REVIEW ARTICLE Indian Journal of Agricultural Research, Volume 57 Issue 3: 273-282 (June 2023)

Trichoderma Species: An Overview of Current Status and Potential Applications for Sustainable Agriculture

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10.18805/IJARe.AF-751

Abstract

In agro-ecosystems, *Trichoderma* species are beneficial microorganisms that improve soil health and crop development. They form mutualistic endophytic relationships with a wide range of plant species, promoting host growth, protecting against pathogen attack, and improving micro-and macronutrient uptake and use efficiency. As a result, they should be promoted because they have the potential to improve agricultural sustainability while reducing the use of harmful chemicals in agriculture. This review provides an overview of the current and potential applications of *Trichoderma* species for sustainable agriculture, their beneficial roles and how they can be used to boost plant growth and crop yield.

Key words: Antagonistic activity, Biofortification, Biopriming, Endophytes, Sustainability.

Soil microbes are important components of nutrient cycling; consequently, the structure and functions of soil microbial communities influence soil health and richness (nutrient pool) (Prakash *et al.,* 2015). Recently, various environmentally friendly approaches, such as the use of natural microorganisms that boost plant development and disease resistance capability, have been frequently utilized to promote sustainable agriculture and environmental protection (Prakash *et al*., 2015; Rajamanikyam *et al*., 2017). Through their various activities, different classes of microorganisms [fungi (endophytic, ectomycorrhizal and arbuscular) and bacteria (cyanobacteria)] play significant roles in nutrient mobilisation and uptake, plant growth promotion, and disease suppression (Cao *et al.,* 2020; Prakash *et al*., 2015). Additionally, these microorganisms assist plant survival by increasing disease resistance and tolerance to various stresses, such as drought and salinity (Fig 1).

Plants host numerous endophytic microbes that improve their performance, particularly under biotic and abiotic stresses (Rajamanikyam *et al.,* 2017; Tseng *et al*., 2020). Endophytic fungi (EF) are organisms which live in healthy plant tissues with no signs of disease or morphological changes during the entire plant's life cycle (Rajamanikyam *et al.,* 2017). Endophytes respond variably to different stressful factors that affect plant growth (Fig 2). Plants colonised by such endophytic plant symbionts are bipartite symbioses in which both members benefit each other; therefore, they have various advantages over similar plants that are not colonised (Harman *et al.,* 2019).

Arbuscular mycorrhizal fungi (AMF) are beneficial soil microorganisms that form mutualistic symbiotic relationships with the roots of important food crops and play critical roles in the soil's long-term fertility and health (Cao *et al*., 2020; Prakash *et al*., 2015). AMF are a biotechnological tool for improving plant stress tolerance and restoring degraded ecosystems (Begum *et al*., 2019; Cao *et al*., 2020).

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How to cite this article: Awad-Allah, E.F.A., Mohamed, I.A.A., Allah, S.F.A.A., Shams, A.H.M. and Elsokkary, I.H. (2023). *Trichoderma* Species: An Overview of Current Status and Potential Applications for Sustainable Agriculture. Indian Journal of Agricultural Research. 57(3): 273-282. doi: 10.18805/IJARe.AF-751.

Submitted: 23-07-2022 **Accepted:** 14-11-2022 **Online:** 14-12-2022

AMF symbiosis protects plants from a variety of abiotic stresses *via* a variety of mechanisms, including increased photosynthetic rate, mineral nutrient uptake, osmoprotectant accumulation, antioxidant enzyme activity up-regulation and changes in the rhizosphere ecosystem (Begum *et al*., 2019).

Ectomycorrhizal (ECM) fungi are key organisms in the nutrient and carbon cycles of forest ecosystems, forming mutualistic symbioses with the roots of many tree species (Anderson and Cairney, 2007; Stuart and Plett, 2020). These fungi colonise the lateral roots of host trees, generating a network of interlacing mycelial filaments that penetrate root epidermal cells (Stuart and Plett, 2020). During this association, three features are generally recognised: (1) the formation of a fungal hyphae mantle or sheath, (2) the development of hyphae between root cells to form a Hartig net and (3) hyphae that grow into the surrounding soil (extra-radical mycelium) (Prakash *et al.,* 2015). These unique structures serve as nutrient exchange sites and provide a large surface area between the two symbiotic partners (Stuart and Plett, 2020).

