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An insightful review on the impact of *Trichoderma* species as potent biocontrol agents for enhancing crop resilience

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Abstract
Recent research has highlighted the various roles of *Trichoderma* species as soil fertility improvers and rhizosphere inhabitants, which enhance root growth, promote plant growth, and increase crop yields. In addition to their well-known function as biocontrol agents, *Trichoderma* species play a significant role in commercial crops such as sugarcane, Paddy, groundnut, plantation crops, vegetables, and flowers. Historically, most plant diseases and nematodes have been controlled using conventional methods. However, recent studies have emphasized the incorporation of biocontrol agents in integrated disease management. Among these, *Trichoderma* species have proven to be particularly effective in managing phytopathogenic fungi and nematodes while also promoting growth and yield in various crops. Some plant diseases require species-specific interactions, so this review focuses on the different strains of *Trichoderma* and their effectiveness in controlling various diseases affecting agricultural and horticultural crops.

Keywords: *Trichoderma* species, biocontrol agent, yield enhancer, phytopathogenic fungi, nematodes and integrated disease management

Introduction
Biological control is an innovative, cost-effective, and eco-friendly approach that utilizes natural enemies to manage diseases. This method serves as an alternative to chemical pesticides. Biological fungicides can suppress pathogenic organisms by competing with them, promoting stimulated plant growth that helps plants quickly outpace pathogen effects, or damaging the pathogens through toxins they produce (Cook, 2000) [14].
Biocontrol agents originate from natural materials, including animals, plants, bacteria, fungi, and certain minerals. Fungi exhibiting mycoparasite behaviour can replace synthetic fungicides. Due to the acknowledged negative effects of synthetic fungicides globally, there is a growing shift toward safer, non-synthetic alternatives. *Trichoderma* species are particularly known for their mycoparasite and antagonistic mechanisms in controlling fungal diseases. Various genera of fungi, such as *Trichoderma*, *Penicillium*, *Gliocladium*, and *Rhizopus*, inhabit the rhizosphere of crop plants and can promote plant growth by producing phytohormones, degrading complex substrates, and suppressing pathogenic soil microbes. As a result, these fungi are considered viable alternatives to chemical treatments in agriculture. Among these, *Trichoderma* has significant potential to reduce reliance on environmentally damaging and unsustainable chemicals for disease control and to enhance crop production (Fantke *et al.*, 2012) [21].
Trichoderma is a genus of filamentous ascomycete fungi (Division-Ascomycota, Subdivision-Pezizomycotina, Class-Sordariomycetes, Order-Hypocreales, Family-Hypocreaceae) and is frequently isolated from soil microorganisms. Traditionally, species of *Trichoderma* have been classified based on morphological features. According to Błaszczyk, L *et al*. (2011) [6], the *Trichoderma* genus comprises approximately 10,000 species, with this number continuing to increase. Initially, *Trichoderma* strains appear white and cottony, later developing into yellowish green to deep green compact tufts, particularly in the centre of the growth area or in concentric ring-like patterns on the agar surface.
Trichoderma spp. are free-living fungi with a diverse range of biotypes, from effective soil colonizers to non-plant symbionts (Cardona and Rodriguez, 2006) [10].

These fungi thrive in the rhizosphere and can successfully colonize the plant epidermis. They have been employed as biocontrol agents against various plant pathogens (Abeysingne, 2007; Harman *et al.*, 2004) [1, 28] and are known to antagonize plant pathogens through competition for substrates, antibiosis, and parasitism. Consequently, *Trichoderma* is widely recognized as an effective biological control agent for diseases caused by soil-borne fungi.

The success of *Trichoderma* species in the rhizosphere can be attributed to their high reproductive capacity, resilience under challenging environmental conditions, efficient nutrient utilization, and strong competitiveness against pathogens (Benítez *et al*., 2004) [7]. These fungi are classified as Plant Growth Promoting Fungi (PGPF), owing to their production of siderophores, phosphate-solubilizing enzymes, and phytohormones. *Trichoderma* species play a vital role in decomposition and mycoparasitism, with empirical evidence indicating their ability to enhance growth in a variety of plants, such as strawberries, tomatoes, and apples (Saravanakumar *et al.*, 2013) [65].

Harman *et al.* (2004) [28] assert that *Trichoderma* spp. contribute to increased nutrient availability by facilitating the solubilization and chelation of essential minerals, thereby augmenting plant metabolism and physiological activities. Plants that are treated with *Trichoderma* exhibit enhanced growth and vigour, primarily due to pathogen control, hormone production, vitamin synthesis, and improved nutrient absorption (Inbar *et al*., 1994) [32]. Over the past six decades, *Trichoderma* spp. has demonstrated their capacity to actively attack fungal pathogens and serve as effective biological control agents. Research indicates that these fungi are capable of eradicating plant pathogens, promoting growth, detoxifying harmful compounds, and hastening the degradation of organic matter.

Trichoderma species have demonstrated significant efficacy as biocontrol agents against a variety of pathogens, including *Fusarium* species, *Rhizoctonia solani*, *Pythium aphanidermatum, Gaeumannomyces graminis var. tritici, Sclerotium rolfsii*, *Phytophthora species, Botrytis cinerea, and Alternaria* species. These organisms include ascomycetous, deuteromycetes, and basidiomycetous fungi, which are primarily soil-borne, although some can be airborne Monte E, 2001) [51]. Research indicates that *Trichoderma* is more effective in acidic soils compared to alkaline environments. The application of *Trichoderma* as a biological agent leads to improved germination rates, increased dry root and shoot weights, and a notable reduction in both pre-emergence and post-emergence diseases (L. Kharel Sharma *et al*., 2022) [45]. Consequently, *Trichoderma* spp. is recognized as a viable alternative for managing plant diseases. We have introduced *Trichoderma* to farmers, who are now regularly utilizing it across various crops, reporting its effectiveness in disease suppression and yield enhancement. The prospects for *Trichoderma* use appear promising, with its application increasing annually across a wide range of crops for diverse disease management purposes. In light of the global shift towards sustainable agriculture, the integration of *Trichoderma* into Integrated Disease Management (IDM) strategies is increasingly significant. This review underscores the disease control capabilities of different *Trichoderma* strains across various crops.

Mode of action

To effectively manage plant diseases, it is crucial to understand how biocontrol agents operate. *Trichoderma* interact with both pathogens and hosts in the soil, either directly or indirectly. In cases of indirect interaction, the presence of the antagonist triggers a response in plants, which can lead to induced resistance or enhanced plant growth. Depending on the type of interaction, the mechanism of action can be categorized as either direct or indirect.

A. Direct Action

1. Competition

Most soil-borne pathogens are controlled by competition for space on roots and seeds.

2. Antibiosis

Antibiotics are low molecular weight secondary metabolites produced under nutrient-limiting conditions. *Trichoderma* species generate more than 43 secondary metabolites, many of which exhibit antibiotic activity. Notable compounds among these include alkyl pyrones, isonitriles, polyketides, petaibols, diketopiperazines, sesquiterpenes, and steroids, all of which are commonly associated with biocontrol activity (Howell, 1998) [31].

