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A THOROUGH ANALYSIS OF *TRICHODERMA* IN SUSTAINABLE AGRICULTURE WITH REGARD TO BIOCONTROL, PLANT GROWTH PROMOTION, AND BIOREMEDIATION

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ABSTRACT

Trichoderma species are now very much essential biological control agents (BCAs) and plant growth-promoting fungi (PGPFs) in contemporary sustainable agriculture. Their ability to inhibit harmful fungus, improve nutrient absorption, withstand environmental stressors, and promote systemic resistance has led to their widespread use in integrated pest management (IPM), compost management, seed treatment, soil amendment, and bioremediation. Alcohols, aldehydes and ketones, ethylene, hydrogen cyanide, and monoterpenes are among the volatile and non-volatile compounds released by *Trichoderma*. They generate substances known to have antibacterial qualities, such as peptaibols, gliotoxin, and gliovirin. *Trichoderma*'s interaction with the host plant results in the production of lytic or cell wall-degrading enzymes, competition for nutrients or space, the development of induced resistance in the plant, and the production of antibiotics in conjunction with mycoparasitism (penetration and infection). The biology, ecological roles, bio control mechanisms, plant growth stimulation, and useful agricultural applications of *Trichoderma* are all well explained in this review with an emphasis on supported by the integration of molecular and field-level evidence.

Keywords: biological control agents, plant growth promotion, sustainable.

INTRODUCTION

Because of its many benefits to crop productivity and health, the fungus *Trichoderma* is essential to sustainable agriculture. It is well known for its capacity to suppress plant infections through the generation of enzymes, secondary metabolites, and volatile organic molecules that compete for resources, induce plant defence systems, and engage in mycoparasitism. *Trichoderma* is the source of around 60% of commercial bio fungicides, highlighting its significance in integrated pest control methods and biological disease management. *Trichoderma* improves plant biomass, yield, and soil health in addition to controlling infections by boosting root development, nutrient uptake, and the production of phyto hormones and growth regulators.

It is used in the field as root dips, soil additives, and seed coatings to promote advantageous colonization and adaptation in a variety of settings. Additionally, by modifying stress response pathways, *Trichoderma* increases plant resistance to abiotic conditions including salinity and drought. By lowering chemical inputs, encouraging better crops, and supporting environmental conservation, *Trichoderma* greatly promotes sustainable agriculture as an environmentally acceptable substitute for conventional pesticides and fertilizers. In order to overcome obstacles like formulation stability and regulatory limitations and to optimize *Trichoderma* strains, formulations, and application techniques, current research aims to maximize its potential in sustainable agricultural systems (Chen *et al*., 2015; Srivastava *et al*., 2025).

In recent decades, there has been a sharp rise in demand for environmentally friendly substitutes for synthetic fertilizers and chemical pesticides. Growing challenges for farmers include residue limitations, fungal resistance, soil degradation, and environmental safety regulations. *Trichoderma* is regarded as one of the most dependable fungal genera among microbial agents for biological control and plant growth enhancement (Harman *et al*., 2004; Woo *et al*., 2023). It is useful in a variety of cropping systems, including cereals, legumes, vegetables, fruit orchards, and ornamentals, due to its capacity to colonize plant roots, modify plant physiology, and control several soil-borne diseases. These days, commercial *Trichoderma* formulations are utilized all over the world in hydroponics, greenhouse nurseries, seed bio priming, and extensive open-field activities. The fungus is becoming more and more involved in integrated nutrient and pest management (INM/IPM) frameworks due to its competitive ecological behaviour, strong environmental adaptability, and variety of methods of action (Keswani *et al*., 2013). These fungi exhibit robust reproductive capacity, efficient nutrient utilization, and competitive prowess in the rhizosphere, enabling them to thrive under adverse conditions and contribute to integrated disease management (Ayyandurai *et al*., 2023; Asghar *et al*., 2024). Their cosmopolitan distribution across diverse climates and resilience to abiotic stressors such as salinity, drought, and nutrient deficiencies further underscore their value in promoting crop productivity under challenging environmental conditions (Aruna *et al*., 2025; Asghar *et al*., 2024). Additionally, through processes including mycoparasitism, antibiosis, and induced systemic resistance, *Trichoderma spp*. form mutualistic endophytic relationships with a variety of plant species, improving nutrient uptake efficiency and providing protection against biotic stressors (Bhandari *et al*., 2021; Ayyandurai *et al*., 2024). *Trichoderma spp*.'s diverse range of functions makes them a viable biological substitute for chemical inputs, addressing issues of global food security in the face of resource depletion and population growth while promoting environmentally benign farming methods (Awad-Allah *et al*., 2022; Ahluwalia *et al*., 2014; Hermosa *et al*., 2013). Agricultural professionals can improve plant growth and disease suppression in field settings by combining molecular characterisation and synergistic consortia of *Trichoderma* strains, such as rhizospheric and endophytic isolates (Ayyandurai *et al*., 2024). The molecular foundations of *Trichoderma*'s genomic and epigenomic adaptations that support its mutualistic symbiosis with plants thoroughly investigated by several studies, which emphasizes secondary metabolite gene clusters and epigenetic priming as critical mediators of pathogen antagonistic behaviour and growth enhancement in a variety of agro-ecosystems (Sun *et al*., 2022; Woo *et al*., 2023). In addition to its uses as bio control agents, this review synthesizes recent advances in *Trichoderma* research, phyllosphere habitats, and modes of action across rhizosphere/endosphere and, alongside its applications as biocontrol agents, biofertilizers, and PGPR activity and long-term agro ecosystem resilience.

