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REVIEW

Trichoderma : A versatile fighter in integrated crop health management

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Trichoderma species are cosmopolitan filamentous fungi that inhabit diverse agro-ecosystems, thriving in the rhizosphere and interacting beneficially with plants, microbes, and the environment.Their versatility stems from an extraordinary capacity for mycoparasitism, antibiosis, competition, induced systemic resistance (ISR), and growth stimulation through secondary metabolite production and phytohormone modulation. Rigorous isolation and evaluation of their multifaceted mechanisms of action are the cornerstones for achieving success in integrated biological crop health management. So far more than 55 isolates of *Trichoderma* isolates mostly belongs to *T. harzianum, T. viride, T. asperellum, T. atroviride* have been isolated from various crop rhizospheres of North Bengal regions and evaluated against various soil borne plant pathogens including *Rhizoctonia solani, Macrophomina phaseolina, Sclerotium rolfsii, Fusarium spp., Ralstonia solanacearum*, etc. However, due to their specificity against pathogenic strains, compatibility with other beneficial microbes and legal complexicity in registration as biopesticide, the use of *Trichoderma* is still facing challenges in agriculture practices. Continuous advancements in strain development, formulation technology, and integration strategies are expected to strengthen its role in global food security and climate-resilient agriculture. A wide array of strategic modules have been developed to introduce efficient crop specific *Trichoderma* isolates in consortia with other plant growth promoting micro-organisms like Azotobacter, Rhizobium, phosphate solubilizing bacteria in various crop rhizospheres especially suitable for the farmers of north bengal regions. Apart from its direct role in pathogen suppression, *Trichoderma* interacts with heavy metals through multiple mechanisms including biosorption, bioaccumulation, transformation, and chelation via metal-binding proteins and extracellular metabolites such as organic acids and siderophores. These mechanisms not only reduce metal bioavailability and toxicity in contaminated soils but also enhance soil health and support plant growth. A study revealed that two *Trichoderma* isolates of north bengal origin are efficient in scavenging heavy metals like nickel and cadmium from polluted rice ecosystem and thereby reducing their uptake in host plants. Further theinduced systemic resistance (ISR) triggerred by *Trichoderma* enhances the plant's defensive capacity against a broad range of herbivorous insects. The fungal colonization triggers biochemical changes, including accumulation of phenolic compounds, pathogenesis-related (PR) proteins, and defense enzymes such as peroxidase, polyphenol oxidase, and chitinase, all of which strengthen plant tissues and deter insect feeding. Hence, appropriate integration of *Trichoderma* into sustainable pest management practices can substantially reduce chemical pesticide dependency, improve crop productivity, and contribute to environmental safety.

Keywords : Mechanisms of action, plant health management, multifaceted role *Trichoderma*

INTRODUCTION

Agricultural sustainability is under increasing concern as a consequence of global population growth, intensive cropping systems, soil degradation and climate variability. Traditional reliance on synthetic agrochemicals has improved short term yields but also has led to soil microbiome disruption, resistance development among pathogens, residual toxicity in produces and environmental pollution. These challenges has prompted a paradigm shift toward ecologically based strategies such as chemical and keeping special emphasis on biological approaches for optimal plant protection (Baker and Paulitz, 2020).

Among biocontrol agents, *Trichoderma* species, an ubiquitous soil fungi belonging to the phylum

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Ascomycota, class Sordariomyceres, order Hypocreales and family Hypocreaceae (Voigt and Kirk, 2011) draw significant attention in modern agriculture due to their multifaceted role in plant health management. Unlike narrow spectrum chemical fungicides, *Trichoderma* offers systemic and sustainable benefits by modulating plant defense systems and reshaping the rhizosphere microbiome.