Plant growth-promoting fungi (PGPF) are a diverse group of non-pathogenic fungi that live freely on the root surface, inside the root, or in the rhizosphere and promote seed germination, seedling vigour, plant growth, flowering, and productivity in a wide range of host plants (Hossain *et al.*, 2017). PGPF have prompted a lot of attention as biofertilizers and biocontrol agents because of their many beneficial impacts on plant quantity and quality, as well as their positive interaction with the environment (Hammad and Elbagory, 2019). Understanding how PGPF induces plant responses is critical for developing new strategies to manage plant growth and disease (Hossain *et al.*, 2017).

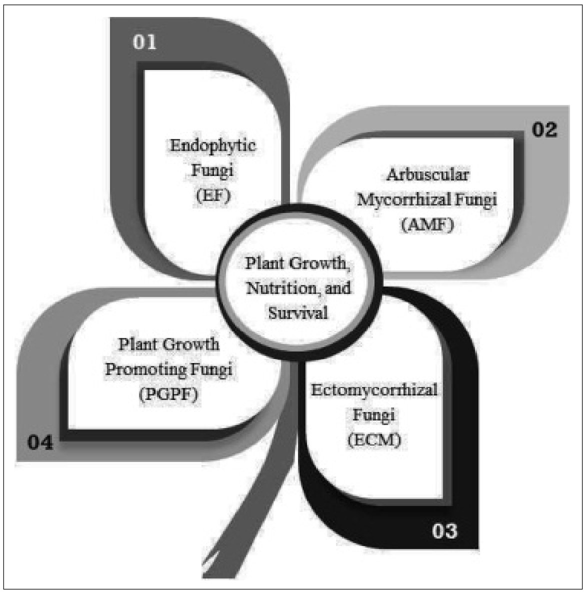

Fig 1: Various fungal partners involved in plant growth, survival and nutrition.

In summary, fungi such as AMF, ECM, EF and PGPF play beneficial roles in plant survival by assisting them in different ways, including induced systemic resistance, plant growth promotion, host resistance to insect feeding, disease resistance, phosphorus solubilisation, production of plant growth-promoting (PGP) hormones, increased aboveground photosynthesis, and plant tolerance to abiotic stresses, such as drought, salt and heavy metals (Fig 3).

Plant growth enhancement by *Trichoderma* spp.

Trichoderma is a fungus belonging to the Hypocreaceae family that is found in all soils (Chen *et al.*, 2021). The majority of *Trichoderma* species studied colonise the root surface or live as endophytes within root tissues; however, some species can be isolated from plant aerial parts (Ruano-Rosa *et al.*, 2016; Samolski *et al.*, 2012; Tseng *et al.*, 2020). As shown in Fig 4A and Fig 4B, *Trichoderma* strains started out white and cottony, then developed into yellowish-green to deep green compact tufts, particularly in the center of a growing spot. Fig 4C depicts a dual culture assay demonstrating the mycoparasitic and antagonistic activity of *Trichoderma* spp. against the pathogen *Fusarium oxysporum*.

Trichoderma species can promote the growth of their hosts while also protecting them from pathogenic attacks (Tseng *et al.*, 2020). Additionally, various *Trichoderma* species can improve root growth and development, confer abiotic stress tolerance and improve micro-and macronutrient uptake and use efficiency, resulting in increased crop productivity (Mehetre and Mukherjee, 2015). Therefore, these species can create mutualistic endophytic relationships with several plant species (Fig 5).

The use of *Trichoderma* spp. has frequently resulted in increased plant growth and improved crop yields, but the

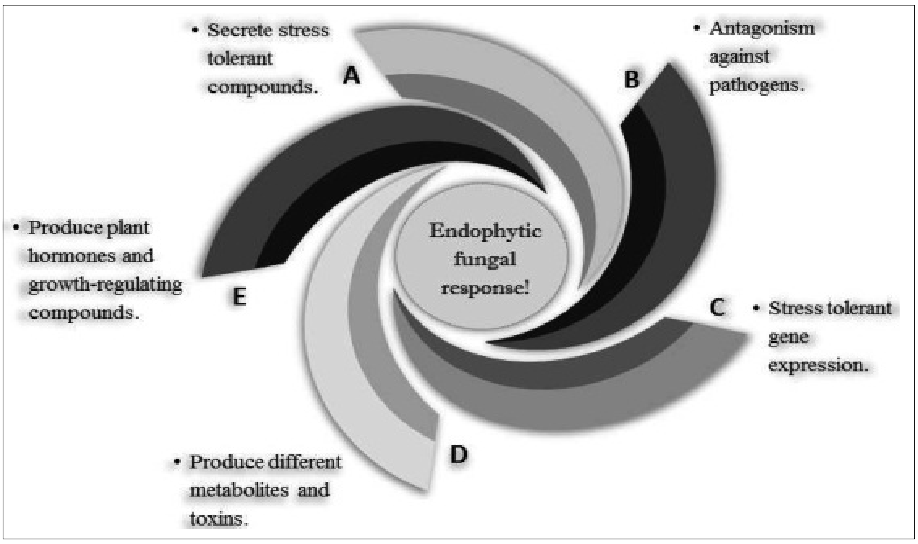

Fig 2: Endophytic fungal response against stressful factors affecting plant growth.

