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Trichoderma spp. and Botanical Inputs in White Mold Disease Management of High Value Crops: An Overview

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ABSTRACT

Organic farming presents a sustainable agricultural pathway for North East India; however, disease management, particularly against soil borne pathogens, remains a major constraint in absence of chemical fungicides. *Sclerotinia sclerotiorum* (Lib.) de Bary, a destructive soil borne fungus causing white mold, incites substantial yield losses across diverse crops worldwide by persisting long term in soil as resilient sclerotia. For its sustainable management, *Trichoderma* species have emerged as highly effective biological control agents. They suppress pathogens through multifaceted mechanisms including direct mycoparasitism, antibiosis, competition for nutrients and space, sclerotial parasitism and induction of systemic acquired resistance (SAR) or induced systemic resistance (ISR) which depends on the *Trichoderma* spp. and plant interaction. *Trichoderma* spp. enhance plant growth through solubilization of essential nutrients such as phosphate, zinc, iron, manganese and production of growth promoting hormones. For optimal ecofriendly disease management, integration of *Trichoderma* spp. with compatible organic amendments and essential oils is highly promising. Compatibility of *Trichoderma* spp. with specific organic inputs such as neem cake and essential oils, which independently reduce disease incidence and improve soil fertility. A strategic approach of *Trichoderma* spp. with organic soil amendments and compatible botanicals offers a strong approach for managing complex soil borne diseases in organic agriculture.

Keywords: Biological control, Essential oil, Mycoparasitism, Organic farming, *Sclerotinia sclerotiorum*

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INTRODUCTION

Organic farming has gained global momentum as a sustainable alternative to chemical intensive agriculture with over 96 million hectares under organic cultivation worldwide. Mannion (1995) defined it as a holistic view of agriculture that aims to reflect the profound interrelationship that exists between farm biota and its production with the overall environment, largely excluding synthetic fertilizers and pesticides and relying on crop rotations, organic manures and biological protection. In North East India, particularly in states like Sikkim and Meghalaya gained significant attention due to its potential for sustainable agriculture (Patle *et al*., 2020). Sikkim was officially recognized as India's first fully organic state. Indigenous farming practices are mostly followed in the region, which depends on indigenous technical knowledge and the systems are mostly organic in nature prevailing for centuries (Singh *et al*., 2021). Being predominantly rainfed, agrochemicals are either not used or applied in very less amount due to poor resources, which provides considerable opportunity for promotion of organic farming and reflects its vast but unexplored scope.

However, significant barriers like yield reduction, soil fertility enhancement, integration of livestock, marketing and policy arise at both macroscopic and microscopic levels, making it practically impossible to go completely organic; rather a blend of organic and other innovative farming systems is needed (Wani *et al*., 2017). A major challenge among them is crop disease management. Without chemical fungicides, farmers must depend on biological and preventive strategies, requiring constant monitoring and agronomical knowledge. Soil borne pathogens are particularly challenging in organic systems due to their long term survival through resting structures with wide host range and difficulty in eradication. *Trichoderma* spp. have emerged as a cornerstone biocontrol agent. This fast growing and rhizosphere competent fungus suppresses pathogens through mycoparasitism, antibiosis, competition and induction of systemic resistance and is fully compatible with organic standards.

A soil borne pathogen is *Sclerotinia sclerotiorum* (Lib.) de Bary, causing white mold and *Sclerotinia* rot. It infects over 500 hosts including high value crops and survives as sclerotia in soil for 5-8 years which making management of this pathogen under organic conditions very difficult. Neem cake acts as a source of organic matter and possesses antifungal limonoids which serves as a synergistic effect with carrier for *Trichoderma*.

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Essential oils of citronella, eucalyptus, thyme, clove and lemongrass contain volatile compounds that disrupt fungal membranes and inhibit sclerotial germination.

Despite individual efficacy, systematic information on the compatibility and integration of *Trichoderma*, neem cake and essential oils against *S. sclerotiorum* in North East organic systems is lacking. Hence, aim of a review article is to evaluate native *Trichoderma* isolates assess neem cake and essential oils alone and in combination and develop an ecofriendly integrated module for management of *Sclerotinia* rot.