Taxonomy and species diversity of *Trichoderma*

The name "*Trichoderma*" was coined by combining the words "hair" (thrix) and "skin" (derma). The genus *Trichoderma* was first discovered by Persoon in Germany over two centuries ago, where he identified four species: *T. viride, T. nigroscens, T. aureum, and T. roseum* (Persoon, 1794). In India, Thakur and Norris successfully isolated *Trichoderma* for the first time in Madras in 1928 (Pandya *et al*., 2011), and it has since been reported from various substrates and locations. Weindling (1932) highlighted the potential parasitic properties of *Trichoderma* fungi. Rifai (1969) categorized *Trichoderma* into nine aggregates, with each aggregate containing a few indistinguishable biological species. Samuels *et al*. (1998) pointed out the limitations of Rifai's classification, concluding that the aggregates failed to clearly define the boundaries of individual species. The original classification system established by Rafai was revised and divided into five sections (Bissett, 1984; 1991a, 1991b, 1991c, 1992). As per the database "http//:www.isth.info," the genus The standard biological classification for *Trichoderma* is as follows (Persoon, 1794) :

Kingdom: Fungi
Phylum (Division): Ascomycota
Subphylum (Subdivision): Pezizomycotina
Class: Sordariomycetes
Subclass: Hypocreomycetidae
Order: Hypocreales
Family: Hypocreaceae
Genus: *Trichoderma* Persoon

Trichoderma exhibits significant diversity, with over 500 species identified worldwide. Thirteen distinct species from diverse locales and substrates have been documented from India (Samuels, 2006). Among the 500 species those have been described, though roughly 20–30 species dominate the agricultural use (Samuels, 2006). Some taxonomically important agricultural species include: *Trichoderma harzianum. T. Viride, T. Virens, T. Asperellum, T. Atroviride, T. Longibrachiatum, T. Koningii, T. reesei* (primarily industrial enzyme production) etc. having properties like *T. harzianum* and *T. asperellum* — strong mycoparasitism and root colonization, *T. viride* — superior chitinase production, antagonism against *Fusarium, T. virens* — production of gliotoxin and viridian, *T. atroviride* — ISR induction and VOC emission, *T. longibrachiatum* — compost decomposition and cellulolytic activity (Jaklitsch, 2009).

Genetic, functional diversity and phylogeny of *Trichoderma*

Unfortunately, the taxonomy of the genus *Trichoderma*, which has over 500 species, is complicated and has changed as a result of the application of molecular taxonomic techniques (WOO *et al.*, 2023). The genetic diversity and population structure within each of those species using the ribosomal internal transcribed spacer (ITS) sequences, RNA polymerase subunit II (rpb2), and translation elongation factor 1α (tef1α) uncover lineages that would have beneficial adaptations to particular geographic regions and disclose lineages that might qualify for new species to be considered as BCBFs. Key aspects of *Trichoderma* species diversity include:

Abundance and Habitat: *Trichoderma* species are ubiquitous, frequently found in soil, rotting wood, and as plant endophytes.

Key Species: Commonly studied and ecologically significant species include *T. harzianum*, *T. viride*, *T. virens*, *T. asperellum*, and *T. koningiopsis*.

Functional Diversity: They act as opportunistic, avirulent plant symbionts, mycoparasites of plant pathogens, and decomposers. They are also major producers of industrial enzymes like cellulases, chitinases, and proteases.

Taxonomic Complexities: The genus is complex, and many species are cryptic, meaning they are morphologically similar but genetically distinct.

The genus *Trichoderma* phylogeny and the prevalence of its most prevalent species phylogeny using ITS and other gene have been shown in Figure 1. The ITS sequence was chosen for this analysis because it has been showed to be more informative with various sections of the genes *Trichoderma* (Ospina *et al*., 1998). *Trichoderma* species that are rare (less than 100 nucleotide sequences in public databases) are not displayed. Systems of molecular markers are helpful instruments for determining the genetic variations between populations or accessions.

Ecology of *Trichoderma* in agricultural environments

Although *Trichoderma* has likely existed for at least 100 million years, it didn't come into scientific prominence until the late 1970s. *Trichoderma sp*. is excellent colonizers of their environments, as evidenced by their ability to secrete enzymes and metabolites of antibiotics as well as their adept use of the available substrate. Numerous species of *Trichoderma* have been identified to date. The phylogenetic profiling of *Trichoderma* species reported from various sources around the world is displayed in Figure 1. According to Harman *et al*.(2004), *Trichoderma* species are often regarded as soil borne organisms with the ability to regulate plant disease. Additionally, *Trichoderma sp*. has been discovered as plant endophytes. Pocasangre *et al*. (2000) isolated a *Trichoderma sp*. from the central cylinder of a banana while surveying the spread of endophytic fungi from bananas in Central America at the beginning of the year 2000. According to Sikora *et al*. (2008), *Trichoderma atroviride* was extracted from banana endorhiza and utilized for nematode biocontrol. Furthermore, thorough research has been conducted on the distribution and composition of endophytic *Trichoderma* species in banana plants (Photita *et al*. 2001). The majority of the varied collection of *Trichoderma* isolates that have been acquired came from live sapwood that was located just beneath the bark of the trunks of *Theobroma cacao* and other *Theobroma* species, both wild and farmed (Evans *et al*. 2003). *Trichoderma harzianum* and *Trichoderma* longibrachiatum were identified by Abo-Elyousr *et al*. (2014) as being connected to onion stalks. Numerous species of

Trichoderma, some of which are novel, are among the various endophytic microbial communities found in cacao plants (Arnold and Herre 2003; Arnold *et al*. 2003; Rubini *et al*. 2005). Verma *et al*. (2007b) conducted a thorough investigation into *Azadirachta indica*'s endophytes.