3. Cellulases and Lytic enzymes

Trichoderma species are well-known biocontrol agents and are effective producers of cellulase (Papavizas, 1985) [46]. The serine proteases derived from *Trichoderma harzianum* play a vital role in mycoparasitism by breaking down the cell walls and proteins of plant pathogens. This process allows the mycoparasite to release and utilize nutrients from the pathogens (Goldman *et al*., 1994) [24].

4. b-1,3 glucanases and chitinase

Lytic enzymes play a vital role in mycoparasitism by degrading the cell walls of pathogens. Enzymes such as chitinases and β-1,3-glucanases disrupt the host's cell wall, leading to protoplasmic leakage, which facilitates mycoparasitism. Mycoparasitic fungi, like *Trichoderma* spp., produce these mycolytic enzymes, which are essential for breaking down fungal cell walls and reducing the incidence of plant diseases.

5. Mycoparasitism

Mycoparasitism refers to the process by which mycoparasites produce lytic enzymes to break down the cell walls of host fungi. For example, *Trichoderma* species wrap around the hyphae of *Rhizoctonia solani*, leading to cell collapse. They also attach to *Sclerotium rolfsii or R. solani* using coils, hooks, or appressoria, which results in lysis and the formation of holes in the pathogen's hyphae. Furthermore, *Trichoderma* coiling around *Pythium* leads to cell wall lysis and protoplasm coagulation.

B. Indirect mode of action

1. Induced resistance

In plants, a response occurs after inoculation with antagonists, triggering genes that encode pathogenesis-related proteins such as chitinases and β-1,3-glucanases, which possess antifungal properties. Additionally, phytoalexin synthesis may also take place.

2. Plant growth promotion

Growth promotion can happen directly or indirectly through biological control of pathogens or the production of plant hormones such as auxin, cytokinin, and gibberellins. This growth stimulation can result from hormone production, improved nutrient uptake, or the suppression of harmful pathogens that can stunt growth and obstruct nutrient absorption.

Method of application

The efficacy of a product is influenced by its formulation and application methods. Inconsistent application may prevent a strain from reaching its full potential. *Trichoderma* can be applied in several ways, including seed treatment, biopriming, seedling dips, foliar, and soil applications.

For seed treatment, talc-based *Trichoderma* at 4g/kg is recommended. It colonizes the rhizosphere and enhances seed germination, while reducing nitrogen requirements by 30-50%. It effectively manages seed and soil-borne diseases by terminating early-stage infections. Available products include Multiplex Nisarga, Multiplex Safe Root, and IFFCO Tricho Powder.

Seed Biopriming

Biopriming is a method of treating seeds with biocontrol agents and then incubating them in warm and moist conditions until just before the emergence of roots. This approach uses fewer biocontrol agents compared to seed coating and helps seeds tolerate adverse soil conditions while promoting uniform germination. The use of plant-beneficial microorganisms as biofertilizers and bioprotectants is becoming increasingly popular for achieving high crop yields with minimal ecological impact. Some available products include Multiplex Nisarga, Multiplex Saferoot, and Farmroot *Trichoderma*.

Seedling Root Dip

This process involves treating cuttings or seedlings with a *Trichoderma* suspension. It is commonly used in transplanted paddy and vegetable cultivation, where it enhances plant vigour and increases chlorophyll content, ultimately reducing transplant shock. Several *Trichoderma*-based products are available, such as Multiplex Nisarga, Multiplex Saferoot, and Farmroot *Trichoderma*.

Soil Treatment

In nurseries and greenhouses, *Trichoderma* can be used for soil treatment. Direct application of *Trichoderma* to the soil helps inhibit the growth of harmful pathogens. Tea growers often struggle with establishing nurseries due to soil containing aluminium and iron complexes, which can hinder root development. However, applying *Trichoderma* as a drench in tea nurseries can enhance root development and increase root biomass. When transplanting vegetable seedlings, *Trichoderma* can be applied directly into the furrow and can also be used as a surface soil application for turf. For greenhouse and nursery planting, *Trichoderma* can be mixed with potting media, and when planting trees or shrubs, it can be directly applied in the planting hole. Available products include Multiplex Annapurna, Multiplex Nisarga, and Multiplex Saferoot.

As a Foliar Spray

Trichoderma can also be mixed with water and sprayed as a foliar treatment. An available product for this is Multiplex Nisarga.

Post-Pruning Application

Trichoderma can be applied after pruning in tea and grape plantations. An available product for this application is Multiplex Nisarga.

The use of various *Trichoderma* strains as biocontrol agents in different crops

Paddy

Several researchers have identified *Trichoderma* species as promising candidates for the management of blast disease in rice (Abeysingne, 2007) [1]. Studies have demonstrated that *Trichoderma* can reduce blast disease intensity by approximately 10 to 25%, depending on the maturity periods of individual rice varieties (Singh *et al*., 2012; Khan and Sinha, 2007; Biswas *et al.*, 2010) [71, 39, 8]. It is evident that *Trichoderma* spp. facilitates seed germination and mitigates the severity of rice blast disease (Singh *et al*., 2012) [71].

Among the *Trichoderma* species, *T. harzianum* has exhibited the most efficacy against rice sheath blight caused by *Rhizoctonia solani*, achieving reductions in disease severity by 38.8% and incidence by 24.6%. *T. virens* is a close second, demonstrating a 36.1% reduction in severity and a 24.1% reduction in incidence. Additionally, *T. harzianum* has been associated with a 21.0% increase in grain yield per plant and a 6.3% increase in the weight of 1,000 grains (Khan and Sinha, 2007) [39]. *T. asperellum* has also shown potential, reducing sheath blight severity by 19%, increasing grain weight by 34%, and enhancing yield by 41% in tropical lowland rice. Biological seed treatments utilizing effective antagonists such as *T. harzianum* and *T. viride* either individually or in combination with adhesives like methylcellulose or $MgSO_4$ are emerging as effective and cost-efficient management strategies against sheath blight in rice (Das and Hazarika, 2000) [15]. Furthermore, *Trichoderma viride* exhibits robust antagonistic properties against brown spot (Gomathinayagam *et al*., 2010) [25].

The inoculation of *Trichoderma* as a seedling treatment has the potential to enhance rice production and productivity in Nepal, particularly when integrated with System of Rice Intensification (SRI) methods and organic fertilization. This comprehensive approach can reduce the reliance on and costs associated with chemical fertilizers (Khadka and Uphoff, 2019) [38].

The application of *Trichoderma* induces various biochemical changes within the leaves of rice plants, including increases in soluble proteins, total phenols, ascorbic acid, and non-reducing sugars, along with an improved K/N ratio. Concurrently, there is a reduction in levels of reducing sugars and the Fe/Mn ratio, indicating enhanced resistance (Biswas *et al*., 2010) [8]. *Trichoderma* species have been found to improve various physiological parameters, resulting in increased rice yields. These enhancements include elevated chlorophyll levels and improve stomatal conductance. The inoculation of rice plants with *Trichoderma* spp. significantly impacts the internal CO_2 concentration, thereby enhancing the rate of photosynthesis and ultimately increasing production.