Importance of soil borne fungal diseases

Soil borne fungal diseases constitute important constraints to crop production as they can cause damping off, root rot, stem rot, wilting, reduced plant vigour and ultimately result into the yield losses. Their management is challenging because many pathogens survive in soil and crop residues through resistant structures and persist between cropping seasons. In organic farming systems, where the use of synthetic fungicides is restricted and management of these pathogens relies more heavily on biological, cultural and preventive approaches. Among the important soil borne pathogens like *S. sclerotiorum* (Lib.) de Bary is particularly significant owing to its wide host range and ability to persist in soil as sclerotia (Boland and Hall, 1994; Saharan and Mehta, 2008; Garg *et al*., 2010). The pathogen infects a wide range of crops and incites stem and leaf lesions, wilting and plant death. Under favourable conditions, it produces characteristic white cottony mycelial growth and black sclerotia on infected tissues (Purdy, 1979; Bolton *et al*., 2006; Sharma *et al*., 2016).

The persistence of sclerotia with broad host range and responsiveness to suitable temperature and moisture conditions make *S. sclerotiorum* difficult to manage and capable of causing considerable economic losses. Significant disease incidence and yield losses by *S. sclerotiorum* have been seen in high value crops like broccoli, capsicum, lettuce, cherry tomato, cucumber, asparagus etc. Therefore, sustainable and environmentally compatible approaches with biological control using *Trichoderma* spp. and compatible organic inputs which are imperative for the management of this pathogen in organic farming systems.

***S. sclerotiorum* causing white mold**

S. sclerotiorum (Lib.) de Bary belongs to the kingdom Fungi, phylum Ascomycota, class Leotiomycetes, order Helotiales, family Sclerotiniaceae and genus Sclerotinia (Quandt and Haelewaters, 2021). Fuckel (1870) described the fungus as *Sclerotinia libertiana* Fuckel; currently accepted name is *Sclerotinia sclerotiorum* (Lib.) de Bary. The proper name and authority for the fungus seems to be *S. sclerotiorum* (Lib.) de Bary (Purdy, 1979).

Host range

S. sclerotiorum appears to be the most voracious, generic and harmful plant pathogen. The wide host range makes disease control in agricultural crops challenging as it limits the number of non host crops that can be included in crop rotations. *S. sclerotiorum* has wide host range and infects more than 500 plant species (Borah *et al*., 2024). The pathogen has a wide host range belonging to families Fabaceae, Brassicaceae, Solanaceae, Asteraceae, Apiaceae, Cucurbitaceae, Amaranthaceae, Polygonaceae and Liliaceae (Boland & Hall, 1994; Purdy, 1979). *S. sclerotiorum* can infect broccoli which contains glucosinolate compounds. The fungus detoxifies the glucosinolate hydrolysis products and hence can contribute to its virulence on glucosinolate producing hosts (Chen *et al*., 2020).

Symptomatology

S. sclerotiorum causes significant yield losses in vegetable crops including cabbage and broccoli, both in the field and during post harvest storage and transit (Dillard and Hunter, 1986). Initial symptoms appear as elongated, water-soaked lesions on stems and leaves at various growth stages (Purdy, 1979). These lesions become covered with white, cottony mycelium and the affected stems turn soft, shredding easily. As the disease progresses, infected tissues become mushy and slimy and eventually developing dry lesions that enlarge and girdle the stem typically at the base, leading to yellowing, wilting and death of distal plant parts (Bolton *et al*., 2006; Sharma *et al*., 2016). The formation of abundant black sclerotia within the white mycelium is characteristic of infection (Shrestha *et al*., 2018). The pathogen survives in soil as sclerotia which germinate myceliogenically for direct infection or carpogenically to produce airborne ascospores that infect aerial plant parts (Jones *et al*., 2014).

Effect of temperature on mycelial growth and disease incidence

Temperature is a critical factor regulating both the mycelial growth and pathogenicity of *S. sclerotiorum*. Optimal mycelial growth is generally observed at 20-25°C. However, low temperatures such as 4°C can enhance mycelial growth, oxalic acid secretion and polygalacturonase activity in certain isolates (Jia *et al*., 2021). Temperature adaptation also varies among isolates from different climatic zones with influencing virulence and oxalic acid production (Uloth *et al*., 2015). Similarly, disease incidence is highly temperature dependent, with optimal ascospore germination at 21°C and markedly lower germination at 10°C and 30°C (Shahoveisi and del Río Mendoza, 2020; Clarkson *et al*., 2014), which is crucial for disease forecasting and management.