Trichoderma spp. was isolated from the roots of *C. arabica* from the main coffee-growing regions of Ethiopia (Mulaw *et al*. 2013). In the Amazon region of Peru, *Trichoderma theobromicola* and *T. paucisporum* were identified as endophytes from the trunk of a robust chocolate tree (Theobroma cacao, Malvaceae) and frosty pod rot-infected pods, respectively (Samuels *et al*. 2006b). In New York, the rhizosphere soil of beans, maize, tomatoes, and radish was used to isolate *Trichoderma harzianum* (T-12) and *Trichoderma koningii* (T-8) (Ahmad and Baker 1987). *Trichoderma harzianum* and *Trichoderma longibrachiatum* were identified by Abo-Elyousr *et al*. (2014) as being connected to onion stalks. Endophytic microbial populations can be found in large quantities, some of which are novel like *Trichoderma ovalisporum* (Holmes *et al*. 2004), *Trichoderma martial* (Hanada *et al*. 2008), *Trichoderma stromaticum* (Samuels *et al*. 2000), *Trichoderma theobromicola*, *Trichoderma paucisporum* (Samuels *et al*. 2006b), and *Trichoderma evansii* (Samuels and Ismaiel 2009) are among the recently discovered endophytic *Trichoderma* species. In Korea, the roots of Panax ginseng plants yielded *Trichoderma citrinoviride* PG87 (Park *et al*. 2018). The rDNA-ITS1 analysis and globally primed polymerase were used to describe 42 isolates of *Trichoderma* from rice fields in four Philippine regions and among them *Trichoderma asperellum*, *Trichoderma atroviride*, *Trichoderma brevicompactum*, *Trichoderma crassum*, *Trichoderma erinaceum*, *Trichoderma gamsii*, *Trichoderma hamatum*, and *Trichoderma harzianum* were isolated by Hoyos-Carvajal *et al*. (2009). In a detail study, 46 strains of *Trichoderma* were isolated by Wuczkowski *et al*. (2003) from the rhizosphere of a Populus and Salix forest area southeast of Vienna, Austria. *Trichoderma koningii*, which protects wheat from take-all disease and boosts grain output in Australia, China, and the US, was identified from a take-all suppressive soil in Western Australia (Duffy *et al*. 1997).