Reports indicate that *Trichoderma* spp. provide beneficial effects on vegetative growth parameters, such as plant height, root length, total tiller number, and flag leaf length. They also positively affect reproductive parameters, including the number of panicles, panicle length, and the test weight of 1,000 grains in paddy, while effectively suppressing disease incidence (Singh *et al*., 2012) [71]. *Trichoderma* inoculation promotes growth and development through the enhancement of beneficial microflora in the soil, thus improving rhizosphere health and facilitating better nutrient uptake (Doni *et al*., 2017) [18].

Moreover, foliar application of *T. harzianum* has proven to be more effective than soil application in controlling sheath blight in rice. Control can be achieved following the second foliar spray, which occurs 30 days after the initial treatment, rather than after the first spray at 15 days. An even greater response may be obtained by employing a mixed delivery system that incorporates soil treatment, root dips, and foliar applications. The effectiveness of this strategy is particularly enhanced when soils are adequately supplemented with phosphorus and potassium, especially in combination with neem and *Trichoderma* (Tewari and Singh, 2005) [76]. Notably, the efficacy of *T. harzianum* surpasses that of propiconazole, one of the most widely utilized fungicides (Naeimi *et al*., 2010) [55].

Sweet corn

Trichoderma harzianum seed treatment promotes strong growth and root development (Harman, G.E., 2000) [29]. It helps control corn leaf blight (Limdoltham and, S. *et al*., 2023) [44] and contributes to improved vegetative growth and increased yield. The use of *Trichoderma viride* as a seed treatment reduces pre-emergent damping-off and protects for up to one month (Kommedahl, T. and Windels, C.E., 1978) [41].

Maize

Trichoderma harzianum and *Trichoderma viride* have demonstrated significant effectiveness in combating a variety of fungal pathogens, including *Fusarium oxysporum*, *Helminthosporium tetramera*, *Penicillium notatum*, and *Rhizoctonia solani*, as well as *Alternaria alternata*. These biocontrol agents play a crucial role in managing diseases such as stalk rot, which is primarily caused by *Fusarium* species. Their use not only helps in mitigating plant disease but also contributes to sustainable agricultural practices by reducing the reliance on chemical fungicides.

Wheat

Trichoderma harzianum is effective in managing *Fusarium* wilt caused by *Fusarium culmorum*, demonstrating its potential as a biological control agent in agriculture (Sivan, A. *et al*., 1987) [75]. Additionally, both *Trichoderma aureoviride* and *T. harzianum* have been observed to significantly enhance seedling Vigor and improve emergence rates. They also provide protective benefits against various pathogens, including *Diaporthe sorokiniana*, which leads to leaf blotch diseases, as well as *Fusarium culmorum* and *Rhizoctonia solani*, which are responsible for causing rot (Wu, W.S., 1976) [82]. These findings highlight the critical role of these *Trichoderma* species in promoting healthy crop development and disease resistance in wheat.

Millets

Trichoderma species play a significant role in the biological control of plant diseases, particularly in managing anthracnose in sorghum and combating downy and powdery mildew in pearl millet (Manzar, N *et al*., 2021) [48]. These beneficial fungi not only help in suppressing pathogenic fungi but also promote the overall growth and yield of millet crops by enhancing soil health, improving nutrient uptake, and stimulating plant resistance mechanisms. As a result, the application of *Trichoderma* can lead to healthier plants and increased agricultural productivity in millet farming systems.

Pulses

Trichoderma, a genus of beneficial fungi, serves as a potent seed treatment that significantly mitigates wilt disease in Bengal gram (*Cicer arietinum*) and demonstrates notable efficacy in managing various soil-borne diseases affecting pulses. Specifically, *Trichoderma harzianum* plays a crucial role in combating cowpea root and collar rot, a condition induced by the pathogen *Rhizoctonia solani*. Moreover, this versatile fungus proves effective against a variety of other pathogens, including *Macrophomina phaseolina*, *Fusarium oxysporum*, and foliar diseases caused by *Alternaria* species in Black gram (*Vigna mungo*).

In addition, synergistically combining *Trichoderma viride* with neem cake—a natural byproduct derived from the seeds of the neem tree—has shown promising results in the management of plant-parasitic nematodes. This combination not only enhances the biological control of these harmful organisms but has also been observed to boost agricultural yields, achieving increases of up to 8.60 quintals per hectare. This multifaceted approach not only supports sustainable agricultural practices but also contributes to improved crop productivity and soil health (Sharma P *et al*., 2014) [69].

Beans

Trichoderma harzianum has demonstrated substantial efficacy in mitigating bean diseases specifically attributed to the fungal pathogen *Botrytis cinerea*, as reported by Elad and Kapat in 1999 [19]. This biocontrol agent not only reduces the incidence of this detrimental pathogen but also enhances plant resilience overall. Furthermore, *T. harzianum* has proven effective in controlling various soil-borne diseases caused by *Sclerotium rolfsii*, a notorious pathogen responsible for stem rot, and *Rhizoctonia solani*, which is linked to root rot diseases. These findings were established by Sivan *et al.* in 1984 [74], highlighting the significance of utilizing *T. harzianum* as a biological pesticide in agricultural practices.

In addition to *T. harzianum*, other species within the *Trichoderma* genus, such as *Trichoderma asperellum* and *Trichoderma astroviridae*, have also shown remarkable abilities in combating wide-ranging plant diseases. *T. asperellum* has been particularly effective against *Sclerotium sclerotiorum*, which causes wilt and blight in various crops, while *T. astroviridae* exhibits significant control over *Fusarium graminearum*, a serious pathogen associated with head blight in cereals, as well as contributing to the management of *Rhizoctonia solani*. These advancements, investigated by M. Calin *et al*. in 2019 [49], underscore the potential of *Trichoderma* species as valuable tools in sustainable agriculture for disease management and crop protection.

Pea

Trichoderma harzianum has emerged as a highly effective biocontrol agent against the plant pathogen *Sclerotinia sclerotiorum*, as noted in the research by Knudsen *et al.* (1991) [40]. This beneficial fungus is particularly renowned for its efficacy in managing damping-off diseases caused by pathogens such as *Pythium aphanidermatum* and various *Fusarium* species, as reported by Sivan *et al*. (1984) [74].

Moreover, the application of *T. hamatum* as a seed coating has shown promising results in mitigating the infestation of *Rhabdospora solani* and *Pythium* species, underscoring its utility in seed treatment strategies (Sivan *et al.*, 1984) [74]. Specifically, studies indicate that the seed coating with *T. harzianum* reduces the incidence of *R. solani* by an impressive 58%, while simultaneously promoting robust root development, as highlighted by Chet *et al*. (1979) [13].

Furthermore, *T. hamatum* has also proven effective in diminishing the presence of *R. solani* and *Pythium* spp., supporting the findings of Sivan *et al*. (1984) [74]. Research conducted by Harman *et al.* (1980) [27] suggests that in pea plants, *T. hamatum* significantly reduced the infestation levels of both *R. solani* and *Pythium,* thereby enhancing plant health and resilience. This body of evidence illustrates the potential of *Trichoderma* species not only as biocontrol agents but also as valuable components in sustainable agricultural practices.