Economic losses

S. sclerotiorum (Lib.) de Bary, the causal agent of white mold is an important pathogen of high value crops, causing pre and post harvest losses through infection of stems, leaves, fruits, roots and storage organs. Disease development is favored by cool, humid conditions and dense crop canopies. Cherry tomato and cucumber may suffer severe stem and vine infections particularly under protected cultivation. Broccoli

and other cole crops are highly susceptible and may experience severe crop losses under conducive conditions. Lettuce is particularly vulnerable to lettuce drop, with losses 10%; up to 50% under wet conditions (Young et at., 2004; O'Sullivan *et al*., 2021). Baby corn and asparagus are also recognized hosts, although crop specific quantitative estimates of yield loss are limited. Diseases caused by *Sclerotinia* spp. in vegetables have been associated with yield losses of 10–50% (Rudolph *et al*., 2025).

Ecofriendly approaches for management against soil borne pathogens

Biological control has been proved to be a promising disease management technology against plant pathogens. Baker and Cook (1974) in their first book "Biological Control of Plant Pathogens" defined biological control as "the process by which one or more organisms reduce the density of their inoculum or the disease causing activities of a pathogen or parasite in either an active or dormant state. This can be done naturally, by manipulating the environment and host or antagonist or by introducing one or more antagonists in large quantities". Several advantages of using biological agents have been reported by different workers (Lewis and Papavizas, 1991) such as ecofriendly nature (Bohra *et al*., 2006), effective in managing diseases caused by soil borne plant pathogens which chemicals cannot easily control (Howell, 2003; Harman, 2010), ease of multiplying antagonists with less cost of production (Gaur *et al*., 2005) and long lasting effective disease management.

Over the years, many biological control agents including *Pseudomonas fluorescens, Bacillus subtilis, Gliocladium* spp. and *Trichoderma* spp. have been evaluated for their potential biocontrol activities against various soil borne pathogens through systematic screening techniques to select the best performing antagonist. Among them, *Trichoderma* spp. has consistently emerged as the most promising and widely commercialized biocontrol agent with owing to its ecological versatility, rapid growth rate and multipronged antagonistic arsenal. *Trichoderma* spp. deploys various mechanisms to control plant pathogens both directly as well as indirectly. The direct mechanisms include mycoparasitism, antibiosis through production of volatile and non volatile antibiotics such as trichodermin, viridin, gliotoxin and harzianic acid and competition for nutrition and space while indirect mechanisms involve induced systemic resistance and enhancement of plant growth. Biocontrol ability is culmination of various mechanisms working to control disease and may get influenced by various environmental factors like temperature, soil type, pH and soil microflora, besides compatibility with other bioinputs used in integrated disease management.

Trichoderma

Taxonomy, diversity and distribution

The first description of *Trichoderma* as a fungus was given by Persoon in 1794 as appearing like mealy powder enclosed by a hairy covering. Weindling in 1932 suggested the use of *Trichoderma* as a biocontrol agent. In 1945, Brian and McGrown isolated antibiotic viridin from *Trichoderma viride*. *Trichoderma* is a diverse genus of filamentous fungi belonging to the family-Hypocreaceae, order-Hypocreales, class-Sordariomycetes and phylum-Ascomycota. The genus having many morphologically similar but genetically distinct species, making the use of molecular techniques for proper identification of *Trichoderma* at species level (Kamala *et al*., 2015).

The genus exhibits a predominantly soil associated distribution and is commonly recovered from agricultural and forest soils, rhizosphere, decaying plant residues, wood and other organic substrates. Its frequent occurrence in the rhizosphere is attributed to the availability of root exudates and organic nutrients while several species are capable of colonizing roots and establishing beneficial plant and fungus interactions (Harman *et al*., 2004; Woo *et al*., 2023). *Trichoderma* is widely distributed across tropical, subtropical and temperate environments, although species abundance and community composition vary considerably with soil properties, climatic conditions, crop type and geographic location.

Considerable diversity exists at both species and strain level within the genus. Agriculturally important species include *T. harzianum, T. viride, T. asperellum, T. atroviride, T. virens, T. gamsii, T. hamatum* and *T. longibrachiatum*. These species differ substantially in growth rate, rhizosphere competence, enzyme production, antagonistic activity and plant growth promoting ability. Consequently, *Trichoderma* spp. should not be considered functionally identical and selection of appropriate strain is critical for effective biocontrol agent and growth promotion. state and are served by 12 out of 28 sugar factories in Bihar.