Historical context and discovery of Trichoderma

Although first found in Germany in 1671, it took more than a century to be first described by Persoon (1794). Tulasne and Tulasne (1865) postulated a sexual relationship between *Hypocrea* (the teleomorph or sexual stage) and *Trichoderma* (the anamorph or asexual stage). Early observation noted their rapid growth and green conidia, but it was not until 1932 when Weindling proved biocontrol potential of *T. lignorum* against *Rhizoctonia solani* followed by discovery of gliotoxin as first antimicrobial compound from *Trichoderma* species (Weindling, 1932; Weindling, 1934). In next 30 years *Trichoderma* researches were concentrated on mechanism of action and species identification. In 1960s with awakening concern of using hazardous pesticides in agriculture and the need for integrated management by putting more reliance on biocontrol agents opened up the *Trichoderma* research under laboratory to field scale commercialization after the Barkleys international convention on "Ecology of Soil Borne Plant Pathogens: A prelude to Biological Control". The ability of *Trichoderma* to promote plant growth was first demonstrated in 1986 (Chang *et al.* 1986) while The first commercial *Trichoderma* formulation for biocontrol, Binab T, was registered in 1989. *Trichoderma*'s ability to induce systemic resistance (ISR) in plants was discovered in 1997 (Bigirimana *et al.* 1997) and direct evidence was provided for internal coiling of plant roots by *Trichoderma* spp., and the induction of systemic resistance in cucumber plants (Yedidia *et al.* 1999). From 2008 genomic research on *Trichoderma* got a momentum with the first *Trichoderma* genome (*T. reesei*) was completely sequenced, followed later by *T. virens* and *T. atroviride* (Schmoll *et al.* 2016). The mating type locus of *T. reesei* was identified, proving its heterothallic nature and opening possibilities for strain development (Zheng *et al*. 2017). During 2010 to 2020 advances in "omics" technologies (genomics, transcriptomics, metabolomics, proteomics) have led to an exponential increase in the number of recognized *Trichoderma* species (from around 100 to over 400) and a deeper understanding of its complex, multifaceted mechanisms in plant interactions and bioremediation. Current research focuses on developing advanced bioformulations (e.g., using nanotechnology or microbial consortia) and utilizing genetic engineering tools like CRISPR/ Cas9 to optimize specific traits for sustainable agriculture and biotechnology.

Classification

Earlier classification proposed by Rifai (1969) introduced the concept of species aggregate and identified nine species under the genus based on morphological variation. Later Bissett (1991) attempted to classify *Trichoderma* by integrating similar forms within species concept based on their condiophore branching system into five sections viz., *Pachybasium, Saturnisporum, Trichoderma, Longibrachiatum* and *Hypocreanum*. Modern molecular techniques based on Internal Transcribed Spacer (ITS) regions of 18s mitochondrial rDNA sequence analysis , translation elongation factor (TEF-1) and endochitinase 42 helped to construct phylogenetic tree depicting *Trichoderma* as a monophyletic branch under Hypocreaceae comprising of more than 400 phylogenetically distinct species under three sections namely, *Trichoderma*, *Pachybasium* and *Longibrachiatum* (Bisset *et al.* 2015). Recently Gu *et al.* (2020) identified four new species of *Trichoderma* in the *Harzianum* clade based on ITS, RPB2 and TEF1-α sequence data set. Among the species *T. harzianum*, *T. viride*, *T. asperellum*, *T. atroviride*, *T. virens*, *T. koningii* and *T. longibrachiatum* are the most commonly exploited for agricultural applications. Each species exhibits unique ecological niches, physiological capacities and interaction mechanisms with plants and pathogens. For instance, *T. harzianum* is known for its mycoparasitic activity against *Rhizoctonia* and *Sclerotium* spp., whereas *T. asperellum* and *T,*

Table 1: Assessment of different *Trichoderma* isolates in maize for biocontrol of turcicum leaf blight

Cluster	Area under SPAD Decline Curve (AUSDC)	Disease severity (%)	Yield (g/plant)	Isolates
I	5235.38 ± 52.79	16.86 ± 4.36	232.27 ± 30.16	UBT-19, UBT-23, UBT-35, UBT-37. UBT-43, UBT-49. UBT-50, UBT-52, UBT-53, UBT-55
II	5245.02 ± 93.04	12.26 ± 2.89	340.25 ± 43.71	UBT-20, UBT-25, UBT-26, UBT-30. UBT-31, UBT-40. UBT-42, UBT-46, UBT-54
III	5324.67 ± 92.89	6.86 ± 4.28	243.51 ± 34.98	UBT-21, UBT-22, UBT-24, UBT-27. UBT-32, UBT-39. UBT-41, UBT-44, UBT-47, UBT-51
IV	5047.97 ± 119.30	10.08 ± 2.22	227.79 ± 24.77	UBT-18, UBT-28, UBT-29, UBT-33. UBT-34, UBT-36. UBT-38, UBT-45, UBT-48

Fig 1: Seedling growth of tobacco under influence of bioinoculants. (a) Untreated control, (b) treated with *Trichoderma viride* , (c) treated with *Pseudomonas fluorescens* (d) jointly treated with *T. viride* + *P. fluorescens*

