et al. (2011) had revealed that due to an increase in root surface area by swollenin molecule, *Trichoderma* takes extra benefit during its establishment in the rhizosphere. The plant-derived sucrose is an important resource by which *Trichoderma* cells assist three aspects, i.e., root colonization, synchronization of defense mechanisms, and improved photosynthetic rate (Vargas et al. 2009). In root colonization process, *Trichoderma* swaps molecular messages and also causes fungal deposition by elicitors in apoplastic cells of roots

(Contreras-Cornejo et al. 2014; Gupta et al. 2014). Shoresh and Harman (2008) had shown that though *T. harzianum* Rifai strain 22 (T22) resides in roots, only their role during colonization is prominent as it stimulates impactful alterations in proteome of corn shoot seedlings. Morán-Diez et al. (2009) had also revealed that *T. harzianum* secretes endopolygalacturonase, ThPG 1 (plant cell wall-degrading enzymes) during active root colonization. Furthermore, Chacón et al. (2007) had illustrated that after 72 h of colonization of roots with *Trichoderma*, cell walls of plant epidermis and the cortex are much stronger than nontreated plants, and even they possess cellular deposition (consists of an abundance of callose) which acts as a barrier for the pathogens.

3 Role of *Trichoderma* in Agriculture

Trichoderma is a well-known fungus for its diverse uses in agriculture. Some strains of this fungus cause a direct impact on the plant by enhancing their growth and uptake of nutrients (Table 15.1). The nutrient uptake by *Trichoderma* causes the secretion of organic acids which help in dissolving many minerals and trigger the uptake of nutrients from soil. This in turn led to consumption and movement of nutrients. Besides, the involvement of *Trichoderma* in the soil causes expansion in the area of rhizosphere and rise in secretion of organic acids and extracellular enzymes (phosphatase, urease, etc.) due to its ability of colonization. This will result in an improvement of cycling of nutrients and enzymatic activity. Harman (2011) and Khan et al. (2017) had revealed that this fungus helps in the conversion of nutrients into useful nutrients as required by the plant. This was also supported by Mbarki et al. (2016) who suggested that rise in nutrient and enzymatic activity helps in improving the quality of soil and enhancing the growth of a plant. Different species of *Trichoderma* are also known to break down N compounds into available N by releasing nitrous oxide (Maeda et al. 2015). Soil-borne diseases are known to arise due to the discrepancy in soil microbes, and *Trichoderma* is effective in controlling soil-borne diseases due to its property of rapid growth and vitality as it covers the space where microbes develop and even uptake the nutrients which otherwise could be used up by the microbes causing soil-borne diseases (Zhang 2015). *Trichoderma* besides increasing nutrient uptake also promotes the growth of beneficial microbes and their biomass (Wagner et al. 2016). Hyperparasitism is another property of this fungus in which there is a secretion of cell wall-degrading enzymes, such as xylanases, cellulases, etc., that helps in good growth and development. Besides, higher-use efficiency of fertilizer, seed germination rate, and plant defense system are also having a strong positive impact of this fungus (Shoresh et al. 2010). *Trichoderma* is also playing an effective role in unraveling the mysteries of the molecular biology of plants. A significant rise in height and weight of dwarf tomato plants has been reported after treatment with *T. viride* by 28% and 8%, respectively (Lindsey and Baker 1967). This was also seen in other plant species too such as pepper, chrysanthemum, and periwinkle where this fungus (*Trichoderma*

Table 15.1 Role of certain *Trichoderma* species in plant growth promotion and nutrient uptake