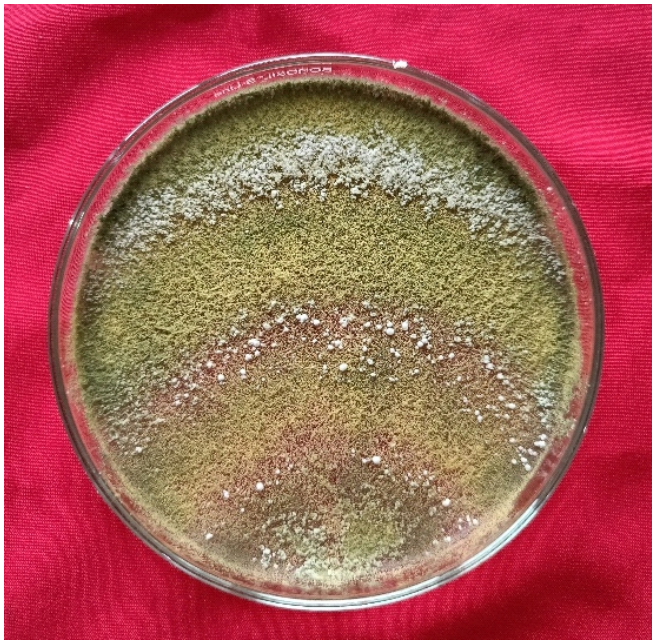


Fig. 1: Pure Culture of *Trichoderma* isolate on potato dextrose agar

Morphological characteristics and identification of *Trichoderma* spp.

Macroscopic features

Trichoderma spp. exhibit distinct macroscopic features that help in their identification and characterization. *Trichoderma* spp. show distinct macroscopic features like colony colour, pigmentation, colony type, growth pattern, growth rate and diameter which are key for species differentiation and vary among isolates from different regions (Woo *et al*., 2003; Saputra *et al*., 2022). They grow fast at 25-30°C but morphology depends differently depending upon temperature. The temperature response is used as a diagnostic trait e.g., *T. harzianum* can be separated from morphologically similar *T. atroviride* and *T. aggressivum* by measuring colony growth at 35°C (Samuels *et al*., 2002). The morphology of *Trichoderma* isolates can vary in terms of growth rate and diameter and some isolates showing higher growth rates and larger diameters compared to others while other not.

Microscopic features

Microscopically, the mycelium is hyaline, tubular and septate with conical, verticillate conidiophores. *Trichoderma* isolates can be differentiated based on mycelial growth rate, colony appearance, phialides and spores, with identification challenges due to the complexity and closely related characters of the species. The conidiophores show pyramidal paired branching, smoothly bent and clustered with penicillate apices and sometimes end in elongations (Samuels *et al*., 2002; Sharma and Singh, 2014). Phialides are 1-2 per axis near the tip, flask shaped with a swollen middle and pointed apex. Conidia are broad oval to globose/sub-globose, green in mass but colourless individually, 2.92-5.10 µm in length (Woo *et al*., 2003). Identification remains difficult due to closely related.

Molecular identification

Molecular identification is essential for accurate species level delineation of *Trichoderma* as closely related and cryptic species often cannot be reliably distinguished based on morphological characters alone. Although the internal transcribed spacer (ITS) region is useful for genus level confirmation and it exhibits limited resolution among closely related species within the genus. Therefore, additional protein coding loci particularly translation elongation factor 1 alpha (*tef1-α*) and RNA polymerase II subunit (*rpb2*), are recommended for species level identification. A multilocus approach employing ITS + *tef1-α* + *rpb2* provides greater taxonomic accuracy and should be further validated through integration of phylogenetic, morphological and ecological information (Cai and Druzhinina, 2021).

Mode of action of *Trichoderma* spp.

Trichoderma species use several strategies such as mycoparasitism, nutritional competition, antibiosis and the induction of defensive responses in plants. It also help in plant growth promotion, nutrient solubilization and sclerotial colonization to effectively manage plant pathogenic fungi (Biswas and Sen, 2000; Howell, 2003; Mukhopadhyay and Kumar, 2020).