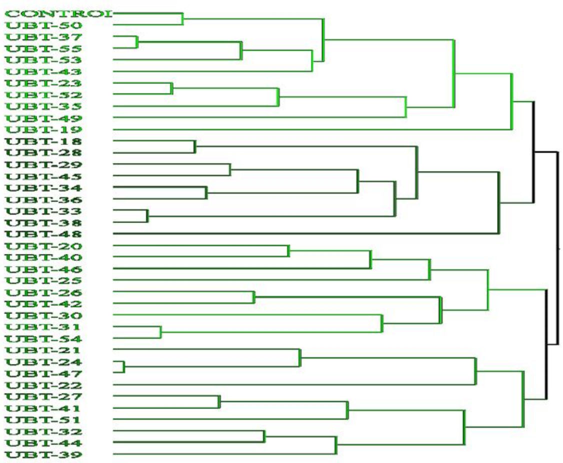

Fig 2: Cluster analysis of *Trichoderma* isolates with Area under SPAD Declinecurve (AUSDC, Turcicum Leaf Blight and Yield as variables in maize

virens demonstrate potent abilities to induce systemic resistance in host plants (Hermosa *et al*. 2012).

Ecological fitness and abundance

Physiologically *Trichoderma* spp. are saprophytic, fast growing, cosmopliton thriving as dominant microflora in soil including agricultural, orchard, forest, soil with high organic matter, pasture land

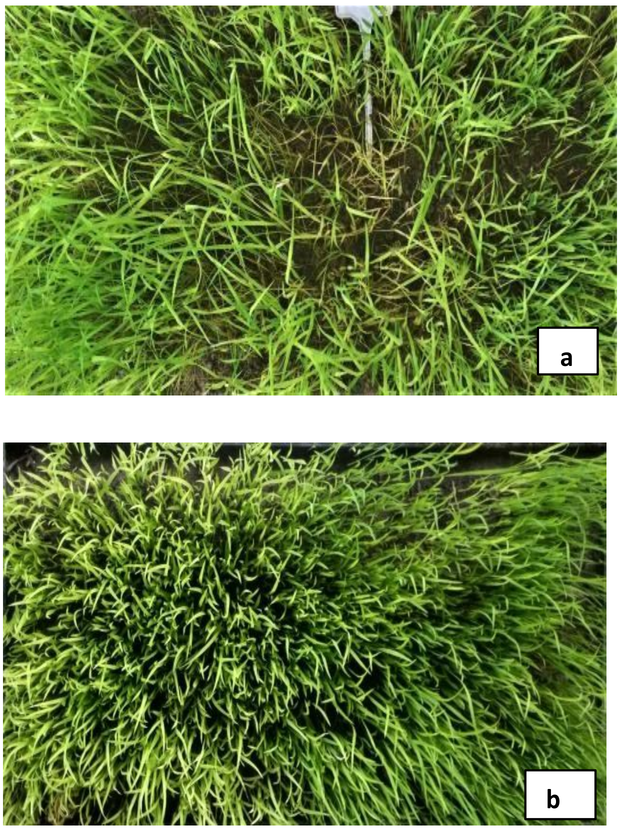

Fig. 3: Rice mat nursery (a) *Rhizoctonia solani* infected seedling mortality (b) *Trichoderma* treated with reduced seedling mortality.

and desert soil from cool temperature to tropical climates and in decaying wood too. Their prevalence in rhizosphere soils highlights their ecological versatility and adaptibility to different soil types and cropping systems (Papavizas, 1985). However, soil colonization, composition, biomass and biological activity of *Trichoderma* spp. are influenced by ecological parameters like moisture, temperature, pH, organic matter, nutrient content and plant types (Verma *et al.* 2007). *Trichoderma* spp. have been reported in a wide range of soil temperature from 0°C to 40°C favouring *T. viride* and *T. polysporum* in cool temeprature whereas, *T. harzianum* in warm tropical soils (Klein and Evileigh, 1998). Temperature variation affects the growth, metabolic activity, volatile antibiotic and enzyme production in *Trichoderma*. The reduction of soil moisture coupled with increased soil temperature affect *Trichoderma* population in soil by reducing the hyphal growth, germination and spore production (Clarkson *et al.* 2004). The optimum pH range for growth and development of *Trichoderma* spp. in soil is 3.5 to 5.6 but can also thrive to extreme pH up to 2.1 (Ghazanfar *et al.* 2018). Carbon dioxide content in soil and atmosphere also affects growth of *Trichoderma* by affecting soil pH upon combining with water to form weak acid i.e., carbonic acid which ready dissociates into H^+ and HCO_3^- thus decreasing soil pH (Kilham, 1994). After application survivability of *Trichoderma* spp. in soil is basically mediated by hyphae aggregate, or mycelial fragments, resting structure such as chlamydospore and conidia (Papavizas, 1985). Persistence of conidia lasted up to 110-113 days without any amendments or decreased initially, then stabilized to the extent of 1/10th of original population in soil for 24 month, while in case of chlamydospore although survive for longer time but require biological inducer to break dormancy. In natural and agricultural systems, *Trichoderma* acts as key component of the soil microbiome, contributing to nutrient cycling and suppression of soil borne patogens. Its saprophytic lifestyle allows colonization of plant residues and root surfaces, establishing a beneficial microzone that protects roots from pathogenic invasion (Alfiky and Weisskopf, 2021). The rhizosphere competence of *Trichoderma*- its ability to survive, multiply and exert activity in association with plant roots is a crucial determinant of its success as biocontrol agent.