Trichoderma species	Plants	Role of the fungus on plant	References
Plant growth promotion			
T. harzianum	Pepper, chrysanthemum, and periwinkle	• Improved the germination. • Flowering incidence and occurrence. • Height and fresh weight.	Chang et al. (1986)
T. viride	Tomato	Height and weight of dwarf tomato plants	Lindsey and Baker (1967)
T. harzianum and *Trichoderma koningii*	Corn, tomato, tobacco, and radish	Increased germination rates, emergence, and dry weights	Windham et al. (1986)
Trichoderma harzianum T22	Crack willow (*Salix fragilis*)	Shoots and roots that were 40% longer and more than double the dry biomass of controls	Adams et al. (2007)
Trichoderma asperellum PR11	Cacao seedlings	Significantly increased plant height, fresh root, and shoot weight against control	Tchameni et al. (2011)
Nutrient uptake			
Trichoderma asperellum PR11	Cacao seedlings	Increase in acid phosphatase activity and phosphorus uptake	Tchameni et al. (2011)
T. harzianum T447	Tomato seedling	Increase in calcium, magnesium, phosphorus, and potassium concentration	Azarmi et al. (2011)
Trichoderma virens As19-1 (T.v7)	Soya bean	Fe uptake is increased up to 77%	Entesari et al. (2013)
Trichoderma asperellum CHF 78	Tomato	Increase dry weight of plant	Li et al. (2018)

harzianum) improved the germination and flowering incidence and occurrence, besides height and fresh weight of plant. Furthermore, Windham et al. (1986) had also revealed that in corn, radish, tomato, and tobacco, *T. harzianum* and *T. koningii* play an important part in augmenting the germination rate of the plant along with its emergence and dry weight.

The following are the major role of *Trichoderma* (Fig. 15.1) in agriculture:

1. *Bio-fertilization*: *Trichoderma* plays an efficient role in improving plant health even when there is no pathogen present. This fungus shows its maximum production in acidic soil as it creates favorable conditions for itself by secreting organic acids which in turn gives additional benefit to the crop grown in such soils. This fungus helps in dissolving mineral ions (Fe, Mn, and Mg) and phosphate ions present in the soil that cause the crop to absorb these nutrients in an easier and better way in which in general condition may not be sufficiently available.
2. *Plant defense system*: This fungus secretes a number of lytic and proteolytic enzymes as well as volatile and secondary metabolites (Table 15.2) for surviving

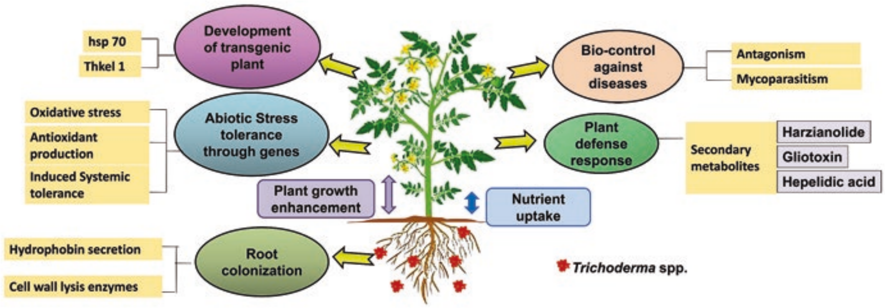

Fig. 15.1 Different responses of *Trichoderma* on plant and its panoply mechanism. *Trichoderma* works in a plant through five ways, i.e., as developer of transgenic plant, biocontroller against diseases, abiotic stress alleviator, root colonizer, and plant defense response

Table 15.2 Some of the secondary metabolites secreted by different species of *Trichoderma*

Trichoderma species	Secondary metabolites	References
T. harzianum	Azaphilone	Vinale et al. (2006)
	Butenolide	
	Harzianolide	Almassi et al. (1991), Claydon et al. (1991), Ordentlich et al. (1992)
	Harzianic acid	Vinale et al. (2009)
	Trichorzianines	Hajji et al. (1987)
	Harzianopyridone	Cutler and Jacyno (1991)
	Dehydroharzianolide	Almassi et al. (1991)
T. viride, *T. atroviride*, *T. harzianum*, *T. koningii*	6-Pentyl-α-pyrone	Vinale et al. (2014), Marra et al. (2006)
T. virens	Gliotoxin	Rajasekaran and Murugesan (2005)
	Heptelidic acid	Pachauri et al. (2020)
T. viridens	Viridian	Awad et al. (2018)
T. viridens	Viridiol	Moffatt et al. (1969)
T. koningii	Koninginin A 1	Harman (2000)
T. koningii	Trichoviridin	Nobuhara et al. (1976)
	Cyclonerodiol	Cutler et al. (1991)
T. cerinum	Cerinolactone	Cutler et al. (1986)