Direct antagonism

Mycoparasitism: The mycoparasitic behaviour of *Trichoderma* spp. are well recognized and involves direct parasitization and confrontation of other fungi particularly phytopathogenic fungi. The antagonist penetrates the hyphae of the target fungus, obstructs its growth and ultimately leads to its death (Harman *et al*., 2004). Mycoparasitism is a genetically regulated process. Zeilinger *et al*. (1999) reported that genes governing mycoparasitism are differentially regulated based on specific function. For instance, expression of 42 kDa endochitinase begins before contact between *T. harzianum* and *Botrytis cinerea* whereas 72 kDa N-acetyl-β-D-glucosaminidase is expressed only upon direct contact between the antagonist and the pathogen.

Competition: Competition is a classical mechanism of biological control. *Trichoderma* spp. effectively compete with phytopathogens in the rhizosphere for space and essential nutrients. Baker and Cook (1974) stated that competition predominates when no mycoparasitism and antibiosis are detected in a particular interaction. It hinders pathogen establishment by outcompeting them for resources such as carbon and nitrogen (Howell, 2003). *Trichoderma* is ubiquitous in natural and agricultural soils worldwide shows its highly competitive saprophytic ability. Howell *et al*. (2003) and Zhang *et al*. (1996) observed that *Trichoderma* spp. applied either as seed treatment or soil application which rapidly colonize and proliferate along with the developing root system of the treated plant.

Antibiosis and Secondary Metabolites: *Trichoderma* spp. produce a wide range of secondary metabolites including volatile and non volatile antibiotics and cell wall degrading enzymes that exhibit antifungal properties and directly damage pathogen cell walls (Howell, 2003). Gajera *et al*. (2013) reported that *Trichoderma* secretes numerous bioactive metabolites effective against phytopathogens including tricholin, peptaibols, viridin, gliovirin, glisoprenins, heptelidic acid, 6-pentyl-α-pyrone and harzianic acid. Notably, *Trichoderma* may produce over 190 antibiotic peptides belonging to the peptaibol family. Trichokonin VI (TK VI), a peptaibol from *T. pseudokoningii* induces significant programmed cell death in fungal pathogens such as *Fusarium oxysporum*.

Indirect disease suppression

Induction of resistance: *Trichoderma* spp. are recognized for their ability to elicit plant defence thereby enhancing resistance against pathogenic threats. They induce production of defence related enzymes such as peroxidase and chitinase which strengthen plant immunity (Contreras-Cornejo *et al*., 2009). This involves activation of systemic acquired resistance (SAR) and induced systemic resistance (ISR) through modulation of phytohormones including salicylic acid (SA)

and jasmonic acid (JA) and providing prolonged protection against diverse pathogens (Shoresh *et al*., 2010; Yoshioka *et al*., 2012). *Trichoderma* also primes plant defence which resulting in faster and stronger response upon subsequent pathogen attack (Segarra *et al*., 2007).

Plant growth promoting mechanisms

Nutrient solubilization and mobilization: *Trichoderma* isolates are efficient phosphate solubilizers (El-Katatny and Idres, 2014). The mechanism involves secretion of chelating compounds such as siderophores, organic acids, secondary metabolites and growth regulators, primarily indole-3-acetic acid (IAA). Altomare *et al*. (1999) and Harman (2000) reported that *T. harzianum* strain T-22 solubilizes Fe^{3+}, Cu^{2+}, Mn^{4+}, Zn^{2+} and rock phosphate rendering otherwise unavailable nutrients accessible to plants.

Root colonization and root development: *Trichoderma* spp. colonize the entire root system and persist throughout the crop life (Harman *et al*., 2004) through molecular dialogue with root exudates that triggers auxin production and nitrogen metabolism (Zin & Badaluddin, 2020). Colonization enhances root size, rooting depth and lateral root formation in an auxin dependent manner, mediated by fungal IAA, harzianic acid and volatile 6-pentyl-2H-pyran-2-one (Contreras-Cornejo *et al*., 2009; Garnica-Vergara *et al*., 2016).

Sclerotial parasitism: *S. sclerotiorum* is a destructive phytopathogenic fungus that persists in soil for prolonged periods through the formation of highly resistant resting structures which known as sclerotia. Mycoparasitism mediated by *Trichoderma* spp. including *T. harzianum* and *T. asperellum* represents a highly effective biological control strategy to disrupt this survival mechanism. *Trichoderma* spp. actively colonize melanized sclerotia through the secretion of cell wall degrading enzymes notably chitinases and glucanases which facilitate hyphal penetration and subsequent degradation of internal tissues (Macena *et al*., 2020). This mycoparasitic activity substantially impairs sclerotial viability and apothecial germination, thereby reducing the primary soil borne inoculum available for future crop infections (Silva *et al*., 2022).