Oil seeds

The application of *Trichoderma* as a seed treatment for various crops significantly enhances their health and resilience against early infections by phytopathogenic fungi. This is particularly effective in preventing common issues such as wilt and root rot, which are prevalent in oilseed crops. By forming a protective barrier around the seeds and promoting beneficial root colonization, *Trichoderma* not only safeguards against these detrimental infections but also improves overall plant vigor and yield potential. (Chandrika, K.P., *et al*., 2024) [11]

Soyabean

The application of *Trichoderma harzianum* has demonstrated remarkable efficacy in agricultural practices, resulting in a substantial yield increase of 123%. This boost in yield is accompanied by enhanced overall growth and development of the plants, as evidenced in the research conducted by Harman (2000) [29]. Furthermore, *Trichoderma* species have shown impressive performance in promoting seed germination, achieving an 83.4% germination rate. Additionally, they contribute to a significant reduction in root rot incidence by 70.9%, which further supports robust crop performance, with reported seed yields reaching 1239 kg/ha, as noted by Chandrika *et al*. (2024) [11].

Moreover, *Trichoderma viride* has proven effective in managing root rot diseases specifically caused by the pathogen *Pythium arrhenomanes f.sp. adzuki*, as discussed in the study by John *et al.* (2010) [35]. The efficacy of *Trichoderma* extends beyond root rot, offering substantial control over a range of other plant pathogens, including *Alternaria, Rhizoctonia, Sclerotium, Curvularia,* and various *Fusarium* species. This multifaceted pest control capability underscores the importance of *Trichoderma* in sustainable agricultural practices, enhancing crop resilience and productivity while minimizing reliance on chemical fungicides.

Safflower and sunflower

Trichoderma, a genus of beneficial fungi, demonstrated a remarkable seed yield of 793 kg per hectare, alongside an impressive seed germination rate of 84.7%. Furthermore, it significantly mitigated the incidence of wilt and root rot diseases by an astounding 64.7% (Chandrika, K. P *et al.*, 2024) [11]. This biocontrol agent plays a crucial role in managing soil-borne diseases caused by various pathogens, including *Aspergillus, Curvularia, Fusarium, Rhizopus*, and *Penicillium.* These findings underscore the potential of *Trichoderma* as a natural alternative for enhancing agricultural productivity and plant health, providing a sustainable solution for disease management in crop production (Anis, M., Zaki, M.J., and Dawar, S., 2010) [3].

Groundnut

Trichoderma species such as *T. harzianum, T. viride*, and *T. longibrachiatum* play a crucial role in the biocontrol of various soil-borne pathogens, including *Thielaviopsis basicola*, *Aspergillus niger*, *Rhizoctonia solani*, *Pythium aphanidermatum*, *Macrophomina phaseolina*, and *Sclerotium rolfsii*. These beneficial fungi enhance seed germination rates, achieving an impressive 88.6%, while also contributing to a significant 72% reduction in the incidence of root rot diseases. Furthermore, the application of these *Trichoderma* species has been associated with a notable seed yield of 3040 kg per hectare, indicating their effectiveness in promoting healthy plant growth and improving agricultural productivity (Chandrika, K.P *et al.*, 2024) [11].

Sesame

T. viride and *T. harzanium* have shown significant efficacy in managing various plant pathogens, particularly those belonging to the *Fusarium* species and *Alternaria* species. These beneficial microorganisms play a crucial role in plant health by combating a range of soil-borne and foliar diseases. Through mechanisms such as mycoparasitism, competition for nutrients, and the production of beneficial secondary metabolites, they help to suppress the growth of harmful fungi and promote the overall resilience of plants against disease. Integrating these biocontrol agents into agricultural practices can lead to healthier crops and improved yields (Chandrika, K.P *et al.*, 2024) [11].

Cucurbitaceae

Significant enhancements have been recorded in various growth parameters of plants when *Trichoderma harzianum* is introduced to the soil. Specifically, improvements can be seen in rates of germination, as well as in the root and shoot area, overall length, and dry weight of the plants. This fungal species promotes the development of the root system—manifested through increased root length, expanded root surface area, and a higher number of root tips—which collectively enhance the plant's ability to absorb vital nutrients. This augmented nutrient uptake is a key factor in supporting robust plant growth and overall development.

In the context of hydroponic cultivation, particularly with cucurbits, these plants display remarkable efficiency in absorbing nearly all essential nutrients from the nutrient solution. This optimized nutrient uptake contributes to superior plant health and significantly boosts production yields, as corroborated by the findings of Yedidia *et al.* (2001) [84].

Trichoderma harzianum also plays a crucial role in phytopathology by preventing and controlling damping-off disease, a common issue affecting seedlings. Its efficacy is further demonstrated in promoting vigorous vegetative growth and seedling establishment, as noted by Inbar *et al*. (1994) [32]. Additionally, this beneficial fungus is effective in managing Fusarium wilt, a devastating disease that affects many crops, as detailed by Sivan *et al*. (1987) [75].

Moreover, related species such as *T. asperellum* and *T. hamatum* have also shown strong antagonistic effects against prominent phytopathogens, including *Pseudomonas syringae* and *Phytophthora capsici*. These findings, reported by M. Shoresh *et al.* (2005) [53], highlight the potential of *Trichoderma* species in integrated pest management strategies, paving the way for healthier crops and more sustainable agricultural practices.

Solanaceae

The introduction of various strains of *Trichoderma* into the plant system triggers a robust activation of the plant's innate defence mechanisms. This response is characterized by an increase in the production of critical enzymes such as peroxidase, polyphenol oxidase, and chitinase. These enzymes play vital roles in fortifying the plant against a wide array of pathogens and diseases, effectively enhancing its resilience.

Furthermore, *Trichoderma* species have been shown to significantly promote the growth of plants within the Solanaceae family. Through the colonization of root systems, these beneficial fungi contribute to an expansion of the foliar area and a proliferation of secondary roots. This not only alters the root system architecture, improving overall plant stability and nutrient uptake but also fosters a more extensive and efficient root network (Bjorkman *et al.*, 1998) [9]. As natural bio-fertilizers, *Trichoderma* spp. effectively mitigate diseases associated with Solanaceae, while simultaneously enhancing the development of the root zone and increasing the availability of essential nutrients. Ultimately, these interactions lead to marked improvements in plant growth, yield, and quality, affirming the significance of *Trichoderma* as a key player in sustainable agriculture practices (Uddin, A.J. *et al.*, 2016) [77].

Tomato

Trichoderma isolates demonstrate notable antifungal activity against *Pythium aphanidermatum,* the pathogen responsible for damping-off disease, achieving a remarkable efficacy rate of 88.8%. Various species of *Trichoderma* are particularly effective in combating both pre-emergent and post-emergent damping-off in tomato crops, with effectiveness rates calculated at 71.4% and 64.2%, respectively. Additionally, these beneficial fungi contribute to the reduction of root rot diseases in tomato plants, further supporting crop health and yield. The use of *Trichoderma* spp. has been shown to enhance germination rates and promote vigorous growth in tomatoes following application (Kommedahl, T. and Windels, C.E., 1978) [41].