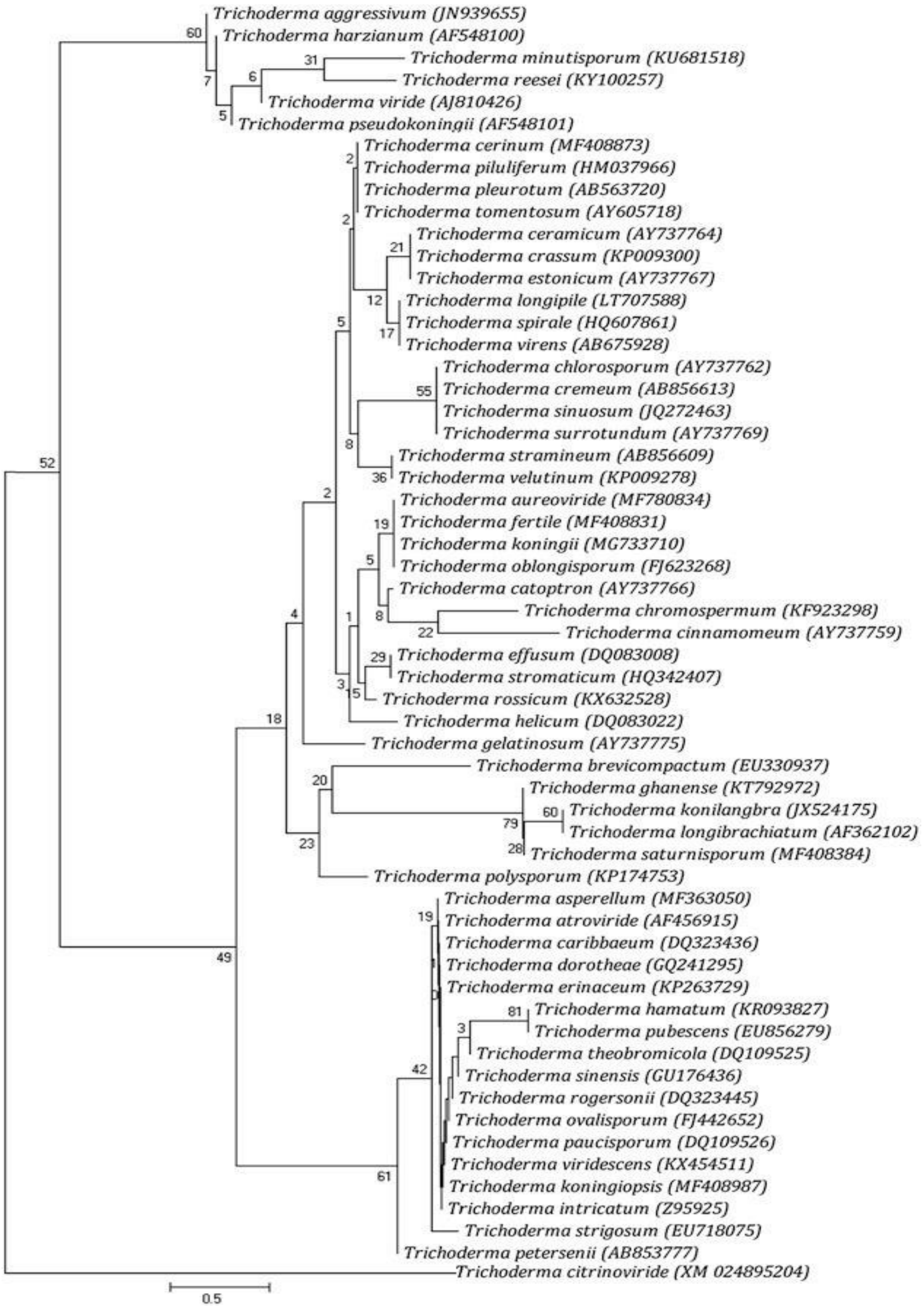

Figure 1. A phylogenetic tree revealed the connections between different *Trichoderma* species that were isolated from various sources (Sharma *et al*., 2019).

Northern Iranian rice paddy fields were used to extract *Trichoderma harzianum* and *Trichoderma virens* (Kredics *et al*. 2011). In the middle regions of Gansu Province, China, 146 isolates of *Trichoderma sp*. were gathered from the rhizosphere surrounding potato plants (Ru and Di 2012). *Trichoderma harzianum*, *Trichoderma hamatum*, and *Trichoderma viride* were identified by Kale *et al*. (2018) from tomato rhizosphere soil. *Trichoderma hamatum*, *Trichoderma harzianum*, *Trichoderma koningii*, *Trichoderma longibrachiatum*, *Trichoderma longipile*, *Trichoderma pseudokoningii*, *Trichoderma virens*, and *Trichoderma viride* were all recovered from the chilli rhizosphere by Nawaz *et al*. (2018).

Mechanisms of bio control in agriculture by *Trichoderma*

According to Holwell (2003), biocontrol is the outcome of several intricate processes working together to control illness. The ability of *Trichoderma* biocontrol agents to produce and/or resist metabolites that either hinder spore germination (fungistasis), kill the cell (antibiosis), or alter the rhizosphere for example, by acidifying the soil so that pathogens cannot grow or competition for nutrients and space are the two main causes of biocontrol. Biocontrol can also result from a direct interaction between the pathogen and *Trichoderma*, similar to mycoparasitism, which involves physical contact and the production of hydrolytic enzymes, toxic compounds, and/or antibiotics that cooperate with the enzymes. In addition to its positive effects on plant-like root colonization, plant growth stimulation, bio fertilization, and induction of plant defence mechanisms, *Trichoderma*'s three most significant antagonistic reaction processes as a biocontrol agent are competition for nutrients, mycoparasitism, and antibiosis (Cook and Baker, 1983).

Antibiosis

All antagonistic chemical compounds emitted into the environment by live *Trichoderma* are considered to be part of antibiosis. This includes substances that harm plant pathogens, such as antibiotics and extracellular enzymes, as well as substances that could help *Trichoderma* maintain a healthy balance as a component of the biota. Since hyphal touch is necessary for this kind of interaction to occur, it is commonly referred to as indirect antagonism (Dix and Webster, 1995). It is commonly recognized that the genus *Trichoderma* produces a large number of fungicidal metabolites, both volatile and non-volatile (Dix and Webster, 1995). Weindling and Emerson (1936) made the initial discovery of antibiotic production while researching *T. lignorum* (Tode) Harz., a synonym of *T. viride*, which is linked to the creation of viridin and gliotoxin (Weindling, 1941; Weindling and Emerson, 1936). However, it was eventually determined that the isolates that produced gliotoxin were a kind of Gliocladium (Dennis and

Webster, 1971a). Additionally, it was later determined that the isolates that produced viridin and gliotoxin (Brian *et al*., 1946; Brian and Hemming, 1945) were Gliocladium. Subsequent research by Webster and Lomas (1964) noted that several isolates found in soil had been demonstrated to produce viridin and gliotoxin, and it was not impossible that many of these were not *Trichoderma*. According to Godtfredsen and Vangedal (1965), *Trichoderma* produces the sesquiterpene, trichodermin, which are antibiotics. *Trichoderma* produces dermadine, an unsaturated monobasic acid that is effective against a variety of fungi and both Gram-positive and Gram-negative bacteria (Pyke and Dietz, 1966). *Trichoderma* produces the peptides suzukacillin and alamethicin which have antifungal and antibacterial qualities (Ooka *et al*., 1966). Acetaldehyde was identified by Dennis and Webster (1971b) as the primary volatile antibiotic that *Trichoderma* generated. Luckner (1990) and Turner and Aldridge (1983) classified the various secondary metabolites, along with their structure, produced by *Trichoderma* in the form of volatile and non-volatile compounds that inhibit growth processes of pathogens. The pyrone 6-pentyl-2H-pyran-2-one is the representative metabolite common to *the Trichoderma genus and has been isolated* from many *Trichoderma* species (Ghisalberti and Sivasithamparam, 1991; Scarselletti and Faull, 1994) which is a flavoring agent and supposed to be responsible for the coconut aroma associated with *T. viride* (Rifai, 1969). According to Zeppa *et al*. (1990), *Trichoderma spp*. produces volatile terpenes and grouped as monoterpenes, sesquiterpenes, diterpenes, triterpenes, and tetraterpenes. Among the sesquiterpenes, two powerful antibiotics named gliocladic and heptelidic acid have been isolated from *T. virens* (Ghisalberti and Sivasithamparam, 1991; Howell *et al*., 1993). Steroids are derived from terpenes, and the well-known antibiotic compounds viridin and viridiol belong to this group. They are secreted by both T. *virens* and T. *viride* and are associated with the suppression of plant pathogens such as R. *solani* (Lumsden *et al*., 1992b) and Penicillium ultimum (Howell and Stipanovic, 1984). Most of the compounds isolated in different studies from Trichoderma have been shown in the table no 1.