Table 1. Classification of different *Trichoderma* spp. with different modes of action

Mode of action	*Trichoderma* spp.	Principal effect	References
Mycoparasitism	*T. harzianum*, *T. asperellum*, *T. atroviride*, *T. viride*, *T. longibrachiatum*	Recognition, attachment, coiling and penetration of pathogen hyphae, followed by enzymatic degradation	de la Cruz *et al*., 1995; Almeida *et al*., 2007; Qualhato *et al*., 2013; Guzmán-Guzmán *et al*., 2023; Stange *et al*., 2024; Garcés-Moncayo *et al*., 2025
Competition for nutrients and space	*T. atroviride*, *T. harzianum*, *T. asperellum*, *T. gamsii*, *T. viride*	Rapid colonization of the rhizosphere and depletion of nutrients required by pathogens	Guzmán-Guzmán *et al*., 2023; Stange *et al*., 2024
Antibiosis	*T. virens*, *T. longibrachiatum* , *T. harzianum*, *T. viride*, *T. koningii*	Inhibition or destruction of pathogens through volatile and non volatile secondary metabolites (e.g. gliotoxin, gliovirin, peptaibols, viridin, pyrones)	Contreras-Cornejo *et al*.,2016; Khan *et al*., 2020a; Manzar *et al*., 2022
Hydrolytic enzyme production	*T. harzianum*, *T. asperellum*, *T. virens*, *T. viride*	Breakdown of pathogen cell walls through chitinases, β-1,3-glucanases, β-1,6-glucanases, cellulases and proteases	Stange *et al*., 2024; Garcés-Moncayo *et al*., 2025; Qualhato *et al*., 2013;
Induced systemic resistance	*T. harzianum*, *T. asperellum*, *T. atroviride*, *T. virens*, *T. hamatum*	Activation or priming of SA, JA and ethylene dependent plant defence pathways and defence related genes (e.g. *PR1*, *NPR1*, *JAR1*, *MYC2*)	Khan *et al*., 2020b; González *et al*., 2012
Plant-growth promotion	*T. harzianum*, *T. atroviride*, *T. asperellum*, *T. viride*	Improved root development, nutrient acquisition, biomass production and stress tolerance via phytohormone modulation and metabolic changes	González *et al*., 2012; Contreras-Cornejo *et al*., 2009

Plant growth promoting activities of *Trichoderma* spp.

Trichoderma spp. improve plant growth activities through multiple direct and indirect mechanisms including nutrient solubilization and production of phytohormones along with antagonistic metabolites.

Nutrient solubilization and mobilization

Zinc and Phosphate Solubilization: *Trichoderma* spp. can solubilize insoluble zinc compounds in the soil and convert

them into available forms for plants for easy absorption. The ability of *T. harzianum* T-22 to solubilize insoluble minerals via chelation and reduction process was first shown by Altomare *et al*. (1999). *Trichoderma* spp. enhance Zn^{2+} bioavailability essential for various metabolic activities. *T. viride* showed maximum efficiency with clearing zone (Anuradha and Syed, 2016). Similarly, despite high total soil P, plant available P is limited. *Trichoderma* spp. mineralize insoluble phosphates by hydrolysis process and forming halo zone on Pikovskaya's medium (Bononi *et al*., 2020). *T. gamsii* helps common bean to absorb P nutrition and improve growth factors under P deficient conditions (Bedine *et al*., 2022).

Potassium solubilization and iron sequestration: Recent studies show *Trichoderma* solubilizes potassium from feldspar and mica through organic acid production. *Trichoderma* produced siderophores can chelate iron and may contribute to competition for iron with phytopathogens (Cui *et al*., 2025). *T. virens* produces hydroxamate siderophores - fusarinines, dimerum acid and coprogen (Jalal *et al*., 1986; Chet and Inbar, 1994) indirectly promoting plant growth.

Phytohormone production

IAA and Gibberellins: *Trichoderma* spp. produce IAA and GA_3 hormones which regulate root initiation and shoot development (Strobel, 2004; Harman *et al*., 2004). IAA from *Trichoderma* spp. specifically promotes lateral root growth and root hair proliferation that increasing nutrient uptake absorption area (Contreras-Cornejo *et al*., 2009; Nieto-Jacobo *et al*., 2017).