Among the species, *Trichoderma harzianum* is particularly noteworthy due to its dual role in biological control. It effectively suppresses phytopathogenic nematodes such as *Meloidogyne incognita* and *Meloidogyne javanica*, as highlighted in the research by E. Sharon *et al.* (2007) [20]. Furthermore, *T. harzianum* has proven effective in managing crown rot disease caused by *Fusarium oxysporum f.sp. radicis-lycopersici*, particularly when utilized as a seed treatment, leading to healthier plant establishments (Sivan, A. *et al.,* 1987) [75]. Additionally, T. *harzianum* has been shown to significantly mitigate damage from *Sclerotium rolfsii*, a pathogen known for causing severe losses in tomato crops, thereby enhancing overall agricultural productivity and sustainability.

Chilli

Trichoderma species, particularly *T. viride* and *T. harzianum*, play a crucial role in managing various phytopathological challenges in agriculture, especially in chili cultivation. These beneficial fungi are effective in preventing and controlling diseases such as damping off, caused by pathogens like *Pythium* and *Rhizoctonia*, as well as anthracnose and fruit rot, which are typically instigated by *Colletotrichum* spp. and other fungi (Inbar *et al*., 1994) [32]. Beyond their protective capabilities, *Trichoderma* species are known to enhance vegetative growth and promote robust seedling development, contributing to healthier plants and potentially higher yields.

Furthermore, they are instrumental in accelerating the early germination of chili seeds, increasing the overall Vigor and establishment of the plants (GE, H., 1998) [23]. In addition to their role as growth promoters, both *T. viride* and *T. harzianum* are utilized effectively as biological nematicides to manage *Meloidogyne* species, commonly known as root knot nematodes. These nematodes inflict significant damage to the root systems of chili plants, leading to stunted growth and reduced productivity (Waweru *et al.*, 2019) [80]. By incorporating *Trichoderma* species into agricultural practices, farmers can achieve a dual benefit of disease management and enhanced growth, leading to more sustainable and productive farming systems.

Potato

Trichoderma, a genus of fungi, is increasingly recognized for its role as a biocontrol agent in agricultural practices, particularly in potato cultivation. It serves to mitigate various plant diseases while simultaneously enhancing the availability of essential nutrients within the root zone. This dual function not only promotes vigorous plant growth but also significantly improves yield attributes and overall crop quality.

Notably, *Trichoderma harzianum* has demonstrated high efficacy in managing damping-off diseases, a common issue that affects seedling survival. Additionally, *Trichoderma viride* is effective against a range of pathogens that threaten potato crops, including *Fusarium oxysporum*, *Pythium* spp., *Rhizoctonia solani*, *Sclerotium rolfsii*, *Streptomyces scabies*, *Alternaria* spp., and *Phytophthora infestans*, as highlighted by VP Zope *et al*. (2019) [79].

The application of *Trichoderma* in potato production is particularly advantageous; it enhances the bioavailability of nutrients from the soil, thereby improving root health and increasing biomass. Research by Rakibuzzaman *et al.* (2021) [61] indicates that the use of *Trichoderma* can lead to an impressive increase in yield by as much as 23.8% when compared to crops that have not been treated. This makes

Trichoderma a vital component in integrated disease management and sustainable agricultural practices, offering a natural approach to improving potato crop resilience and productivity.

Brinjal

The incorporation of *Trichoderma* species, coupled with biofertilizers and well-decomposed farmyard manure, plays a significant role in enhancing various growth parameters, overall quality, and yield of brinjal (eggplant) plants. Specifically, research has demonstrated marked improvements in plant height, fruit length, and both the fresh and dry weight of key plant components, including the stem, leaves, and fruits. These enhancements are primarily attributable to the increased bioavailability of essential macro and micronutrients within the growing medium. Furthermore, analyses of post-harvest soil samples reveal that the application of *Trichoderma* not only elevates nutrient availability but also positively impacts the physical structure and health of the soil. This improved soil condition effectively prepares it for subsequent cropping cycles, fostering sustainable agricultural practices (Hossain, S. and Akter, F., 2020) [30].

In addition to its growth-promoting properties, *Trichoderma harzianum* proves to be a potent biocontrol agent against root rot diseases in brinjal, particularly those caused by *Macrophomina phaseolina* (Ramezani, H., 2008) [62]. It has also shown efficacy in mitigating the effects of several other pathogenic fungi, including *Fusarium solani*, *F. oxysporum f.sp. lycopersici*, and *Sclerotinia sclerotiorum*. The application of *Trichoderma harzianum* contributes to the development of robust seedlings with reduced incidences of root galling, and it promotes the parasitisation of *Meloidogyne incognita* (root-knot nematodes) females, thereby aiding in nematode management (Rao, M.S., 1998) [63]. Additionally, various isolates of *Trichoderma harzianum* have been effectively utilized against damping-off and wilt diseases in brinjal, both of which are associated with *Fusarium oxysporum*, highlighting its significance in integrated pest management strategies (Sain, S.K. and Pandey, A.K., 2018) [64].

Tobacco

The application of *Trichoderma* species, particularly *T. harzianum*, has been documented to significantly enhance the germination rates and subsequent growth of various crops, making it a valuable biological agent in agriculture. This biocontrol fungus is especially effective in managing brown spot disease, which is caused by the pathogen *Alternaria alternata*, thereby contributing to healthier plant development and increased yields. In addition to its effects on foliar diseases, *T. harzianum* also demonstrates efficacy against soilborne pests and pathogens, specifically in the management of root-knot nematodes, the fungal pathogen *Rhizoctonia solani*, as well as *Fusarium oxysporum* and *Pythium aphanidermatum*. This multifaceted ability to combat both above-ground and below-ground threats solidifies *Trichoderma harzianum's* role as an integral component in sustainable agricultural practices. (Windham, M.T., Elad, Y., and Baker, R., 1986) [4].

Cauliflower

The treatment of seeds with beneficial fungal species, specifically *Trichoderma harzianum* and *Trichoderma viride*, in conjunction with the application of farmyard manure, has demonstrated significant improvements in managing damping-off disease, while also promoting robust seedling growth in cauliflower (*Brassica oleracea var. botrytis*). Both seed treatments and seedbed applications involving these *Trichoderma* species, paired with nutrient-rich farmyard manure, are highly recommended strategies for effectively controlling specific soil-borne pathogens, including *Pythium aphanidermatum*, *Sclerotinia sclerotiorum*, and *Rhizoctonia solani*. These integrated approaches not only mitigate the risks associated with these detrimental diseases but also enhance overall plant vigor and growth performance (Shabir-u-Rehman *et al*., 2012) [68]. By improving soil health and biological activity, such treatments can lead to healthier seedlings and more resilient crops.

Radish

In a seminal study conducted by Baker *et al*. (1988) [5], the authors investigated the effects of applying the fungus *Trichoderma harzianum* on the growth of radishes in untreated soil. They found that both conidia of *T. harzianum* and a peat-bran culture formulation significantly enhanced radish development. Remarkably, after a growth period of six weeks, the dry weight of the radish plants exhibited a substantial increase ranging from 150% to over 250%. This finding highlights the potential of *T. harzianum* as a biological agent for promoting crop growth in agricultural practices.