Versatile Role in Crop Health Management

Direct action against pathogens and indirect effect on hosts: *Trichoderma* species functions through multiple mode of action either through direct mechanisms viz., mycoparasitism, competition and antibiosis or complex indirect mechanisms by stimulating induced systemic resistance (ISR), solubilization and sequestration of nutrients, nutrient uptake and plant growth promotion by inducing production of growth hormones (Harman *et al.* 2012, Lorito and Woo, 2015). The mycoparasitism mechanism occurs as a sequential events involving three steps, including chemotrophic growth, coiling of host hyphae and secretion of lytic enzymes (Dix and Webstar, 1995). The interaction is usually governed by host derived chemicals that are recognized by *Trichoderma* species through specific signalling mechanisms mediated by diffusible signal molecules such as oligochitins, enzymes like exochitinases, endochitinases, β-1,4 N acetylglucosaminidases, extracellular β-1,3 glucanases, proteases and lipases (Viberto and Horwitz, 2010). Upon establishment of contact with pathogen cell, *Trichoderma* forms papillae/ appressoria like structure and starts coiling the target fungus mediated by hydrophobin like proteins and a lectin complex from the cell wall of *Trichoderma* and target pathogen, respectively. The lytic enzymes such as chitinases, glucanases, pectinases and peptaibol antibiotics induce a cascade of physiological changes within the target pathogen facilitating the flow of nutrients to *Trichoderma* and degeneration of target fungus (Howell, 2003).

The production of antimicrobial compounds by *Trichoderma* spp. is strain specific, which includes volatile and nonvolatile antimicrobial compounds, suchas 6-pentyl-α-pyran-2-one, gliotoxin, viridin, harzianopyridone, harziandione, and peptaibols. Synergistic effects between cell wall–degrading enzymes and plethora of secondary metabolites/antibiotics of *Trichoderma* spp. on fungal pathogen growth have been well documented (Vinale *et al.* 2008). These antibiotics act as metabolic inhibitors or block