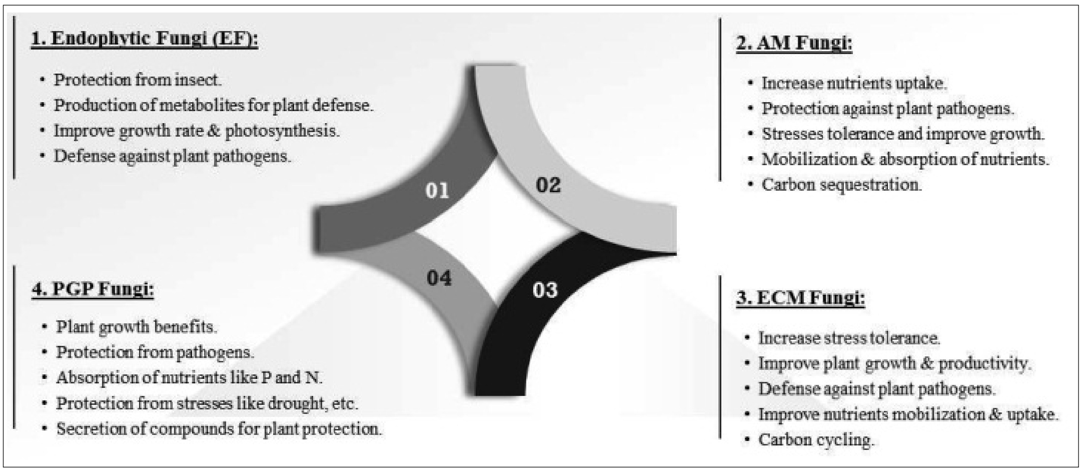

Fig 3: Beneficial roles of arbuscular, ectomycorrhizal, endophytic and plant growth-promoting fungi in plant nutrition and growth.

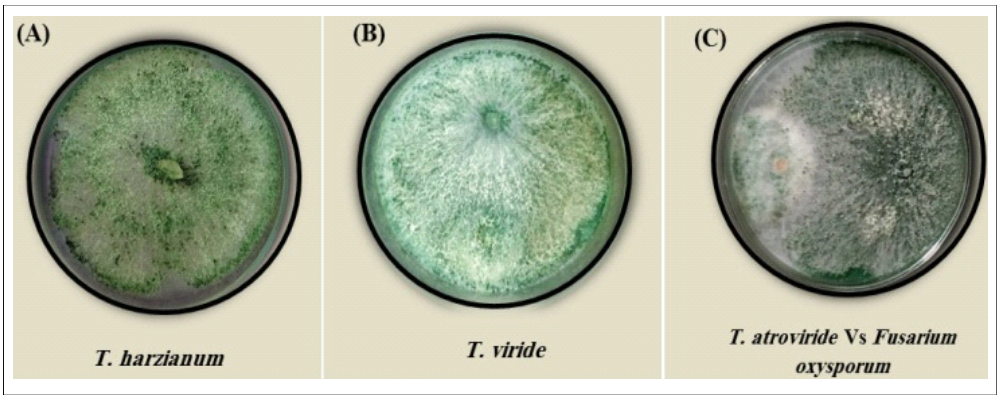

Fig 4: Different isolated strains of *Trichoderma* spp., (A) *T. harzianum*, (B) *T. viride*, (C) A dual culture plate demonstrating the mycoparasitic behaviour of *Trichoderma* spp. and the soil-borne pathogen *Fusarium oxysporum* 10 days post inoculation.