Beetroot

The application of *Trichoderma* viride as a seed treatment has been shown to effectively reduce pre-emergent damping-off, a common fungal disease affecting seedlings, offering protective benefits for up to one month (Kommedahl, T. and Windels, C.E., 1978) [41]. This biological control agent works by colonizing the seed surface and creating a protective barrier against pathogenic fungi.

In field studies, the use of *Trichoderma harzianum* has demonstrated a remarkable reduction in the incidence of Sclerotium root rot, achieving an impressive 76% disease control rate. This outcome not only enhances plant health but also significantly boosts agronomic yields, leading to increased root development, vibrant green foliage, and higher sucrose yields per hectare (Upadhyay, J.P. and Mukhopadhyay, A.N., 1986) [78]. The incorporation of these fungal species into crop management strategies can thus contribute to sustainable agricultural practices by reducing chemical inputs while improving overall crop performance.

Sugarcane

Trichoderma possesses the potential to inhibit pathogens such as *S. rostrata*, *U. scitaminea*, and *Fusarium moniliformae*, establishing it as an effective biocontrol agent against wilt disease in sugarcane (Gawade, D.B. *et al*., 2012) [2]. Species of *Trichoderma* are also beneficial in managing red rot disease in sugarcane while enhancing drought tolerance. Both *Trichoderma harzianum* and *T. viride* have been found to substantially improve germination rates by 6-14%, increase tiller populations by 21-78%, enhance the number of millable canes by 5-30%, and boost yield by 6-38%, as well as commercial cane sugar (CCS) production per hectare by 30-34% in CoS plant cane. In ratoon crops, *T. viride* demonstrated superior outcomes in clump emergence, resulting in a 75% increase in tillers and a 40% increase in millable canes. The application of *T. harzianum* and *T. viride* is cost-effective and non-toxic, contributing positively to soil health and yielding significant returns on investment. This evidence suggests that the most effective treatment for enhancing tiller growth, millable canes, and overall yield in sugarcane involves the application of *Trichoderma*. Consequently, it is recommended that farmers utilize either *T. harzianum*, *T. viride*, or both for their sugarcane crops, either through soil application or by dipping the sets, to achieve improved financial outcomes. Furthermore, this approach effectively mitigates pineapple disease caused by *Creatocystis paradoxa*. The cost-benefit analysis of *Trichoderma* application indicates favorable returns, with ratios of 1:10 in the initial crop and 1:16 in the ratoon crop (Singh, V *et al*., 2008) [73].

Cotton

Trichoderma viride and *Trichoderma harzianum* are both highly effective in managing soil-borne pathogens, including *Rhizoctonia solani*, *Sclerotium rolfsii*, and *Pythium aphanidermatum*. Their application can significantly enhance plant health by suppressing these harmful organisms in the soil.

Ginger and Turmeric

Trichoderma harzianum is effective in controlling various diseases that affect ginger, including *Pythium* species (soft rot), *Fusarium oxysporum* (dry rot), *Ralstonia solanacearum* (wilt), and the root lesion nematode *Pratylenchus coffeae*, especially when used in combination with *F. oxysporum* (Rajan *et al*., 2002) [59].

A combination of *Burkholderia cepacia* and *T. harzianum* has demonstrated a maximum rhizome production efficiency of 84% and a 79.7% reduction in the incidence of soft rot under polyhouse conditions. This reduction is attributed to increased levels of defence-related gene products, such as chitinase, which may play a crucial role in suppressing disease.

The application of *Trichoderma* species provides an effective biological method for managing plant diseases, particularly those caused by soil-borne pathogens. The growth of *F. oxysporum f.sp. zingiberi* is effectively inhibited by *T. harzianum*, *Gliocladium virens*, and *T. viride*, either alone or in combination. In polyhouse studies, a mixture of *Bacillus cepacia* and *T. harzianum* resulted in increased rhizome production and decreased incidence of yellows. In field experiments, this combination reduced the incidence of yellows and increased rhizome yield by 45.9% and 60.0%, respectively (Meenu and Kaushal, 2017) [50].

Additionally, rhizome rot caused by *Phytophthora* and *Fusarium* species can be managed by using *Trichoderma* species as a seed treatment, followed by the application of neem as a soil treatment. In the case of turmeric, rhizome rot caused by *Phytophthora graminicola* and *P. aphanidermatum* can be managed through the use of *T. viride* and *T. harzianum*.

Onion and garlic

Trichoderma species serve as effective biocontrol agents, specifically utilized to mitigate various soil-borne diseases such as damping-off, basal rot, white rot, and infections caused by *Alternaria* species. These beneficial fungi play a crucial role in promoting plant health and vigor by enhancing key physiological traits. Research indicates that the application of *Trichoderma* not only increases the length, diameter, and weight of bulbs but also significantly boosts the accumulation of photosynthetic pigments in leaf tissues, which is essential for optimal photosynthesis and overall plant growth. Moreover, these fungi enhance the mineral content within the bulbs, leading to improved nutritional profiles. Additionally, the antioxidant properties of the bulbs are elevated, contributing to their resilience against oxidative stress and improving their health benefits. Overall, the integration of *Trichoderma* in agricultural practices yields multiple advantages, including increased productivity and nutritional value of crop yields (Akter, M., *et al.* 2016) [2].

Fruit crop

Apple

Trichoderma species are recognized as effective biocontrol agents for managing apple replant diseases while also promoting overall plant growth. Among their notable benefits, these fungi exhibit strong efficacy against apple scab, a common fungal disease that can significantly affect apple yield and quality. Field studies have demonstrated that the application of spore suspensions from *Trichoderma harzianum* and *Trichoderma atroviride* effectively controls infections caused by *Botryosphaeria berengeriana f. sp. piricola*, which manifests as canker on apple shoots and stems, as well as contributing to the decay of fruit.

The mode of action of *Trichoderma* includes direct competition for resources, production of antifungal metabolites, and the enhancement of the plant's defence mechanisms. Notably, the efficacy of *Trichoderma* in controlling these diseases is on par with traditional chemical treatments, offering a sustainable alternative for apple growers. Such findings underscore the potential of integrating *Trichoderma* species into apple production systems to improve disease resistance and promote healthier crop development (Kexiang *et al*., 2002) [37].

Grapes

Trichoderma strains and their bioactive secondary metabolites have been shown to exert a range of beneficial effects on Vitis vinifera, primarily by enhancing the plant's disease resistance, promoting vigorous growth, and elevating the polyphenol content, which contributes to the antioxidant activity in grapes. These beneficial fungi play a crucial role in suppressing the development of various fungal diseases, notably powdery mildew caused by *Uncinula necator*, as well as downy mildew instigated by pathogens such as *Penicillium expansum, A. carbonarius*, and the bacterial antagonist *B. subtilis*. Among the *Trichoderma* species, *T. harzianum* is particularly recognized for its efficacy as a biocontrol agent in managing grey Mold, a major threat to grape production.