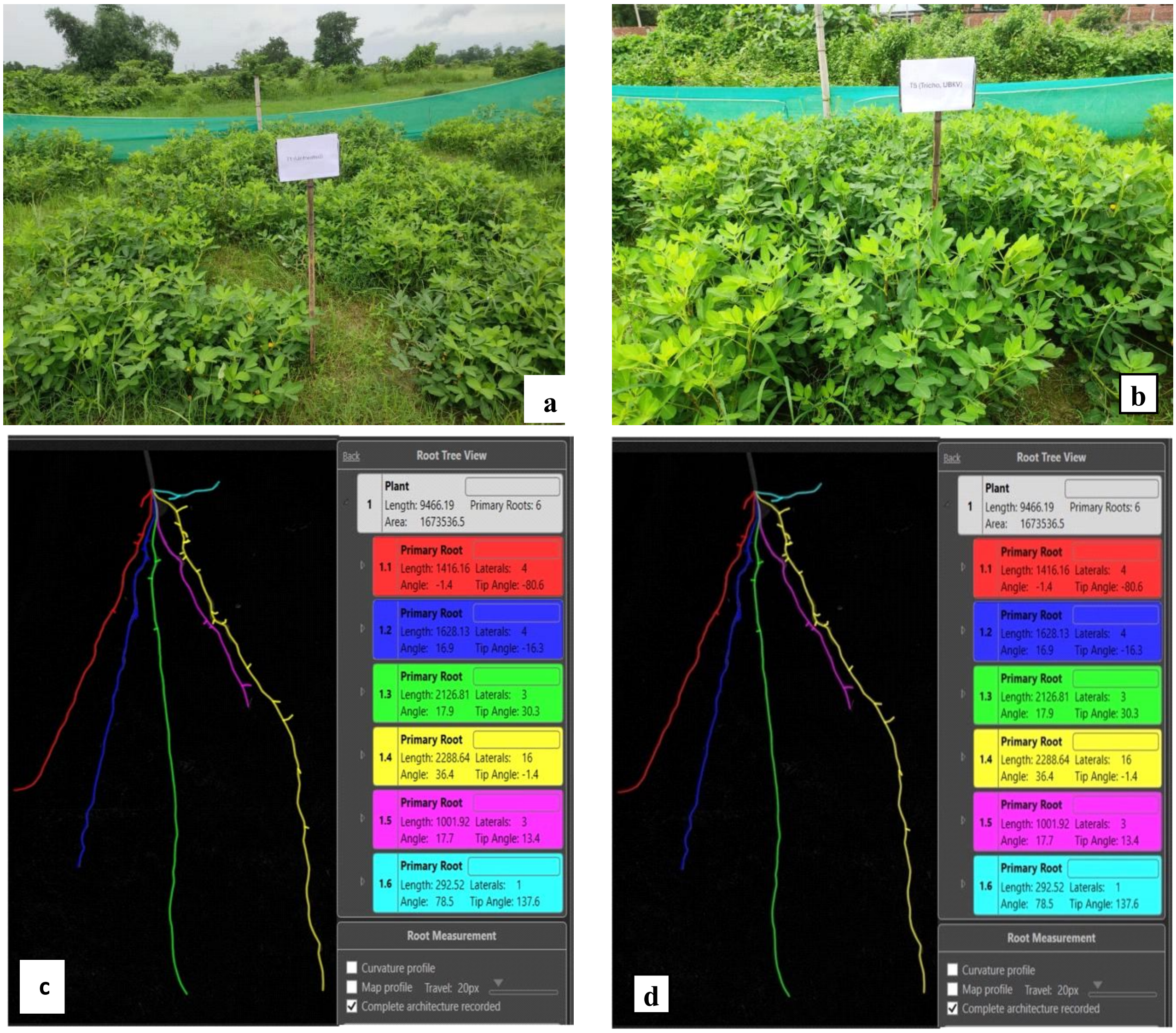

Fig 4 : Effect of seed bioinoculation of groundnut with *Trichoderma harzianum* (UBT 18) on growth (a &b) and root architecture (c& d). Untreated control (a &c) ;Treated with *T.harzianum* (b & d).

protein synthesis, penetrate host cells inhibit cell wall syntheis, growth uptake of nutrients, sporulation and metabolite production by target pathogen (Dutta *et al.* 2022). P group strains of *Trichoderma* (*Gliocladium*) *virens* produced the gliovirin, which was very active against *Pythium ultimum*, but inactiveagainst *Rhizoctonia solani*. Similarly, strains of the Q group produced gliotoxin, which was veryactive against *R. solani*, but less active against *P. ultimum* (Howell, 1993) indicates the strain specificity and determine the success or failure of biological control.

Competition is on other hand is one of the classical mechisms by eliminating indirectly the pathogens through reduction of food source and niche exclusion (Elad *et al.* 2000). High competitive saprophytic attribute in *Trichoderma* helps to exert resistance against a variety of toxins or antimicrobial compounds produced by other microorganisms due to presence of cassettes of transporters. However, such competitiveness may vary between isolates (Roy and Pan, 2005) which further determine the rhizosphere colonization property (Roy and Pan, 2004) and is governed by extensive communication via exchange and perception of signaling molecules i.e., deposition of fungal elcitors, auxin like metabolites and proteinaceous compounds released by *Trichoderma* and are perceived by plant rhizosphere (Garnica-Vegara *et al.* 2015).