against pathogens present in the same environment. These secondary metabolites are known to be produced at minimal nutrition requirements and are even used in various purposes due to its beneficial properties (Khan et al. 2020). The antifungal activities exhibited by this fungus are known against many fungal pathogens (Vizcaino et al. 2005) wherein secondary metabolites are being involved (Vinale et al. 2008). Besides, it also secretes hydrolytic enzymes such as chitinases, proteases, and glucanases, which are the bases of its relationship with pathogens. This relation is known as mycoparasitism.

3. *As plant survivor under abiotic and biotic stress*: *Trichoderma* fungus is also being used for coping out the plant from abiotic and biotic stress conditions. The interaction of *Trichoderma* and plants exposed to biotic and abiotic stress with pathogenic microbes particularly nematode and fungus is antagonistic (Singh et al. 2004). This antagonistic activity helps in enhancing plant growth, root growth, and resistance to many diseases and abiotic stress (Lorito et al. 2010; Bae et al. 2011; Harman 2000; Shoresh et al. 2010), nitrogen use efficiency, P solubilization, availability of nutrients, and humic acid content (due to organic matter decomposition) (Harman 2011a; Harman and Mastouri 2010; Shoresh et al. 2010). The abiotic stress includes salt stress, high temperatures, and drought (Shoresh et al. 2010). Zaidi et al. (2014) showed that the use of this fungus helps in declining the use of nitrogen efficiency by 30% in certain crops without affecting the crop yields. Such application of this fungus has repercussion in agriculture.
4. *Development of transgenic plants*: Several studies had illustrated that in transgenic plants in which overexpression of genes isolated from *Trichoderma* occurs is a new approach to overcome the situation of adverse condition. For example, development of transgenic plants such as *Nicotiana tabacum* and *Solanum tuberosum* using genes isolated from *T. harzianum* revealed to be tolerant to diseases like *Alternaria*, *Botrytis*, or *Rhizoctonia* (Lorito et al. 1998), and overexpression of chitinases in the same plants were tolerant to abiotic (salt stress and heavy metals) and biotic stress (diseases including fungal and bacterial). Montero-Barrientos et al. (2010) had revealed that cloning of heat-shock protein, HSP 70 gene, from *T. harzianum* in *Arabidopsis* resulted in providing tolerance to heat stress and other associated stresses like salt, osmotic, and oxidative stress. Another gene encoding protein, Thkel 1, from *T. harzianum* showed regulation in glucosidase activity which helped in improving plant growth in *Arabidopsis* plant by providing tolerance against salt and osmotic stress (Hermosa et al. 2011). Studies had also shown that there are many proteins isolated from *Trichoderma*, like small protein 1 (Sm1), PKS/NRPS hybrid enzyme, etc., which are useful in bestowing resistance against various pathogens either soil-borne or foliar (Howell et al. 2000; Perazzoli et al. 2012; Viterbo et al. 2005).

4 Property and Mechanism of *Trichoderma* in Disease Management

Trichoderma strains have long back identified as a biological agent that helps the plant to improve its growth and productivity (Ansari 2017; Singh et al. 2006). It is considered as one of the best biocontrol agents known so far and has attracted the interest of many scientists as a promising substitute to chemical fungicides against several disease-causing pathogenic organisms (Kubicek et al. 2001). Among many of the species identified in *Trichoderma*, five species are known as biological agents (Rifai 1969; Benitez et al. 2004). These are *T. harzianum*, *T. asperellum*, *T.*