Mycoparasitism

One definition of mycoparasitism is "direct antagonism," which is the direct attack of one fungus on another (Dix and Webster, 1995). The direct attack of one fungus on another, known as mycoparasitism, is a very complicated process that includes a series of steps, such as identifying other fungi, moving in their direction, attacking them, and then penetrating and killing the host. *Trichoderma* was first identified as a mycoparasite of R. *solani, S. rolfsii,* *Phytophthora sp., Pythium spp.,* and *Rhizopus spp*. by Weindling (1932). *Trichoderma* develops tropically in the direction of other fungi's hyphae, coils around them in a lectin-mediated response, and breaks down the target fungus' cell walls by secreting several enzymes. *Trichoderma* penetrates the host cell wall and clings to the host hyphae by coiling, hooks, and aspersorium-like structures. It is more than just a contact response; the engagement is specific which initiates coiling and host penetration when it detects signals from the host fungus (Denis and Webster, 1971b; Sivan and Chet, 1989). At this point, the host is penetrated and extracellular hydrolytic enzymes are released (Chet, 1990). It has been proposed that the primary enzymes in mycoparasitism are *Trichoderma*'s cell wall-degrading enzymes, including β-1,3-glucanases and other chitinolytic enzymes (Elad *et al*., 1982; Cherif and Benhamou, 1990). Prior to lyses and death, the host fungus's hyphal wall is first weakened by the poisonous compounds, such as enzymes. The enzymes break down the chitin and glucans in the walls of *R. solani* and the glucans in the walls of *Pythium sp*. (Chet and Baker, 1980). Dennis and Webster (1971) showed how the host mycelium penetrates and produces the lytic enzyme b-1,3-glucanase to parasitize both *S. sclerotia* and its mycelium. *T. harzianum* and *Sclerotinia sclerotiorum* have been shown to interact hyphalically in dual culture by light and electron scanning microscopy. According to Michalikova and Michrina (1996), mycoparasitism between *J. culmorum* and *T. harzianum* strain B results in winter wheat fusariosis, which causes the hyphae of *N. culmorum* to collapse. Trichonitin is produced by strain B-1 where Benhamou and Chet (1996) used scanning and transmission electron microscopy to investigate the interaction between *T. harzianum* and *S. rolfsii's* sclerotia in order to evaluate the part that enzymatic hydrolysis plays in the antagonistic process. In vitro tests have demonstrated the capacity of a number of isolated and described enzymes to prevent the hyphal extension and spore germination of pathogenic fungus (Lorito *et al*., 1998). *T harzianum* and *T hamatum* were found to be mycoparasites of both using fluorescence and scanning electron microscopy showed the antagonists, *S. rolfsii* and *A. solani*, adhered to the pathogen and released the enzymes chitinase and glucanase, which functioned through the cell wall (Elad *et al*., 1983). *T harzianum* strain T24's culture filtrate showed inhibition of *S. rolfsii* indicating that these enzymes are involved in the biocontrol process (El-katatny *et al*., 2001).

Induced systemic resistance and plant defence

Through biochemical cross-talk between *Trichoderma spp*. and plants, which directly alters plant metabolism and empowers plants to fight off invasive diseases, *Trichoderma spp*. directly interact with the pathogens and also cause gene expression in the host. Plants undergo biochemical changes during *Trichoderma*-plant-pathogen interaction, including lignin deposition, an increase in total phenolic content, modifications to the profiles of enzymes such as chitinase, β-1, 3-glucanase, peroxidase, and phenyl alanine ammonia lyase, and changes in phenylpropanoids in response to pathogen attack (Bisen *et al*., 2019; Jain *et al*., 2012; Keswani, 2015; Keswani *et al*., 2019; Keswani, 2016; Singh *et al*., 2013; Singh *et al*., 2014; Singh *et al*., 2017). The level and consistency of illness management may be improved by using a consortium of two or more microorganisms rather than a single microorganism mixture. by offering a variety of methods and possibly being more resilient to a broad range of environmental circumstances (Abeysinghe, 2009; Basco *et al*., 2017; Fraceto *et al*., 2018; Keswani *et al*., 2019; Singh *et al*., 2013; Srivastava *et al*., 2025). Thus, this study's primary goal was to assess how *Trichoderma spp*. affected the defense system of brinjal plants after an infection with *S. sclerotiorum*.

Competitive Exclusion

Widespread occurrence of *Trichoderma* in natural and agricultural soils across the globe suggests that it must be a fierce rival for nutrients and space. *Trichoderma* species grow quickly, are thought to be fierce competitors, and quickly colonize substrates to keep diseases like *Fusarium spp*. out (Samuels, 1996).