Trichoderma as inducer of disease resistance and plant growth promoter

Colonization of plant roots by *Trichoderma* initiates a complex molecular dialogue involving recognition of fungal microbe-associated molecular patterns (MAMPs), activation of mitogen-activated protein kinase (MAPK) cascades, heterotrimeric G-protein signalling, cAMP pathway (Zeilinger and Omann, 2007), modulation of phytohormonal networks, and priming of systemic immune responses. These interactions lead to enhanced expression of pathogenesis-related (PR) genes, accumulation of defense enzymes, reinforcement of cell walls, and metabolic reprogramming. Simultaneously, *Trichoderma* promotes plant growth through phytohormone production, modulation of auxin signaling, phosphate solubilization, siderophore-mediated iron acquisition, improvement of nitrogen use efficiency, and enhancement of photosynthetic capacity. Recent advances in genomics, transcriptomics, proteomics, metabolomics, and microbiome research have elucidated the molecular basis of these beneficial effects. Reithner *etal.* (2005) identified heterotrimeric G-protein signalling genes (TGA of *T. virens*, GNA3 of *T. reesei* and TGA 1 and TGA3 of *T. atroviride*) played an important role in regulation of antifungal metabolites and coiling around host hyphae. MAP-kinase TVK1 characterized in *T. asperellum*, *T. atroviride* and *T, virens* mediated the transfer of information from sensors, regulate signalling mechanisms, cellular responses in plant roots and increased biocontrol against *R. solani* (Mendoza-Mendoza *et al.* 2003). The perception of signals transmitted by *Trichoderma* in plants facilitated root colonization by swollenin and enhanced systemic resistance by ceratoplantanin family proteins. MAPK functions indirectly leading to enhanced root proliferation, better growth and protection of plants. Contreras-Cornejo *et al.* (2016) showed root inoculation of *T. virens* and *T. atroviride* in *Arabidiopsis thaliana* increased the level of phytoalexin camalexin along with induction of PR-1a and LOX2 SA-responsive gene expression. Similarly root inoculation of *A. thaliana* with *T. asperelloides*T203 rapidly increase the transcription factors WRKY18, WRKY40, WRKY60 and WRKY33 having positive role in JA mediated defense (Brotman *et al.* 2013; Abbas *et al.* 2022).

Trichoderma as endophytes

Trichoderma species such as *T. harzianum*, *T. viride*, *T. asperellum* have been reported as endophytes. Hasan *et al.* (2023) showed the beneficial effect of two endophytic strains of *Trichoderma* spp. ReTk1 and ReTv2 with respect to plant growth promotion and biocontrol of clubroot disease in mustard. Moreover both the strains inhibited the germination of resting spores of *Plasmodiophora brassicae* indicates the possible mode of action. Additionally both endophytic strains stimulated the expression of defense related markers involved in jasmonate, ethylene, auxin and salicyclic acid pathways demonstrating the excellent potential of these strains with multiple benefits in mustard. Rajani *et al.* (2021) exhibited endophytic strains of *Trichoderma* which can restrict *Sclerotium rolfsii*, *Sclerotinia sclerotiorum* and *Fusarium oxysporum* through mycoparasitism and production of volatile organic compounds. Phoka *et al*. (2020) reported volatile compounds such as 2-methyl-1-butanol, 2-pentylfuran, acetic acid, and 6-pentyl-2H-pyran-2-one (6-PP) stimulate growth and defense responses in *A. thaliana*.

In recent years, there has been an effort to find genetic or genomic differences that result in intrinsic characteristics that differentiate *Trichoderma* strains capable of living as endophytes from those that do not. The rationale is based on studies showing that plants produce metabolites, such as flavonoids, phenolics, and terpenes, which have defensive functions, and that endophytes must have tolerance/resistance mechanisms against these plant compounds. Therefore, only those species of *Trichoderma* with these capabilities will be able to colonize the interior space of a plant, including vascular tissues, without causing damage or colonizing various aerial and root parts.

Trichoderma as bioremidiator of heavy metals

Trichoderma species are now at the forefront of research for their remarkable capacity to reclaim heavy metals cadmium, nickel, lead, chromium, and copper in contaminated soils and plant tissues, revealing their potentials in bioremediation (De Padua and Dela Cruz, 2021) through diverse mechanisms. Our study revealed that biomass production of *Trichoderma* isolates was initially found to increased at lower level of nickel but subsequently decreased at significant rate and calculated Minimum Inhibitory Concentration (MIC) of nickel ranged between 313.49-1884.93ppm while for cadmium significant decrease in biomass production irrespective of isolates was observed with cadmium gradient and MIC of cadmium for *Trichoderma* isolates ranged between 57.41-227.92 ppm (Nongmaithem *et al.* 2016a,b). The fungal cell wall, rich in chitin and diverse functional groups (phenolic polymers, melanins), acts as a natural biosorbent that can bind metal ions like lead, cadmium, and chromium independently of metabolic processes. Intracellularly, species such as *T. atroviride* can sequester metals within vacuoles to minimize toxicity (Poothenchery *et al.* 2026). *Trichoderma* secretes low-molecular-weight compounds like siderophores (e.g., salicylic acid), which chelate metal ions. This process can either immobilize toxic metals to prevent plant uptake or increase the bioavailability of essential nutrients like iron, helping plants thrive in stressed environments.Fungi produce various enzymes, including laccases and antioxidant enzymes (SOD, POD, CAT), which mitigate oxidative stress induced by heavy metals. Recent studies on laccase-biochar coupling systems involving *T. reesei* show enhanced simultaneous remediation of heavy metals and organic pollutants (Xia *et al.* 2025). By colonizing plant roots, *Trichoderma* creates a protective barrier that reduces the translocation of toxic metals from roots to shoots, thereby safeguarding the plants.