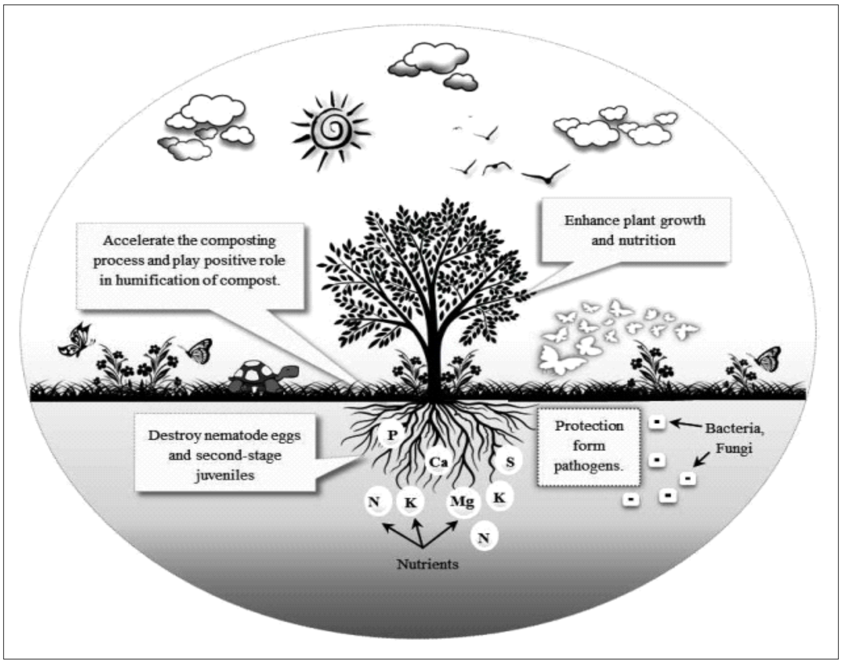

Fig 5: Diagrammatic depiction of beneficial effects of *Trichoderma* spp.

exact mechanism of action remains unknown (Mehetre and Mukherjee, 2015). One possible mechanism for increased plant growth is an increase in the total absorptive surface, which facilitates nutrient uptake and translocation in the shoots, resulting in increased plant biomass through the efficient use of macronutrients (N, P and K) and micronutrients (Samolski *et al*., 2012). Several mechanisms for how *Trichoderma* spp. impact plant growth and development have been proposed, including solubilisation of many plant nutrients from their solid-phase compounds (Altomare *et al.,* 1999), production of growth hormones (Jaroszuk-Ściseł *et al*., 2019), upregulation of genes and pigments that improve the plants' photosynthetic capability and activate biochemical pathways that reduce reactive oxygen species to less harmful molecules (Harman *et al*., 2019), increased uptake and translocation of less available minerals (Fiorentino *et al.,* 2018) and suppression of pathogens (Khalili *et al.,* 2016; Awad-Allah *et al*., 2022). Plant growth stimulation is evidenced by increases in biomass, productivity, stress resistance and nutrient absorption (Guzmán-Guzmán *et al.,* 2019). Moreover, PGP compounds produced by certain *Trichoderma* species stimulate plant growth (Studholme *et al*., 2013). Most studies found that *Trichoderma* spp. improve overall plant health and growth by providing a suitable environment and producing a large number of secondary metabolites, as shown in Table 1.

Furthermore, *Trichoderma* and other microorganisms in soil can detoxify toxic compounds and accelerate the degradation of organic material (Zin and Badaluddin, 2020). Recent research has shown that *Trichoderma* spp. can degrade chemical pollutants by acting on chemicals and metal contaminants *via* the activity of various enzymes, as

Table 1: Effect of *Trichoderma* spp. on plant growth and development.