According to the law of competitive exclusion, the stronger species will occupy the ecological niche and push the weaker species out if it has even the smallest advantage or edge over the other competing species. The stronger species will push out the weaker species when their niches overlap with those of closely related species. One of the two competing species will always overwhelm the other, and in the case of soil, the species in question are on a microscopic level. A wide range of microorganisms are antagonistically affected by *Trichoderma spp*. (López-Bucio *et al*., 2015). Their quick colonization and spread in ecological niches would be facilitated by this extremely hostile trait (Schuster and Schmoll, 2010). *Trichoderma spp*. aid in inhibiting the growth of phyto pathogenic fungi by competition for resources and space, the ability to stop spore germination, cell death (antibiosis), or modifying the rhizosphere, such as by making the soil acidic. Because iron uptake is necessary for the majority of plant pathogenic fungus to survive (Migheli *et al*., 1998) fungal phyto pathogens are biologically controlled by competition for these (iron)-limited nutrients. Siderophores, which are low-molecular-weight ferric iron-specific chelators, are released by fungi to mobilize ambient iron when iron levels are low (Eisendle *et al*., 2004). *Trichoderma* produces very efficient siderophores that chelate iron and stop fungal development (Chet and Inbar, 1994). Antibiosis is caused by interactions with low-molecular-weight diffusible compounds or medicines made by *Trichoderma* strains that stop other plant harmful microorganisms from growing. Additionally, the majority of *Trichoderma* release both volatile and non-volatile metabolites, including 6-penthylpyrone, alamethicins, gliovirin, glisoprenins, harzianic acid, heptelidic acid, massoilactone, peptaibols, tricholin, and viridin (Vey *et al*., 2001).

Table 1. List of secondary metabolites/bioactive compounds produced by *Trichoderma*

***Trichoderma* spp.**	**Chemical group**	**Compounds**	**References**
T. lignorum	Epidithiodioxo piperazine (sulphur containing mycotoxin)	Gliotoxin	Weindling(1934); Radebe *et al.* (2022)
T. harzianum	Anthraquinone	Pachybasin	*Lin et al.* (2012)
T. atroviridea, *T. asperellum,* *T. reeseia, T. virensa*	Siderophore	Ferricrocin	Kubicek *et al.*(2011)
T. longibrachiatum	Bisorbicillinoid	Bisvertinolone	Ngo *et al.* (2021)
Trichoderma spp.	Hydrolytic enzymes	1,6-Glucanases Chitinases	Druzhinina *et al.* (2011)
			Gruber and Seidl-Seiboth(2012); Saravanakumar *et al.*(2017)
T. pseudokongii	Peptaibol	Trichokonin	Shi *et al.* (2012)
Trichoderma spp.		Alamethicin	Bortolus *et al.*(2013)
T. aureoviride,T. viride	Anthraquinone	Chrysophanol	De Stefano and Nicoletti (1999); Liu*et al.* (2009)
T.koningii	Pyrane	Koninginin D	Dunlop *et al.* (1989); Chen *et al.* (2015)
T. koningii, T. virens, *T. viride*	Furanosteroids	Viridin	Reino *et al.*(2008)
T. viride,T. polysporum, *T. sporulosum, T. reesei*	Trichothecene	Trichodermin	Reino *et al.*(2008)
T. atroviride	Alcohol	1-Octen-3-ol	Stoppacher *et al.* (2010)
T. atroviride	Ketone	3- Octanone	Stoppacher *et al.* (2010)

T. harzianum	Alcohol	2-Phenylethanol Tyrosol	Chang *et al.* (2015) Albuquerque and Casadevall (2012)
T. arundinaceum; *T. harzianum*	Nitrogen heterocyclic compound	Harzianic acid	Malmierca *et al.,* (2013)
		Harzianopyridone	Kawada *et al.* (2004); Ahluwalia *et al.*(2015); Khan *et al.* (2020)
Trichoderma koningii, *T. viride*	Isocyano metabolite	Dermadin	Dutta *et al.* (2022a)
T. harzianum	Polyketides	Trichoharzianol	Jeerapong *et al.* (2015)
T. viride	Peptide	Alamethicin	Engelberth*et al.* (2001)
T. longibrachiatum	Butenolide	5-Hydroxyvertinolide	Andrade *et al.* (1992)
T. hamatum *T. viride* *T. virens*	Epipolythiodioxo piperazines Or Diketopiperazine/NRP	Gliotoxin	Mukherjee *et al.* (2012)
		Gliovirin	Nakano *et al.* (1990)
Trichoderm apseudokoningii	Peptaibols	Trichokonins	Li *et al.*(2014)
T. longibrachiatum		Trichokonins VI,VII, And VIII	Zhao *et al.* (2018)
T. harzianum		Trichorzianines A1 and B1	Goulard *et al.*(1995);Lee*etal.*(1999)
T. citrinoviride		Amino isobutyric acid and isovaline	Dutta *et al.* (2022b)
T. stromaticum		Tricho stromaticins A–E	Degenkolb *et al.* (2008)
T. longibrachiatum		Trichogin G A I V and its derivatives	Baccelli *et al.* (2022)
T. brevicompactum	Trichothecene	Trichodermin	Shentu *et al.* (2013); Shentu *et al.* (2014)
		Trichobreols A–E	Yamazaki *et al.*, (2020) aand Yamazaki *et al.,(*2020b)
		Trichothecinol A, 8-deoxy trichothecin, tricho hecinol B, and trichodermene A	Du *et al.* (2020)
T. harzianum *T. viride*	Pyrone	1-Pentenyl	Parker *et al., (*1997)