During the initial phases of grape cultivation in nurseries, deploying *Trichoderma* can be instrumental in mitigating root decline—a condition often instigated by various root pathogens that adversely affect root health and overall vine performance. Furthermore, integrating *Trichoderma* species into vineyard management practices can provide an innovative solution for protecting grapevine pruning wounds from trunk disease pathogens, which are increasingly recognized as significant factors in vineyard decline. The effectiveness and longevity of the protective benefits offered by *Trichoderma* in these pruning wounds are influenced by specific intrinsic factors associated with the wounds themselves and may vary significantly among different grapevine cultivars. This variation suggests a need for tailored applications of *Trichoderma* based on the unique characteristics of individual cultivars and environmental conditions (Pascale, A. *et al.*, 2017; Mutawila, C. *et al.*, 2011) [58, 54].

Pomegranate

The application of, in conjunction with NPK biofertilizers and other biocontrol agents, has been shown to significantly enhance fruit quality and yield in various crops (Jat, R.K. *et al*., 2023) [33]. *Trichoderma viride.* Specifically, certain species of *Trichoderma* have demonstrated remarkable efficacy in combating bacterial diseases affecting pomegranate trees, including those caused by *Xanthomonas axonopodis* strain MSR1, *Xanthomonas campestris* strain MSR2, and *Xanthomonas vesicatoria* strain MSR3. Furthermore, *Trichoderma* species have proven beneficial in managing anthracnose disease, a prevalent fungal infection that jeopardizes fruit production (Sattar, S.R.A., 2024) [67]. The synergistic effects of these biocontrol agents and biofertilizers not only bolster plant health but also contribute to sustainable agricultural practices by reducing the reliance on chemical pesticides.

Guava

Research indicates that the application of a fungal concentration of 10^7 spores/ml significantly retards the development of root-knot nematodes in guava roots. The commercial product derived from *Trichoderma harzianum* has proven effective in controlling these nematodes in guava plants, as noted by Jindapunnapat *et al.* (2013) [34]. The findings highlight the dual benefits of *Trichoderma harzianum*, which not only aids in controlling root-knot nematodes but also promotes guava plant growth and delays nematode development.

Additionally, *Trichoderma* species have shown effectiveness against various fungal diseases, including pathogens responsible for guava fruit decay, such as *Fusarium* wilt (*F. sp. psidii*, *F. solani*), and issues related to guava decline. Furthermore, these fungi are recognized for their potential to enhance crop yield, as discussed by Gupta and Misra (2009) [26].

Papaya

The application of *Trichoderma* species post-harvest is effective in mitigating the impact of Anthracnose, a disease caused by the pathogen *Colletotrichum gloeosporioides*. This biocontrol agent not only reduces the incidence of the disease but also maintains the quality of the fruit without causing any detrimental changes in colour. Furthermore, specific strains of *Trichoderma*, when used in conjunction with other biological control agents, have demonstrated significant efficacy in decreasing infections caused by the root-knot nematode *Meloidogyne* spp. Additionally, *Trichoderma* plays a crucial role in managing Damping-off disease in nursery-grown papaya, effectively promoting healthy plant development and enhancing overall yield. These findings underscore the importance of integrating *Trichoderma*-based biocontrol strategies in sustainable agriculture practices for disease management. (Singh, R.N. *et al*., 2019) [72].

Mango

Species such as *Trichoderma reesei*, *Trichoderma harzianum*, and *Trichoderma viride* have been shown to be effective in managing several significant diseases affecting mangoes, including stem-end rot, mango malformation, and anthracnose. These beneficial fungi not only contribute to disease control but are also instrumental in mitigating post-harvest diseases that can severely impact mango quality and yield. By employing these biocontrol agents, farmers can potentially improve the shelf life and marketability of mangoes, as highlighted in the study by Kumar *et al*. (2012). The application of these *Trichoderma* species represents a promising strategy for sustainable agricultural practices in mango cultivation.

Dragon fruit

Trichoderma species help control Brown Spot disease and stem canker in dragon fruit (*Hylocereus* spp.). These fungi fight harmful pathogens by competing with them for nutrients and space, which helps reduce their growth. *Trichoderma* species also boost the plant's immune system, making dragon fruit more resilient to diseases. Using *Trichoderma* in farming not only protects crops but also supports healthy growth and improves yields. This natural method offers a sustainable way to manage diseases in dragon fruit farming, leading to stronger plants and better harvests.

Citrus

Trichoderma lignorum is a highly effective biocontrol agent for managing various plant diseases, including damping off in acidic soils, Anthracnose, and root and crown rot (GE, H., 1998) [23]. Research has shown that when *T. harzianum* is combined with neem cakes, there is a significant reduction in the population of the citrus nematode *Tylenchulus semipenetrans*, which in turn helps mitigate the incidence of slow decline in plants. Furthermore, several studies have reported a decrease in infection rates of *M. javanica* when using various isolates of *T. lignorum* and *T. harzianum* (Sharon, E *et al*., 2001) [70].

Banana

The application of *Trichoderma* in soil significantly enhances nutrient availability, particularly phosphorus and potassium, at the root level, thereby bolstering disease resistance in plants. This remarkable fungus not only promotes plant growth through mechanisms such as phosphate solubilization but also facilitates the synthesis of auxins and hydrolytic enzymes, vital for robust development.

Moreover, various species of *Trichoderma* function as powerful biocontrol agents, effectively combating a range of plant diseases, including Fusarium wilt, post-harvest crown rot, tip rot of banana (caused by *Colletotrichum* species), and fruit rot of banana (induced *by Lasiodiplodia theobromae*). With these capabilities, *Trichoderma* emerges as an invaluable ally in sustainable agriculture, enhancing both plant health and productivity (Mortuza, M.G. and Ilag, L.L., 1999) [52].

Floriculture crop

Magie (1980) [47] reported that treating gladioli corms *T. harzianum* suppressed the *Pythium* species that cause pre and post-emergent damping off disease. Recently, many nursery people started using *Trichoderma* in a potting mixture to avoid early soil-borne pathogens as well as improving soil texture and properties, which is helpful in the growth and development of floricultural crops in green house (Yang, Y *et al*., 2004) [83]. Helps in early flowering and bloom in Periwinkle and Petunia. *T. harzianum* bulb coating reduced the diseases caused by *R. Solani* and *S. rolfsii* to 73 and 85 % respectively. **(**Chet, I *et al.,* 1979) [13].

In carnation, *Rhizoctonia solani* causing cutting rot is controlled by *using Trichoderma harzianum* (Baker, R., 1986) [4].

Many pasture species suffer from disease caused by *Rhizoctonia solani*, *Pythium ultimum* and *Sclerotinia trifoliorum*. This can be suppressed by *T. atroviride* and hence promote the growth and development of the crops (Kandula, D.R.W *et al.,* 2015) [36].

Chrysanthemum

The use of *Trichoderma viridae* in chrysanthemum cultivation reduces the incidence of Fusarium wilt by 50% (Locke, J.C. *et al*., 1985) [46]. Additionally, cuttings treated with *Trichoderma* species tend to root more rapidly, typically rooting at least two days earlier than untreated cuttings. This treatment not only enhances rooting but also results in greater plant height, increased dry and wet weights, and a higher number of flower buds (Baker, R., 1988) [5].