Trichoderma spp.	Crop plant	Significant findings	References
T. harzianum	*Cucumis sativus* L. *Solanum lycopersicum* L.	Root architectural modification, resulting in enhanced total absorptive surface, improved nutrient absorption and translocation in the shoots and higher plant biomass *via* effective mineral element usage.	Samolski *et al.* (2012)
T. tomentosum *T. harzianum*	*Zea mays* L.	Beneficial impacts on plant development in maize (height, root length, leaf area and root, stem and total dry weight).	Herrera-Jiménez *et al.* (2018)
T. harzianum	*Medicago sativa* L.	Alfalfa growth was significantly increased by changing soil available nutrients, rhizosphere soil chemical compounds and soil microbial community in a synergistic way.	Zhang *et al.* (2019)
T. harzianum	*Brassica juncea* L.	Significantly beneficial in conferring resistance to NaCl stress on mustard plants *via* improved uptake of essential elements, modulation of osmolytes and antioxidants.	Ahmad *et al.* (2015)
T. harzianum	*Solanum lycopersicum* L.	Plant growth, absorption and utilisation efficiency of macronutrients and oligo/micronutrients, activation of plant secondary metabolism and disease resistance were all enhanced.	Vukelić *et al.* (2021)
T. harzianum	*Lycopersicon esculentum* L.	Improved soil fertility, nutrient absorption and rhizosphere fungal and bacterial population expansion, all of which resulted in better tomato yields, antioxidants and minerals.	Sani *et al.* (2020)
T. harzianum *T. virens*	*Pinus sylvestris* L.	In the rhizosphere soil of *P. sylvestris*, increased total biomass, seedling height, ground diameter, root length, root area, root diameter, number of root tips and branches, soil nutrient content and soil enzyme activity.	Halifu *et al.* (2019)
T. longibrachiatum	*Triticum aestivum*	A remarkable effect on alleviating the adverse effects of salt stress on wheat seedling growth and development by increasing the activity of antioxidative defence system.	Zhang *et al.* (2016)
T. asperellum	Sugarcane (*Saccharum sp.*)	Changed physiological parameters such as photosynthetic pigments, photosynthesis rate, stomatal conductance, water use efficiency, carboxylation efficiency, nitrate reductase enzyme activity and antioxidant metabolism alleviated the deleterious impacts of drought stress in sugarcane.	Scudeletti *et al.* (2021)
T. viride	*Triticum aestivum*	Plant height, panicle weight, number of grains, grain yield, biological yield and biomass yield all increased slightly. Most of the growth and yield parameters show the greatest value when *Trichoderma* and NPK are combined with farmyard manure, however the yield was slightly greater than the NPK alone treatment.	Mahato *et al.* (2018)

well as improve soil physical and chemical properties and make nutrients available to plants from agrochemicals (Tripathi *et al.,* 2013; Awad-Allah *et al.*, 2022).

Trichoderma-mediated nutrient use efficiency (NUE) of crop plants

Agricultural production is based on the ability of plants to convert solar energy into chemical energy through photosynthesis with the help of chlorophyll (Kathpalia and Bhatla, 2018). Importantly, plants require an adequate supply of 13 essential mineral elements in addition to carbon, hydrogen and oxygen to accomplish this critical role (Vatansever *et al.,* 2017). Mineral nutrients are classified into two types: macronutrients and micronutrients (Vatansever *et al.,* 2017). Macronutrients are nutrients that are needed in relatively large amounts and are further classified into two types: primary and secondary nutrients (Shang *et al*., 2014). N, P and K are primary nutrients, while Ca, Mg and S are secondary nutrients (Shang *et al*., 2014). In contrast, micronutrients (trace/minor elements) are essential elements for plant growth and are required in very small quantities, for example, Zn, Mn, Fe, Cu and Mo (Kathpalia and Bhatla, 2018).

NUE is a measure of how effectively plants use available mineral nutrients (Baligar and Fageria, 2015). It is defined as the yield (biomass) per unit of nutrient intake from the soil and/or fertiliser (Baligar and Fageria, 2015; Mehetre and Mukherjee, 2015). NUE is divided into two interactive components: nutrient acquisition efficiency (*i.e.* the amount of nutrients taken up by plants from the soil in relation to nutrient supply) and nutrient utilisation efficiency, which informs the biomass generated by the unit of nutrients assimilated by plants (Nieves-Cordones *et al.,* 2020). Improving NUE is not only required for increasing crop production into low-nutrient-availability marginal areas, but it is also a technique to minimise the usage of inorganic fertilisers (Baligar and Fageria, 2015).

Microbe-mediated improvement of NUE is important in alleviating gradual loss of soil fertility/productivity caused by intensive agriculture (Mehetre and Mukherjee, 2015). Microorganisms in the soil and rhizosphere influence plant nutrient availability by facilitating the degradation of soil organic matter during an important process known as composting (Mehetre and Mukherjee, 2015; Mostafa *et al.*, 2019). Humus, or humified organic matter, is found in compost and serves as a "bank" or reservoir for essential plant nutrients (Awad-Allah and Elsokkary, 2020; Mehetre and Mukherjee, 2015; Mostafa *et al.,* 2019). *Trichoderma* spp. can accelerate the composting process and play a positive role in the process of compost humification (Mehetre and Mukherjee, 2015; Randhawa *et al.*, 2020). Therefore, combining organic fertilisers (compost) with *Trichoderma* spp. as biofertilizers may be a more effective way to increase plant biomass than only using organic fertilisers or *Trichoderma* separately (Zhang *et al.*, 2018). This could be because *Trichoderma* biofertilizers effectively regulate soil chemistry and microbial communities, resulting in significantly higher aboveground plant biomass than

Table 2: *Trichoderma* improves nutrient use efficiency in crop plants.