		6-Pentyl-2H- pyran-2-one	Scarselletti and Faull(1994) ;Poole *et al.*(1998)
		Viridepyronone	Evidente*et al.* (2003)
	Lactone	Cremenolide	Vinale*et al.* (2009)
		Aspinolide C	Malmierca *et al.*(2015)
		Cerinolactone	Vinale *et al.* (2012); Arjona-Girona*et al.* (2014)
		Nafuredin C, NafuredinA	Zhao *et al.* (2020)
T. harzianum	Azaphilone	T22azaphilone, harziphilone, fleephilone,	Vinale*et al.* (2006); Pang *et al.* (2020)
T. harzianum	Butenolides	Harzianolide	Vinale*et al.* (2006);Vinale *et al.* (2009)
T. harzianum		T39 butenolide	Manzar *et al.* (2022)
T. longibrachiatum		5-hydroxyvertinolide	Ramasamy*et al.* (2023)
T. longibrachiatum, T. koningii,T.viride	Ergosterol-derived compound	ErgokoninA	Reino *et al.* (2008)
		Stigmasterol	Ahluwalia *et al.* (2014); Ahluwalia*etal.*(2015)
		Ergosterol,3,5,9-trihydroxyergosta-7,22-dien-6-one	Xuan *et al.* (2014)
T. virens	Monoterpenes	Cisandtrans ocimene	Crutcher *et al.* (2013)
T. reesei	Hydrolytic enzymes	Cellulases	Jadhav and Sayyed (2016)
Trichoderma spp.	Siderophore	Coprogen B	Vinale *et al.* (2012)
		Fusarinine C	Anke *et al.* (1991)
T. brevicompactum	*Trichothecene*	*Trichodermin*	Malmierca *et al.* (2013)
T. virens	Carotanes	TrichocaranesA,B,CandD	Macias *et al.* (2000)
T. longibrachiatum	Peptide	Trichokonin	Shi *et al.*(2016)
T. virens	Peptaibol/NRP	TrichovirinII	Mukherjee *et al.* (2012)
T. virens	Peptaibol	sm1	Djonovic *et al.* (2006); (2007)
T. atroviride		Epl1	Vargas *et al.* (2009)
T. viride, T. atroviride, T. harzianum, T. koningii	Pyrone	6-pentyle-2H-pyrone-2-one	Garnica-Vergara *et al.* (2015)
T. koningii	Pyrane	Koninginin A	Khan *et al.* (2020)
T. harzianum, T. koningii	Sesquiterpene	Cyclonerodiol	Vinale*etal.*(2012)
T. harzianum	Setin like metabolite	Trichosetin	Shi *et al.*, 2016
T. atroviride,	Indolic compound	Indole-3-acetic acid	Contreras-

T.virens			Cornejo *et al.*(2009)
		Indole-3- acetaldehyde	Contreras-Cornejo *et al.*(2009)
		Indole-3-carboxaldehyde	Contreras-Cornejo *et al.*(2011)
T.atroviride	Hydrocarbonated compound	Ethylene	Contreras-Cornejo *et al.*(2015a)
T.atroviride,T.virens	Isoprenoid	Abscisic acid	Contreras-Cornejo *et al.*(2015b)

Table 2. List of phytohormones/bioactive compounds produced by *Trichoderma*.

***Trichoderma* spp.**	**Phytohormones**	**Activity**	**References**
T .atroviride	salicylic acid	SAR induction produced disease resistance in plants.	Ruocco *et al.*(2015)
T. virens	Indole acetic acid	aids in the development and expansion of plants and their root systems.	Contreras-Cornejo *et al.*(2009)
Trichoderma spp.	Cytokinin	caused the host to experience growth-promoting and anti-pathogen effects.	Bean *et al.*(2021)
T. atroviride	Ethylene	modulation of salicylic acid and jasmonic acid levels and their signaling pathway to improve resistance to biotic and abiotic stressors	Mukherjee *et al.* (2013)
Trichoderma spp.	Gibberellic acid	Growth promotion through ethylene level lowering and growth-repressing DELLA protein degradation	Hermosa *et al.*(2012)
T. asperellum	jasmonic acid	The signaling molecule for Trichoderma-induced ISR is ethylene, also known as JA.	Yoshioka *et al.*(2012)
T. virens and T. atroviride	Abscisic acid	Alteration in transpiration and control of the stomatal aperture through ABA receptor induction	Contreras-Cornejo *et al. (*2015)