Plantation crops:

Most of the planation crops suffer from Diseases caused by *Phytophthora* can be controlled by using different species of *Trichoderma*. Therefore, blanket use of *Trichoderma* for plantation crops is advisable as it is a perennial crop.

Coconut and Areca nut

Trichoderma species, specifically *T. viride*, *T. harzianum*, and *T. hamatum*, have demonstrated significant efficacy in managing plant diseases such as stem bleeding and black rot. Notably, the application of *T. harzianum*, particularly when combined with Neem cake, has been found to effectively lower the disease index associated with *Ganoderma* infestations while simultaneously improving the yield of coconut palms.

For optimal treatment of coconut trees affected by *Ganoderma*, it is recommended to perform deep incisions along the stem. This procedure should be meticulously carried out to create an extensive area for treatment. Following the incisions, the exposed areas should be drenched with a solution containing *Trichoderma* species. This method promotes enhanced absorption of the biological agent, leading to more efficient colonization of the stem by *Trichoderma*. As a result, the coconut tree can mount a more robust defence against both Ganoderma and the stem bleeding disease, ultimately contributing to its health and productivity. (Sarma, Y.R., and Anandaraj, M., 1998) [66].

Tea

Trichoderma species are well-known for their ability to actively colonize the rhizosphere, which significantly enhances their effectiveness in controlling various soil-borne diseases. In tea nurseries, the development of robust root systems in young plants can be severely impeded by high aluminium concentrations in the soil. This aluminium toxicity can disrupt the availability of essential nutrients, such as phosphorus and iron, which are crucial for healthy plant development.

In this context, the strategic application of *Trichoderma* has been shown to markedly improve root system growth, facilitating earlier and more vigorous establishment of nursery plants. Research indicates that the presence of *Trichoderma* not only promotes root expansion but also increases the overall nutrient uptake efficiency of plants, thereby alleviating some of the adverse effects brought on by aluminium toxicity.

Furthermore, applying *Trichoderma* following the pruning of tea bushes has been found to significantly enhance the establishment of healthy new shoots. The biocontrol properties of this beneficial fungus play a critical role in suppressing pathogenic fungi, thus bolstering the plant's natural disease resistance. The dual benefits of improved root growth and enhanced disease resistance make *Trichoderma* an invaluable tool for tea growers aiming to optimize nursery management and ensure robust plant development (Cheruiyot, H. *et al*., 2015) [12].

Coffee

Since coffee is a perennial crop, the health of its root system is vital for optimal nutrient uptake from the soil. A robust root system not only supports the plant's growth but also increases its resilience to various stress factors. One effective way to promote root health is through the application of *Trichoderma*, a beneficial fungus that plays a significant role in enhancing soil health.

Trichoderma species, particularly *T. harzianum* and *T. viride*, are known for their ability to improve rhizosphere dynamics by fostering beneficial microbial interactions. This results in enhanced root architecture, leading to increases in leaf area, stem diameter, and overall plant vitality. Furthermore, these fungi have been shown to improve graft success rates, which is particularly important in coffee cultivation, where grafting is commonly used to propagate desirable traits.

Moreover, *T. harzianum* and *T. viride* serve as effective biocontrol agents against a spectrum of root diseases, including brown root, red root, black root, and Santa Veri root diseases (Papavizas 1985; Nduka, B.A., *et al.*, 2017) [46, 56]. By colonizing the root system, these fungi compete with pathogenic organisms, suppress their growth, and enhance the plant's innate defence mechanisms. Thus, integrating *Trichoderma* into coffee cultivation practices can lead to healthier plants, greater yields, and improved resistance to diseases.

Black pepper

The utilization of *Trichoderma* species plays a crucial role in the management of a diverse array of plant pathogens, including *Phytophthora, Fusarium*, *Sclerotium*, and *Colletotrichum*. This is particularly significant in multi-storeyed plantation crops, where the complexity of the ecosystem necessitates effective disease management strategies. When *Trichoderma* is employed as a root dip treatment for seedlings, it not only accelerates the establishment of a robust root system but also promotes enhanced lateral root development and overall plant Vigor.

Research has demonstrated that this method facilitates better nutrient uptake and water retention, crucial for the seedlings' early development phases.

Furthermore, *Trichoderma* species act as potent biological control agents against soil-borne diseases such as foot rot and root rot. They do this through various mechanisms, including the production of hydrolytic enzymes that degrade the cell walls of pathogens, competition for resources, and the induction of systemic resistance in plants. Such multifaceted interactions enhance the resilience of the plants against these detrimental diseases, ultimately contributing to improved crop yield and health (Das, M.M. *et al.*, 2019) [16].

Beetle vine

Fusarium wilt, foot rot, root rot, *Sclerotium rolfsii*, and stem rot are significant plant diseases that can severely impact agricultural productivity. Effective management of these diseases can be achieved through the application of *Trichoderma* species, a genus of beneficial fungi known for their antagonistic properties against various soil-borne pathogens. *Trichoderma* spp. not only helps suppress the growth of these harmful fungi but also enhances plant resilience by promoting root health and nutrient uptake.

In addition to their role in managing fungal diseases, these biocontrol agents are also effective in controlling the root-knot nematode *Meloidogyne incognita*, which poses a serious threat to crop yields. Studies, such as those conducted by Datta *et al.* (2011) [17], have demonstrated the potential of *Trichoderma* spp. in reducing nematode populations and mitigating the impact of associated diseases. Utilizing these methods can lead to more sustainable agricultural practices and improved crop health.

Conclusion

Biological control provides a viable alternative to chemical pesticides for managing diseases in agriculture. One such beneficial microorganism is *Trichoderma*, which improves soil health and enhances crop performance due to its ability to combat harmful pathogens. It acts as a biofertilizer and plant growth promoter, contributing to increased crop yield while also exhibiting anti-pathogenic properties. Promoting the use of *Trichoderma* can lead to more sustainable agricultural practices and a reduced reliance on harmful chemicals.

The application of various strains of *Trichoderma* in crop production improves soil texture, increases the presence of beneficial microflora, and enhances the availability of essential plant nutrients for current and future crops. Additionally, *Trichoderma* spp. support overall plant development, which in turn boosts both the quality and yield of crops.

Research has shown that using *Trichoderma* alongside farmyard manure and nematode-based products has a synergistic effect on pest management. Even greater results can be achieved when the bioagent is applied through a mixed delivery system, which includes soil treatments, root dips, and foliar sprays. The effectiveness of these applications is further improved when the soil has sufficient phosphorus (P) and potassium (K) levels.

Recent studies indicate that applying *Trichoderma* can significantly decrease the need for chemical pesticides, yielding results comparable to those of widely used commercial pesticides. This positions *Trichoderma* as a promising option for disease management, aligning with the growing demand for agricultural inputs that are free from harmful residues. As interest in new strains and their potential as biocontrol agents continues to rise, there are significant commercial opportunities for *Trichoderma* on a global scale.

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