atroviride, *T. virens*, and *T. reesei*. These strains can curtail disease severity by inhibiting pathogens which attack the plant either through soil or through roots. They do so by their antagonistic and mycoparasitic property (Viterbo and Horwitz 2010). This fungus stimulates the release of many compounds which provide resistance either in localized or in a systemic manner. In induced systemic resistance (ISR), certain strains of this fungus affect the growth, development, and biochemistry of plant as the fungus colonizes and penetrates inside the root of the plant reaching to its tissues. This helps the plant to defend against many pathogens attacking it (Shoresh et al. 2010; Lorito et al. 2010). Kubicek et al. (2011) had shown its mycoparasitism capability in two species, viz., *T. atroviride* and *T. virens*. Moreover, Druzhinina et al. (2011) had illustrated that there are two aspects which attracted this fungus to grow in rhizosphere, one being the presence of the organism on which it can feed and another being the available nutrients in the root zone of the plants. Both these aspects also help this fungus to improve the growth of the plant. Several studies have reported its role in controlling pathogens of the plant either by elicitation or by developing resistance toward the pathogen (Harman et al. 2004). In addition to this, one of the major mechanisms used in *Trichoderma* for acting as biocontrol agent is its capability of competition for space, nutrients, and formation of volatile compounds (enzymes and antibiotics) against other microbes. The hydrolytic enzymes secreted by this fungus degrade partially the cell wall of pathogen and cause parasitization on the attacked pathogen (Kubicek et al. 2001).

Trichoderma spp. is also known to decline the incidence and severity of disease through plant-mediated mechanism. This mechanism is alike to systemic acquired resistance (SAR) on the phenotypic basis and is known as induced resistance which is mainly concerned with plant parts above the ground and gets activated by this fungus (Singh et al. 2011; Harman 2011). This induced systemic resistance (ISR) is newly discovered in *Trichoderma* and is now attaining much more importance. When roots were inoculated in cucumber plant (of age 7 days), *T. harzianum* helped in increasing plant defense system by increasing activities of peroxidase and chitinase enzyme along with cellulose and cellobiose wall deposition (Yedidia et al. 2001).

5 Interaction of *Trichoderma* spp. with Other Microbes

Trichoderma is an antagonist microorganism that causes a reduction in the growth of the pathogens, and their survival gets difficult by the various mechanisms this fungus adopt (Fig. 15.2) such as enzyme secretion, competition, antibiosis, interactions of its hyphae with another fungus, mycoparasitism, etc. (Singh et al. 2006). During the competition process, this fungus suppresses the growth and survivability of pathogen through its antagonistic property. For instance, 80–85% of collar rot disease in elephant foot yam plant is effectively controlled by *T. harzianum* (Singh et al. 2006). Another important aspect is mycoparasitism where *Trichoderma* attacks the target organism physically not only by acting as a parasite but also by producing toxic chemicals. Some of these chemicals are volatile, like trichothecine,