Plant Growth Promotion in Agriculture

By colonizing roots, promoting root development, improving nutrient uptake (P, Fe), and generating phyto hormones, *Trichoderma* species aid in the growth of plants. As helpful fungi, they improve production, shoot/root weight and seed germination while reducing abiotic stress and establishing systemic resistance to infections (Morales *et al.*, 2024). Several phyto hormones, including auxin and gibberelic acid, jasmonic acid, salicylic acid and ethylene are synthesized and accumulate as a result of *Trichoderma* invasion and colonization (Dutta *et al*., 2023). Considering their capacity to modify, these phyto hormones are key components of plant defence and immunological responses (Table 2). The microbe's strain, time, and/or inoculum concentration have a significant impact on the timing, make-up, and amount of the phyto hormonal blend that plants release in response to microbial invasion (Pieterse *et al*., 2009). Segarra *et al*. (2007) found that after inoculating cucumber roots with *Trichoderma* for four hours, the plants displayed a SAR-like response by up-regulating peroxidase and SA activity. Additionally, the plant system's SA and JA levels increased systemically when a larger inoculum density of *Trichoderma* was applied (Dutta *et al*., 2023). It might be because the plant cells' oxidative bursts brought on by ETI expression trigger a hypersensitive reaction in the plant system, which in turn triggers the activation of SAR through an SA-mediated route. By boosting the plant's JA/ET and auxin responses, which can function as SA antagonists, *Trichoderma* can circumvent these defense mechanisms of plants by activating SA-dependent pathways (Hermosa *et al*., 2012). According to Contreras-Cornejo *et al*. (2009), certain strains of *Trichoderma* can increase the synthesis of plant biomass, stimulate lateral root growth via an auxin-dependent mechanism, and/or generate indole- 3. Analogs of auxin or acetic acid (Hoyos-Carvajal *et al*., 2009).

***Trichoderma* in Bioremediation**

Trichoderma are potentially utilized in the production of cellulolytic and hemicellulolytic enzymes, the biodegradation of chlorophenolic compounds, and the biological management of plant diseases. substances, as well as soil bioremediation (Kidwai *et al*., 2022). One of the most effective hyper producers of cellulase employed in industry is thought to be *Trichoderma reesei*. With relatively quick, early growth on easily metabolized growth medium components (yeast extract), the biomass concentration remained constant over time. This was followed by a second, slower growth phase brought on by cellulose hydrolysis, which came after an increase in cellulase concentration (Ahamed and Vermette, 2008). The innovative technologies of bioremediation and phyto remediation in conjunction with microbes have the potential to alleviate a variety of environmental issues. *Trichoderma* is a genetically diversified genus with a several traits with industrial and agricultural significance among various strains. Additionally, it can withstand a wide range of resistant contaminants, including polyaromatic hydrocarbons, herbicides, and heavy metals. *Trichoderma* has a wide range of potential applications in the biological or phytobial cleanup of environmental pollutants in the future (Tripathi *et al*., 2013).

It was investigated if the polar and nonpolar anthraquinone dyes might be bioremediated by the recently discovered ascomycete fungus *Trichoderma lixii* F21. The findings suggested that *T. lixii* F21 might be a suitable choice for industrial effluents contaminated with anthraquinone dyes to undergo bioremediation (Adnan *et al*. 2017). In agriculture, *Trichoderma* species are said to improve nitrogen use efficiency, boost photosynthetic efficiency, and enhance nutrient uptake. However, they can also be used to produce bioenergy, help plants adapt, and lessen the negative effects of climate change (Kashyap *et al*. 2017). *Trichoderma* species have a variety of biotechnological uses, such as as a biofungicide to prevent plant diseases and a biofertilizer to promote plant growth and produce high yields and productivity that guarantee food security and environmental security by lowering the use of dangerous agrochemicals. manufacturing of compounds of industrial significance and the potential for bioremediation for environmental cleanup efforts (Kidwai and Nehra, 2017). Several heavy metals that can contaminate the environment can be removed with the use of bioremediation employing effective *Trichoderma*. Research has shown that *Trichoderma* isolates have the ability to remediate wastewater biologically in mining industries (Tansengco *et al*., 2018).

Integration into IPM (Integrated Pest Management) of *Trichoderma*

The use of *Trichoderma* within IPM frameworks is now common across many cropping systems. Successful integration depends on compatibility with like commonly used fungicides, soil amendments, fertilizers, irrigation schedules, cultural practices such as crop rotation and residue management etc. Unlike chemical fungicides, *Trichoderma* does not disrupt beneficial microbial communities and can operate synergistically with AMF, plant-growth promoting rhizobacteria (PGPR), and entomopathogenic fungi (Keswani *et al*., 2013). However, some fungicides—specifically broad-spectrum protectants—may reduce *Trichoderma* viability when applied simultaneously. **The key IPM Advantages are** reduced fungicide requirement, improved soil biodiversity, suppression of multiple pathogens simultaneously, enhanced resilience under abiotic stress, compatibility with organic production standards etc. Field-level studies show that combining *Trichoderma* with reduced fungicide dosages can achieve similar or superior control of soil borne pathogens compared to full-dose chemical programs (Woo *et al*., 2014).

CONCLUSION AND FUTURE ASPECT

The extensive use of pesticides negatively impacted the quality of the soil, water, and ecology, which in turn affected the socioeconomic condition of the farmers and agricultural sector. Pesticide resistance is another pressing issue of the twenty-first century. The easiest method is the biological method of sustainable agriculture, which seems to provide an alternative to chemical-based pesticides for disease management and suppression, can be used to address these problems. For this *Trichoderma* has emerged as one of the most important microbial tools for sustainable agriculture. Its multifaceted roles—as a biocontrol agent, plant growth promoter, soil health enhancer, and stress tolerance inducer—make it indispensable in modern IPM and climate-resilient cropping systems. Advances in genomics, formulations, and multi-microbial technologies will further expand its agricultural impact. Widespread adoption of *Trichoderma* can reduce chemical inputs, support ecological balance, and improve crop productivity in environmentally friendly way.

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