Trichoderma spp. exhibit an inhibitory effect on *S. sclerotiorum*

In addition to direct antagonism, *Trichoderma* spp. help plant growth activity by solubilizing soil nutrients, enhancing root hair development for improved nutrient uptake and producing phytohormones such as zeatin, gibberellins, IAA and cytokinins (Harman *et al*., 2004). It also produces antifungal metabolites compounds like hydrogen cyanide and siderophores that suppress phytopathogens (Whipps, 2001).

Owing to its efficacy against soil borne pathogens, *Trichoderma* has been extensively evaluated against *S. sclerotiorum*. *In vitro* dual culture assays have demonstrated significant inhibition of mycelial growth with inhibition rates exceeding 50% (Lopes *et al*., 2012) and more than 90 % (Kumar, 2024). Similar antagonistic potential was reported by Joshi *et al*. (2010) against *S. sclerotiorum*. This inhibition is attributed to production of volatile metabolites, competition and mycoparasitism, where *Trichoderma* isolates were observed to overgrow and colonize the mycelia, sclerotia and apothecia of *S. sclerotiorum* (Troian *et al*., 2014).

Neem cake in disease management

Neem cake is obtained from the extraction of neem oil from neem seeds (*Azadirachta indica*) as a bioproduct that has been explored and shows its potential in disease management in agriculture. Neem cake contains several bioactive compounds including azadirachtin which exhibits antifungal and antimicrobial properties. Kumari *et al.* (2020) reported neem cake enhances and improved soil fertility and can help in managing soil borne diseases due to its beneficial properties. It is a valuable resource for agricultural disease management. Yadav *et al.* (2016) show extract of castor and neem cake at a concentration of 3 % to control *S. sclerotiorum*, with inhibition (40.00 %) of mycelial growth.

Essential oil in disease management

Essential oils have demonstrated antifungal activity against several soil borne pathogens however, their efficacy and compatibility with beneficial microorganisms depend on the oil type and concentration. Essential oil extracted from lemongrass, citronella, eucalyptus *etc*. have the ability to control soil born disease. Eucalyptus oil inhibited growth of *Fusarium* species at concentrations of 7-8 L/mL. These findings confirm the fungicidal properties of eucalyptus essential oils and their potential use in the management of economically important soil born pathogen and as possible alternatives to synthetic fungicides (Gakuubi *et al*., 2017).

Citronella oil shows significant antifungal activity against various soil borne fungal pathogens. Studies have shown that various essential oils inhibit the growth of pathogens like *Candida albicans*, *Fusarium oxysporum*, *Colletotrichum gloeosporioides*, *C. falcatum and Neopestalotiopsis* spp. (Ahmed *et al.* 2023). Aguiar *et al.* (2014) show that citronellal in citronella oil exhibited antifungal activity against various fungal pathogens at 25-50 $mg{\cdot}mL^{-1}$, with essential oils showing efficacy at 100-200 ppm.

Compatibility of *Trichoderma* spp. with organic bioinputs

Trichoderma spp. are widely recognized for their biocontrol capabilities against plant pathogens, promoting plant growth and soil health. Compatibility of the *Trichoderma* spp. with the organic inputs e.g., neem cake and essential oil helps to increase its efficacy to manage the soil borne pathogen. The compatibility of essential oils with *Trichoderma* is concentration and strain dependent whereas some oils may inhibit *Trichoderma* growth at higher concentrations and others may show limited inhibitory effects under specific *in vitro* conditions. The compatibility is assessed by poisoned food technique measuring radial growth inhibition. *In vitro* condition, wintergreen oil and lemongrass oil and their combination did not inhibit the growth of *Trichoderma* (Vanitha, 2010). Similarly, *Garcinia atroviridis* crude extract was non inhibitory to *T. harzianum* with no inhibition zones (Siddiqui, 2026).

Complete inhibition of soil born pathogen by using essential oils *i.e*. carnation, caraway, thyme, peppermint and geranium oils at 4% (Abdel-Kader *et al*., 2011). However, when seeds coated with these oils at 4% were sown in soil treated with *T. harzianum* with pronounced protection was observed with 47.3-55.4% reduction in pre emergence root rot and 40.1-50%

yield increase (Abdel-Kader *et al*., 2011). Clove and cinnamon oils were most effective at 800-1000 ppm against *Trichoderma pseudokoringii* due to eugenol and cinnamaldehyde disrupting cell membranes (Ruiz Medina and Ruales, 2025). Neem cake shows compatibility with *T. asperellum* and *T. viride*. to manage *S. sclerotiorum* (Kumar, 2024). Among cakes, highest inhibition of 19.2% was recorded in neem cake followed by mustard cake 13.9% and castor cake 7.6% and thus all cakes showed compatibility with *T. viride* (Kumar *et al*., 2018). Soil application of neem cake @250 kg/ha + *T. viride* @2.5 kg/ha + azadirachtin spray recorded minimum disease and maximum yield (Jeyalakshmi *et al*., 2013). Neem cake with *Trichoderma* showed 69% reduction in *Phytophthora* infection (Bhai and Sarma, 2009).