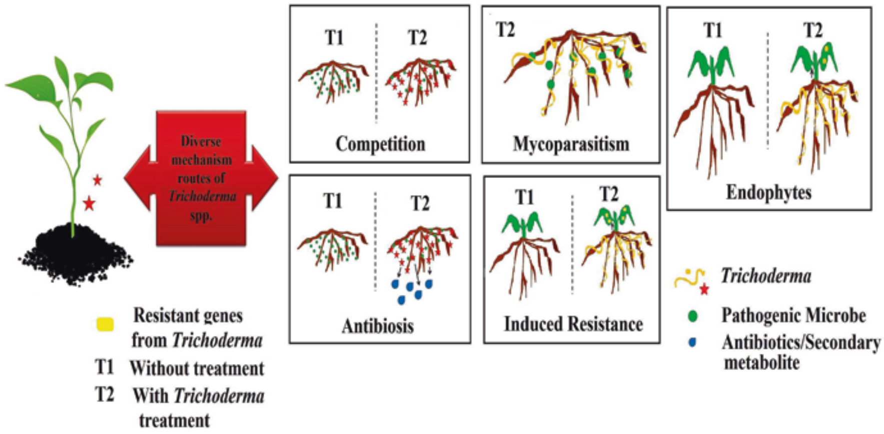

Fig. 15.2 Interaction of *Trichoderma* spp. with pathogens in the plant. *Trichoderma* adopts diverse mechanisms to enhance the overall growth and productivity of the plant. In competition mode, it competes with pathogenic microbe by growing faster and dominating over others. In mycoparasitism, it feeds on to other microbes present in the rhizospheric region of the plant. In antibiosis, secretion of antibiotics or secondary metabolites from this fungus helps in inhibiting the growth of other microbes. In induced resistance, it secretes chemicals which protect the plants from pathogens, and even genes isolated from this fungus provide resistance to biotic and biotic stress. In endophytes, *Trichoderma* can grow in a plant as endophytes, thereby benefiting the plant development

sesquiterpene, etc., and may travel via air. Chitinases and antibiotics secreted by *Trichoderma* spp. work in synergistic manner, causing a relatively stronger impact on the target organisms. The mechanism involves three stages wherein the first stage comprises of the interaction of chemical stimulus of a pathogen with antagonistic nature of *Trichoderma* that results in a chemotropic response, the second stage comprises of identifying and recognizing the pathogen and antagonistic fungi through lectins, and the third stage is the interaction of hyphae of *Trichoderma* with hyphae of pathogen fungi where the hyphae of *Trichoderma* coils around the hyphae of pathogen and secretes enzymes such as pectinase and chitinase. This could be seen in interaction of *Trichoderma* with pathogens like *Fusarium roseum*, *Phytophthora colocasiae*, *F. solani*, etc. (Singh et al. 2006). Besides, this fungus has a characteristic feature to take up nutrients from the source and survive effectively in comparison to other microbes as it can break down chitin component of other fungi or cellulose of plants which are generally difficult to break down by other microbes due to their complexity.

Besides this, some strains of this fungus can even bind with ions of iron present in soil to produce siderophore (Leong 1986), for example, *Serpula lacrymans*. This specialized compound is difficult to be uptake by other microbes, and so it results in unavailability of iron uptake to the microbes present in the same environmental condition. This causes the target organisms not to become resistant toward it as in doing so the organism needs to be resistant to many mechanism routes involved in the mode of action of *Trichoderma*.

6 Role of *Trichoderma* in Management of Viral, Fungal, and Bacterial Pathogens

Trichoderma is well known for its biocontrol activity against several crucial plant pathogens like virus, fungi, and bacteria causing severe diseases (Madan et al., 2000; Al-Ani 2018). As a biocontroller against many fungal infections in plants, several studies had reported that this fungus works either by inhibiting or by parasitizing the pathogen mycelial growth by production of certain enzymes like chitinases, permeases, etc. and thus helps in controlling the disease-causing pathogen to proliferate (Table 15.3). *Trichoderma* was also found to be effective in red rot disease of sugarcane, the most damaging disease (Madan et al. 1997; Ansari et al. 2008; Ansari 2012). In viral infections, Luo et al. (2010) had showed that *T. pseudokoningii* SMF2 have antimicrobial peptaibols referred to as trichokonin which increased upregulation of genes governing plant defense and are being used against tobacco mosaic virus (TMV) infection for coping out the plant from the disease with increased reactive oxygen species (ROS) and phenolic compounds. Cucumber mosaic virus (CMV) also showed effective results in its management by the use of this fungus (Sachdev and Singh 2020). Elsharkawy et al. (2013) had illustrated that *T. asperellum* SKT-1 showed increased levels of genes associated with salicylic acid, jasmonic acid, and ethylene in leaves by inducing resistance in plants with this disease. However, in the case of pretreatment of this fungus in *Arabidopsis* plant against this disease, the defense mechanism gets activated against this disease. In *Solanum lycopersicum*, defense response is induced by *T. harzianum* T-22 strain against CMV disease (Vitti et al. 2015). In bacterial diseases, Al-Ani (2018) had showed that *T. asperellum* T203 gives a protective effect against *Pseudomonas syringae* pv. *lachrymans* in cucumber plants. Studies had revealed another strain of *Trichoderma*, *T. pseudokoningii* SMF2, possessing antibacterial property against a wide range of Gram-positive and Gram-negative bacteria (Bora et al. 2020; Shi et al. 2012; Li et al. 2014). *Pectobacterium carotovorum* ssp. *carotovorum* causing disease of soft rot in Chinese cabbage was able to manage by this *Trichoderma* strain through the production of trichokonins which inhibited bacterial growth by increasing production of PR-1a gene, ROS, and SA (Li et al. 2014). Khalili et al. (2016) had also illustrated that in charcoal rot of soybean, *Trichoderma* acts as an effective biocontrol agent. Studies have also reported that *T. harzianum* also proved to be a positive controller of wilt diseases caused by *Ralstonia solanacearum* in a number of crops such as chili, brinjal, ginger, tomato, etc. (Bora et al. 2013; Deuri 2013). The use of *T. viride* in lettuce plant had reported to effectively manage the disease caused by *R. solanacearum* and *F. oxysporum* f. sp. *lactucae* (Khan et al. 2018).