A study conducted at our laboratory on effect of *Trichoderma* isolates on cadmium uptake in rice plants under cadmium stressed condition showed that plant biomass is negatively correlated with metal contamination with simultaneous increase in cadmium uptake by rice plants. *Trichoderma* aided in plant growth promotion with induction of defense response in plants which helped in production of more biomass and thereby reducing the cadmium uptake in plants. Negative correlation between higher biomass production by *Trichoderma* isolate (UBT-18) and lower residual cadmium concentration in metal amended growth medium supported that cadmium was removed by the *Trichoderma* isolate and hence remained available in lower quantity for uptake by the rice plant (Nongmaithem *et al.* 2017). A 2024 study utilized a co-culture of *T. aspere-llum* and *Rhizomucor variabilis* to remediate mining-impacted soils, resulting in a 64.4% increase in chromium accumulation and a significant boost in plant biomass. Field trials on bean plants irrigated with wastewater demonstrated that inoculation with *T. harzianum* and *T. viride* reduced grain cadmium and lead concentrations by over 60%, effectively mitigating health risks associated with contaminated irrigation. Emerging research highlights *Tricho-derma*'s ability to biosynthesize nanop-articles (NPs), which can be integrated into novel agrochemicals for more sustainable remediation strategies.

Trichoderma as decomposer

Beyond biocontrol properties, *Trichoderma* spp. significantly contribute to the decomposition of organic matter through saprotrophic mechanisms, especially by secreting robust extracellular enzymes that degrade complex plant polymers such as cellulose and hemicellulose.These enzyme systems include exoglucanases and endoglucanaseswhich cleave cellulose polymers, β-glucosidases which convert cellobiose to glucose, xylanases and other hemicellulases known for degrading hemicellulosic backbones and collectively enabling significant polysaccharide breakdown. Importantly, the efficiency of these enzymes varies by species and substrate, with many strains showing substrate-dependent enzyme induction and activity (Druzhinina and Kubicek, 2016; Lima *et al.* 2024). *Trichoderma* species interact with other microorganisms in the soil affecting overall decomposition dynamics and community structure.

Trichoderma in insect pest control

Unlike classic entomopathogens such as *Beauveria* and *Metarhizium*, *Trichoderma* exhibits unique direct and indirect mechanisms against insect pests, including parasitism, production of insecticidal metabolites, plant defense induction, alteration of insect behavior, and disruption of symbiotic microbiota.Several *Trichoderma* species exhibit entomopathogenic activity through adhesion to insect cuticle, penetration, internal growth, and nutrient extraction—similar to canonical entomopathogens. Topical application of spores can result in significant mortality in diverse pest taxa. For example, *T. asperellum*, *T. harzianum*, and *T. viride* show toxicity and parasitism against the American cockroach (*Periplaneta americana*) and termites (*Odontotermes formosanus*), reducing survival rates significantly (Poveda, 2021). He also noted mortality rates close to 100% in adult coleopterans like the coconut rhinoceros beetle (*Oryctes rhinoceros*) and bean weevil (*Acanthoscelides obtectus*) after fungal exposure.These results indicate that *Trichoderma* can directly infect insect hosts, although infection efficiency depends on species, host, environmental conditions, and application method.*Trichoderma* species produce a range of secondary metabolites with insecticidal or deterrent effects which includes peptaibols, cyclic peptides disrupting insect cell membranes, 6-pentyl-β-pyrone (6-PAP), a volatile compound, exhibits insecticidal and antifeedant properties.Other volatiles and non-volatile compounds (trichodermin, harzianolide) can deter feeding or disrupt physiological processes.These compounds can act when ingested with plant material or encountered during insect probing. Enhanced mortality and poor feeding responses in pests like jassids (*Amrasca biguttula biguttula*) have been correlated with the presence of such metabolites (Saud *et al.* 2025). Beyond lethality, *Trichoderma* metabolites often reduce insect feeding or attract avoidance behavior through volatile organic compounds disrupting herbivore feeding, leading to starvation or reduced fitness and repellency reduces pest colonization. Some metabolites degrade insect midgut epithelium or neuroreceptors, inhibiting nutrient uptake (Dwisandi *et al.* 2024).