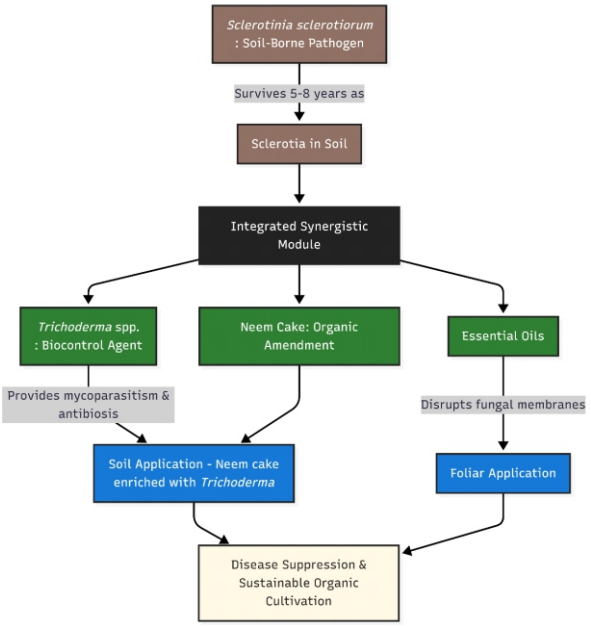


Fig. 2. Integration of *Trichoderma* spp. with neem cake and botanical essential oils for management of *S. sclerotiorum*

Trichoderma spp. offer ecofriendly strategy for the management of white mold in high value perennial and emerging high value crops like jackfruit, passion fruit, dragon fruit and avocado. Both commercial and native isolates of *Trichoderma* including *T. harzianum*, *T. asperellum* and *T. virens* showed strong antagonistic activity against *S. sclerotiorum* under *in vitro* and field conditions with certain strains up to 100% inhibition of pathogen growth (Otithi *et al*., 2026; Kumar, 2024).

The studies conducted directly on effect of *Trichoderma* spp. on white mold in jackfruit, passion fruit, dragon fruit and avocado were limited but the success of *Trichoderma* in other high value crops justifies its use in these systems. *T. harzianum* and *T. asperellum* are highly effective in controlling white mold in common bean, soybean crops which share susceptibility patterns to *Sclerotinia* with many tropical fruits. In avocado, *Trichoderma viride* has shown exceptional efficacy with up to 100% control in field trials against root rot pathogens and suggesting its adaptability to perennial fruit crop environments and potential utility against soil borne pathogens such as *Sclerotinia*. Integration of *Trichoderma* isolates (*T. asperellum* and *T. viride*) with neem cake and citronella oil has been reported to effectively manage white mold disease in broccoli (Kumar, 2024). Similarly, Karadzhova (2024) evaluated various *Trichoderma* isolates against *S. sclerotiorum* and other soil borne pathogens of pepper where all isolates exhibited antagonistic activity and with *T. viride* being the most effective in managing white mold.

CONCLUSION

Organic farming holds significant potential for advancing sustainable and environmentally benign agriculture in North East India where prevailing traditional cultivation practices and historically low reliance on synthetic agrochemicals offer a conducive foundation for organic production. Among soil borne pathogens, *S. sclerotiorum* (Lib.) de Bary assumes considerable importance owing to its extensive host range, long term persistence in soil through sclerotia and potential to inflict substantial yield losses. Biological control employing *Trichoderma* spp. offers a promising alternative attributed to its various mechanisms. Furthermore, organic amendments such as neem cake and essential oils can contribute to disease suppression and improvement of soil health when judiciously applied. However, the compatibility of such inputs with *Trichoderma* is contingent upon the nature of the material along with its concentration and method of application. Hence, integrated deployment of compatible biocontrol agents and organic amendments complemented by appropriate cultural practices could strengthen sustainable disease management in organic farming systems.

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