Crop plant	*Trichoderma* spp.	Nutrient use efficiency: Primary (N, P and K)	Secondary (Ca and Mg)	Micro (Cu, Fe, Zn and Mn)	References
Lycopersicon esculentum L.	*T. harzianum* T22	N (20.8% shoot), P (47.8% shoot), K (15.7% shoot).		Fe (13.3 shoot), Zn (19.5 shoot).	Sani *et al.* (2020)
Solanum lycopersicum L.	*T. harzianum* qid 74-overexpressing mutants T1	N (20.9% shoot), P (29.2% shoot), K (17% shoot).	Ca (24.9% shoot), Mg (35.9% shoot).	Cu (21.4% shoot), Fe (34.1% shoot), Zn (20.6% shoot), Mn (21.7% shoot).	Samolski *et al.* (2012)
	T. harzianum qid 74-overexpressing mutants T2	N (48.6% shoot), P (42% shoot), K (28.8% shoot).	Ca (44.3% shoot), Mg (52.4% shoot).	Cu (42.4% shoot), Fe (46.2% shoot), Zn (50% shoot), Mn (37.3% shoot).	
Lycopersicon esculentum Mill.	*T. harzianum* T22, (BioF/compost)	P (38.3% fruit), K (9.8% fruit).	Ca (22.1% fruit), Mg (20.3% fruit).	Fe (46.2% fruit), Zn (27.3% fruit).	Molla *et al.* (2012)
	T. harzianum T22, (Bio F/liquid)	P (24.8% fruit), K (15.4% fruit).	Ca (18.2% fruit), Mg (24.4% fruit).	Cu (15.4% fruit), Fe (64.6% fruit), Zn (45.5% fruit).	
Camellia sinensis L.	*T. harzianum*	N (44.5% plant), P (50% plant), K (16.3% plant).			Thomas *et al.* (2010)

organic fertilizer without *Trichoderma* (Zhang *et al.*, 2018). In addition, root colonisation by *Trichoderma* spp. promotes root growth and development, which directly leads to enhanced nutrient absorption and translocation in the shoots, resulting in higher plant biomass *via* the effective utilisation of of N, P, K and micronutrients (Mehetre and Mukherjee, 2015; Samolski *et al.*, 2012). As shown in Table 2, there are strong indications and experimental evidence that applying *Trichoderma* spp. increases nutrient absorption. According to Fiorentino *et al.* (2018), *Trichoderma* inoculation could be a viable strategy for managing the nutrient content of leafy horticulture crops grown in low-fertility soils, assisting vegetable growers in reducing the use of synthetic fertilisers and developing sustainable management practises to optimise N use efficiency. Moreover, *Trichoderma* can also improve Fe nutrition of plants and provide long-term control of Fe deficiency in calcareous soils (Santiago *et al.*, 2013). As a result, significant efforts must be made to incorporate the potential of microbes such as *Trichoderma* spp. in the biofortification of Zn and Fe in food grains (Singh and Prasanna, 2020). Hence, *Trichoderma* spp. can be used as bioinoculants for plant growth and development, resulting in eco-friendly and sustainable farming practices (Sharma and Borah, 2021; Molla *et al.,* 2012; Awad-Allah *et al.*, 2022).

Table 3: Effect of *Trichoderma* spp. on some plant diseases.