Some commendable efforts on Trichoderma research in North Bengal conditions

Since last two decades, Department of Plant Pathology, Uttar Banga Krishi Viswavidyalaya is exploring the search of potential *Trichoderma* isolates from different agroclimatic regions of the state of West Bengal and adjoining states and more than 55 isolates have been evaluated in different crop rhizospheres for their diverse mode of action. Antagonism index based *in vitro* evaluation techniques have been suggested accounting the major biocontrol attributes for *Trichoderma* (Debnath *et al.* 2011). *Trichoderma* based microbial consortium have been proved to be an economically viable strategic approach for production of bioenriched vegetable seedling production (Sarkar *et al.* 2016). A similar studies on tobacco revealed that consortium of *T. viride* and *Pseudomonas fluorescens* increased the seedling vigour and reduce the brown spot caused by *Alternaria alternata* (Data unpublished, Fig. 1). A recent field study with 38 *Trichoderma* isolates revealed that UBT 20 and UBT40 were good for their yield improving features in maize whereas UBT 27 and UBT 44 were potential enough based on their ability to reduce turcicum leaf blight caused by *Exserohilum turcicum* (Table 1 & Fig. 2). Genes sensitive to stress, such as AOS, LOX, PR1, PR5, and PAL have been observed to alter their expression levels in presence of *Trichoderma* (UBT 20 and UBT 44) and response to stress after encountering a challenge. The varying expression of these genes were noticed using RT-PCR-based expression analysis in maize during infection at different time points, specifically 0 hours post-infection (hpi) and 24 hours post-infection (hpi) (Shaheen, 2023), Similar trend was also noticed when *Trichoderma* isolates were evaluated in wheat for biocontrol of spot blotch caused by *Bipolaris sorokiniana* (Kundu, 2023). Significant variation in seedling health and reduction of sheath blight was noted in rice mat nursery used for rice transplantor machine by application of *Trichoderma* through seed treatment (Fig.3). It was also associated with marked variation in root architecture as compared to untreated one. A recent study on groundnut revealed that seed treatment with UBT 18 (*T. harzianum*; accession no. MT876632) significantly reduce the collar rot caused by *S. rolfsii* and increased the yield. Also the *Trichoderma* application through seed treatment exhibited enhanced induced resistance by increasing many fold the ascorbate peroxidase, catalase, superoxide dismutase activities and prolific changes in root architecture (data unpublished, Fig. 4)

Focused domain of interest from laboratory to commercialization of Trichoderma

Research on *Trichoderma* must be focused on following phases from laboratory to commercialization for achieving the success. In each and everysteps the stakeholders must put honest effort with utmost importance. In phae 1, the research institutes/ universities/ private companies shall have to isolate *Trichoderma* isolates from different rhizospheres and investigate their biological properties and benefits based on their mechanisms of action either direct or indirect effect on plant pathogens and on plants in particular. From the studies most potential isolates having broad spectrum activity need to be screened out for undergoing multilocational field trials to assess effectiveness under natural conditions in phase 2. In phase 3, the stakeholders should put effort on product formulation strategies to develop various formulations for end user applications. In next phase regulatory approval for navigating legal requirements for biopesticide requirements needs to be completed. In phase 5, market analysis needs to be carried out for understanding market needs and potential customer segment followed by developing market strategy by creating awareness and promoting benefits to target community in phase 6. In last phase, the potent formulations are commercialized through demand driven market channel.

CONCLUSION

In the age of green economy, the use of *Trichoderma* must be encouraged for protecting human health and the environment. Additionally, the current, thorough, developed and yet affordable, quick and successful ways of detecting and evaluating antagonists, integrating multiple mechanisms of action with cascade reactions must be developed in *Trichoderma* research. The research must also focus on their toxicity if any not only *in vitro* but also in natural farming practices before they are commercialized as biostimulators, biocontrol agents or bioremediators along with appropriate policy support for small and marginal farmers interested to adopt natural or organic farming.

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DECLARATION

Conflict of Interest. Author declares no conflict of interest.

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