Table 15.3 Different strains of *Trichoderma* controlling fungal infection and mode of action

Trichoderma species	*Trichoderma* strain	Fungal pathogen	Mode of action	References
T. koningii	MTCC 796	*Macrophomina phaseolina*	Parasitize fungal mycelia growth	Gajera et al. (2012)
T. harzianum	T12			Khalili et al. (2016)
T. harzianum	*Foc*TR4	*Fusarium oxysporum* f. subspecies *cubense*	Restrain the growth of mycelium	Al-Ani et al. (2013)
T. atroviride	Tveg1 and TR10			
T. asperellum	CCTCC-RW0014	*F. oxysporum* f. subspecies *cucumerinum*	Increasing production of protease, cellulose, and chitinase	Saravanakumar et al. (2016)
Trichoderma asperellum strain	T34	*F. oxysporum* f. sp. *lycopersici*	Competition for iron and form siderophores	Segarra et al. (2010)
T. hamatum	URM 6656	*F. solani*	Production of chitinases	da Silva et al. (2016)
T. harzianum	T3	*Ceratocystis radicicola*	Lysis of hyphae, phialoconidia, and aleurioconidia	Al-Naemi et al. (2016)
T. atroviride	T17	*Guignardia citricarpa*	Antagonistic activity by secreting proteins such as chitinase, mutanase, a-1,2-mannosidase, α-galactosidase, a-1,3-glucanase, neutral protease, carboxylic hydrolase ester, etc.	de Lima et al. (2016)
T. harzianum	T39	*Gliocladium virens*	Inhibit growth of fungal mycelia	Bora and Deka (2007)
	CICR G	*S. sclerotiorum*		Mukherjee et al. (2014)
T. atroviride	P1	*Phytophthora cinnanerium*		Olabiyi and Ruocco (2013)
T. viride	T30, T31	*R. solani*		
T. harzianum	T22	*Botrytis cinerea*		

7 Conclusion

Trichoderma is a free-living soil fungus that is frequently seen in the soil and rhizospheric region of the plant. This fungus is known for its many characteristics and peculiar properties which benefit the plant in its growth and development. It is being known worldwide for its protectant activity and growth enhancement. Different strains of *Trichoderma* produce compounds that elicit the plant defense responses. These compounds include low-molecular-weight compounds, proteins, and peptides. *Trichoderma* also have many potential abilities such as tolerant capability against a number of biotic and abiotic stresses, enhancement in nutrient uptake activity of plant, and augmentation in nitrogen use efficiency and even in photosynthetic activity. A large number of genes are known to over express in *Trichoderma* species that helps in abiotic stress tolerance to plants. Some antibiotic substances are also being secreted by this fungus to dominate and kill other fungal pathogens, thereby maintaining its colonization where it uses its hyphae to adhere to plant roots through hydrophobins or swollenin. *Trichoderma* is a renowned biocontrol agent that helps manage the diseases occurring in the plants.

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