Diseases	Pathogens	Crop plant (Host)	*Trichoderma* spp.	Mechanisms/responsible metabolites	References
Stalk rot disease in maize	-*Fusarium proliferatum* -*Fusarium verticillioides*	*Zea mays* L.	*T. harzianum* *T. viride*	The antagonistic strains might be a source of new biological fungicides, particularly against carbendazim-resistant *F. verticillioides*, while avoiding the adverse effects of chemical fungicides.	Yassin *et al.* (2021)
Basal stem rot	*Ganoderma* sp.	*Arabidopsis thaliana*	*T. asperelloides* PSU-P1	Fungal volatile organic chemicals released by the fungus are responsible for antifungal action, plant development and defence responses.	Phoka *et al.* (2020)
Charcoal rot disease	*Macrophomina phaseolina*	*Glycine max* L.	*T. harzianum*	*M. phaseolina* growth inhibition (72.31%) and volatile production (63.36%) and the hyperparasitism test revealed cell lysis following the maximum inhibitory effect on *M. phaseolina* mycelial growth.	Khalili *et al.* (2016)
Dark spot disease	*Alternaria brassicicola*	*Arabidopsis thaliana*	*T. confertum*	A helpful bio-control agent since it activated the plant's immune system against pathogen infection while not interfering with other beneficial microbial interactions in the soil, offering extra advantages in agricultural applications.	Tseng *et al.* (2020)
Damping-off and root rot/wilt diseases	*Fusarium solani* *Fusarium oxysporum*	*Phaseolus vulgaris* L.	*T. harzianum* *T. viride* *T. virens*	Activating defence enzymes such as peroxidase, polyphenol oxidase and chitinase in dry bean plants reduces disease incidence and stimulates systemic defence responses.	Abd-El-Khair *et al.* (2019)
Fusarium wilt disease	*Fusarium oxysporum* f. sp. *lycopersici* (FOL)	*Solanum lycopersicum* L.	*T. viride*	The tomato plants treated with it had the least disease severity, the greatest physiological activity, the highest biochemical and antioxidant contents and the best growth and yield.	Jamil, (2021)
Stem and pod rots, which can be major production constraints	*Sclerotium rolfsii*	*Arachis hypogaea* L.	*T. harzianum* *T. viride*	By increasing the amounts of lytic enzymes (chitinase, -1, 3-glucanase and protease), which destroy the chitin polymers of the fungal cell wall, the antagonist relationship, biocontrol mechanisms and growth inhibition towards fungal pathogen are achieved.	Parmar *et al.* (2015)
Net blotch disease	*Drechslera teres* f. sp. *teres*	*Hordeum vulgare* L.	*T. asperilium* T 34	Endogenous reactive oxygen species such as superoxide (O_2^-) were significantly enhanced, which may play a key role in killing or suppressing the fungus and decreasing disease symptoms; as a result, catalase, peroxidase and polyphenol oxidase activities were significantly increased.	Hafez *et al.* (2019)

Trichoderma as biocontrol agents for plant disease management

Biological control occurs when a biocontrol agent is applied to a host plant to prevent the spread of pathogen-caused plant diseases. It is a viable alternative to chemical control (Awad-Allah *et al.,* 2021). *Trichoderma* spp. are the most widely used biocontrol agents for a variety of root, shoot and postharvest diseases, having antagonistic capabilities based on the activation of several pathways (Abdel-lateif, 2017; Zin and Badaluddin, 2020). According to Benítez *et al.* (2004), *Trichoderma* spp. exert biocontrol against fungal phytopathogens either indirectly (by competing for nutrients and space, influencing environmental conditions, stimulating plant development, plant defence mechanisms and antibiosis), or directly (*via* mycoparasitism). During mycoparasitic interactions, *Trichoderma* spp. initiate the synthesis of hydrolytic or lytic enzymes, such as glucanase, chitinase and protease, which degrade the chitin polymers of the fungal pathogen cell wall (Mukhopadhyay and Kumar, 2020; Parmar *et al.,* 2015). *Trichoderma* may also create antibiotics or low-molecular-weight diffusible compounds such harzianic acid, tricholin, peptaibols, 6-pentyl-pyrone, viridin and heptelidic acid, all of which hinder the development of other microbes (Abdel-lateif, 2017). These indirect and direct mechanisms may work together and their importance in the biocontrol process is influenced by the *Trichoderma* spp., antagonistic fungus, crop plant and environmental conditions, such as nutrient availability, pH, temperature and iron content (Benítez *et al.,* 2004). For these reasons, *Trichoderma* spp. can be used as effective biofungicides and alternative agents against phytopathogens (Belaidi *et al.,* 2022; Srivastava *et al.*, 2016). To provide a better understanding, important studies involving the antifungal potential of *Trichoderma* spp. for controlling plant diseases, as well as several mechanisms for plant disease management, are summarised in Table 3.

Potential use of *Trichoderma*-based products in agriculture

Trichoderma-based agricultural products are marketed worldwide as bio-pesticides, biofertilizers, growth promoters, and natural resistance boosters (Abdullah *et al.,* 2021). They are used in a variety of cultivated environments, such as fields, greenhouses and nurseries, as well as in the production of a wide range of horticultural crops, such as fruits, trees and ornamental crops, to protect crops from various plant pathogens or to boost plant growth and productivity (Meher *et al.,* 2020; Launio *et al.,* 2020; Abdullah *et al.,* 2021). They are applied by seed treatment, bio-priming, seedling dip, soil application, or foliar spray (Meher *et al.,* 2020; Abdullah *et al.,* 2021). A list of marketable *Trichoderma*-based agricultural products is shown in Table 4. Bio Spark *Trichoderma*, for example, is effective against the damping-off of vegetables and some tropical fruit diseases. Notably, *Trichoderma*-based products have been reported as a success story not only in crop disease control but also in enhancing farmer income, particularly in Philippine highland farms (Launio *et al.,* 2020).

The potential uses of *Trichoderma*-based products to promote crop health or control plant diseases are dependent on the development of commercial formulations with appropriate organic and inorganic carriers that enable *Trichoderma* to live for a long length of time (Meher *et al.*, 2020). Moreover, *Trichoderma* formulations with strain mixtures perform better than individual strains for the management of pests and diseases of crop plants, as well as plant growth stimulation (Meher *et al.*, 2020). For example, Biota Max™ is a unique soil probiotic and biofertilizer that

Table 4: Some commercial products of *Trichoderma* spp. used in agriculture.

Commercial products	Species/strains of *Trichoderma*	Agency/Company
Bazodo tricho	*Trichoderma viride*	India MART Inter MESH Ltd., Uttar Pradesh, India.
Agri farm ® *Trichoderma*	*Trichoderma viride*	Indian Agri Farm, Tamil Nadu, India.
Trikologic	*Trichoderma harzianum*	Terra Aquatica, Biopole 32500 Fleurance/France.
Bio spark *Trichoderma*	*Trichoderma* sp.	Biospark Corporation, UPLB College, Laguna, Philippines.
Trianum-P	*Trichoderma harzianum* T-22	Koppert Biological Systems, 2650 AD Berkel en Rodenrijs, The Netherlands.
Trichostart seed treatment	*Trichoderma atroviride*	Agrimm Technologies, Lincoln, 7640 New Zealand.
Trichopel and trichodry	*Trichoderma atroviride*	Agrimm, Mooroopna, Victoria, 3629 Australia.
Biota max™ and custom GP	*Trichoderma harzianum* *Trichoderma viride* *Trichoderma koningii* *Trichoderma polysporum*	Custom Biologicals, Inc., FL 33442, USA.
Eco-T® and Eco-T Ezi-Flo®	*Trichoderma asperellum*	Andermatt Madumbi, 24 Hilton Avenue Hilton, KZN, South Africa.
Trichoderma viride	*Trichoderma viride*	Pioneer Agro Industry, Tamil Nadu, India.
Myco solutions, Bio-agent avengelus.	*Trichoderma atrobrunneum*	Sorbus International Ltd., Frome, Somerset, England (UK)/Ireland Distributor.
SabrEx ® for wheat and cereals	*Trichoderma* sp.	Advanced Biological Marketing (ABM), P.O. Box 222 Van Wert, Ohio, United States.

includes a variety of *Trichoderma* spp., including *T. harzianum*, *T. viride*, *T. koningii* and *T. polysporum*, as well as other beneficial soil microorganisms. Therefore, the beneficial soil microorganisms in Biota Max™ help plants grow stronger, healthier root systems while using less N fertilisers. However, the lack of a proper screening protocol for selecting promising *Trichoderma* candidates, lack of sufficient knowledge on the microbial ecology of *Trichoderma* and plant pathogens and awareness, training and education shortfalls are some of the factors that limit *Trichoderma*-based product development and utilisation worldwide (Meher *et al.,* 2020). Therefore, the sustainability of these commercial *Trichoderma*-based agricultural products is critical for ensuring the productivity of agricultural crops with *Trichoderma* spp. (Zin and Badaluddin, 2020; Launio *et al*., 2020).

CONCLUSION AND FUTURE OUTLOOK

Trichoderma spp. are versatile filamentous fungi that can be found free-living in soil, colonising dead organic matter, and forming beneficial endophytic relationships with plants. They have the potential to be effective biocontrol agents by inhibiting the growth of many phytopathogenic fungi. However, their characteristics and mechanisms must be fully understood before they can be used in the field to limit the spread of phytopathogens. Furthermore, *Trichoderma* spp. promote root growth, induce plant defence, and boost plant growth in the face of biotic and abiotic stresses, such as drought, salinity and the presence of poisonous metal ions. Finally, *Trichoderma* spp. can be used as effective biofungicides and biofertilizers in field crops, reducing the need for harmful synthetic fungicides and fertilisers while also promoting eco-friendly and sustainable farming practices. However, further research is needed to improve the efficacy and safety of these fungi.

Funding

This research received no external funding.

Data availability statement

Data is contained within the article.

Institutional review board statement

Not applicable.

Informed consent statement

Not applicable.

Conflict of interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

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