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Trichoderma as a Green Catalyst: Exploring its Versatile Roles in Sustainable Agriculture

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ABSTRACT

Trichoderma spp. hold immense potential for agricultural applications, including mitigating abiotic stresses, enhancing plant physiological responses, improving nutrient uptake, and increasing nitrogen-use efficiency across various crops. Their versatility extends beyond agriculture, as they find utility in industrial processes and serve as a plant protectants and growth enhancers on a global scale. Extensive genomic studies have revealed a plethora of useful genes within Trichoderma spp., coupled with their ability to adapt to diverse environments, like soil, water, dead tissues, and plant interiors. The metabolomics of Trichoderma spp. are notably intricate, particularly concerning secondary metabolite production. This paper discusses the versatile roles of Trichoderma as a Green Catalyst that contributes to sustainable agriculture, including its role in nutrient solubilisation, induction of systemic resistance, and degradation of environmental pollutants. The integration of Trichoderma into eco-friendly agricultural practices can reduce chemical pesticide and fertilizer dependency, aligning with sustainable development goals and promoting soil and environmental health.

Keywords: *Trichoderma, biocontrol, plant growth promotion, sustainable agriculture, green catalyst*

Introduction

The genus Trichoderma is widely known for its role as an effective biocontrol agent against plant pathogens. Strains such as *T. atroviride* P1 and *T. harzianum* T22 interact with crop plants and soil-borne fungi, improving plant health and resistance. These fungi inhibit pathogens through the production of antibiotics, secondary metabolites, and cell wall-degrading enzymes (e.g., chitinases and glucanases), which support both mycoparasitism and antimicrobial activity [1]. Recent molecular studies have expanded the genus to over 200 phylogenetically defined species, mainly identified using *rpb2* and other marker genes. Trichoderma spp. also enhance plant growth, nutrient uptake, and degradation of toxic compounds, strengthening their value in sustainable agriculture [2-3]. *Trichoderma's* versatility extends beyond agriculture, finding applications in various industries, including bioremediation, biodegradation and in the production of food additives and bioethanol from farm waste. The fungus produces an array of lytic enzymes, including cellulase, hemicellulase, and pectinase, which find utility in animal feed, alcohol, and brewing industries. These enzymes aid in partially hydrolyzing food walls, thereby enhancing nutritional value and digestion, ultimately leading to increased animal weight and milk production. Moreover, *Trichoderma's* enzymatic potential holds promise for applications in the paper industry, where it can modify fiber properties and reduce lignin content in pulp, improving paper quality [4].

The green catalytic nature of *Trichoderma* spp. is because of their adaptability to different agricultural practices, including organic and conventional farming methods. Their ability to thrive in diverse environmental conditions makes them suitable for use in various cropping systems, ranging from monocultures to polycultures. This adaptability is particularly valuable in addressing the challenges posed by climate change, where shifts in temperature and precipitation patterns require resilient agricultural solutions (Figure1). In addition to their role in disease management and nutrient enhancement, *Trichoderma* spp. also contribute to soil fertility and health. Their activity in decomposing organic matter and cycling nutrients helps in improving soil structure and fertility over time. By promoting beneficial microbial communities and suppressing harmful pathogens, it plays a crucial role in balancing soil ecosystem and sustainability. Moreover, the multi-functionality of *Trichoderma* spp. opens up opportunities for integrated pest management (IPM) strategies, where they can be integrated with other biological, cultural, and chemical control methods. This holistic approach to pest and disease management reduces reliance on synthetic pesticides, minimizes environmental impacts, and promotes long-term agricultural sustainability.

The increasing demand for food production alongside environmental sustainability necessitates the exploration of eco-friendly alternatives to conventional agricultural practices. *Trichoderma* species, enzymatic arsenal, secondary metabolites, and synergistic interactions with plant roots enhance their application in both crop protection and environmental remediation, positioning them as effective green catalysts for sustainable agriculture and environmental biotechnology, the functions and characteristics of *Trichoderma* that determines its potential for being green catalyst in agriculture.

Trichoderma as a biopesticide in modern agriculture

Recently, biological control agents (BCAs) derived from *Trichoderma* account for approximately 60% of all fungal-based BCAs, with an increasing array of *Trichoderma* species-based BCA products being routinely registered. *T. harzianum* has emerged as a prominent active agent within various commercially available biofertilizers and biopesticides in recent times [5]. The mechanisms by which exerts its antagonistic effects against phytopathogenic fungi includes competition, colonization, antibiosis, and direct mycoparasitism [6]. This remarkable antagonistic capability strengthens the efficacy of diverse strains in biological control applications, presenting a viable alternative to chemical methods for managing a broad spectrum of plant pathogens.

Competition

Competition plays a crucial role in the biological control exerted by a *Trichoderma* strain against various fungal phytopathogens. *Trichoderma* strains, including *T. harzianum*, effectively compete for these nutrients, thereby inhibiting the growth of pathogens like *Fusarium oxysporum* and *Pythium* spp. [7]. Siderophores synthesized by specific *Trichoderma* isolates function as highly effective chelators of iron, thereby augmenting their competitive superiority by inhibiting the proliferation of alternative fungal species [8] This competition extends to pathogens like *Botrytis cinerea,* a significant cause of pre- and post-harvest losses globally [9]. The molecular and proteomic machinery of *Trichoderma* exhibits remarkable efficiency in mobilizing and utilization of soil nutrients when compared with numerous other pathogens and organisms. *Trichoderma's* ability to efficiently utilize various sugars, including those derived from common fungal polymers like cellulose, glucan, and chitin, emphasizes its adaptability to diverse environmental conditions. Recently it has been established that antifungal properties of *Trichoderma* filtrates in control pathogens like *Ceratocystis paradoxa*, responsible for pineapple disease in sugarcane. Additionally, proteins generated by *Trichoderma* play essential roles in root colonization and competition with other root colonizers, further contributing to its biocontrol efficacy [10,11].

Antibiosis

Antibiosis, a mechanism characterized by the production of inhibitory compounds, is a prominent feature observed in various species, including microorganisms like *Trichoderma* and plants. *Trichoderma* species are known to produce diffusible compounds or antibiotics that hinder the growth of other microorganisms, contributing to their biocontrol efficacy [12]. While some isolates of *T. harzianum* did not produce volatile compounds, strains of *T. virens* are capable of producing gliovirin, a compound involved in antibiosis, which enhances their effectiveness as biocontrol agents [13].

Studies revealed the role of specific compounds produced by *Trichoderma* in antibiosis. A mutant variant of *T. harzianum* exhibiting higher amounts of extracellular enzymes and α-pyrone showed enhanced resistance to *Rhizoctonia solani* and *Botrytis cinerea*, emphasizing the significance of these substances in biocontrol [14].

Furthermore, the external application of peptaibols, generated by *Trichoderma*, triggered the activation of genes related to defense in tobacco plants, leading to a decreased vulnerability to Tobacco mosaic virus. The distinct coconut fragrance associated with certain *T. viride* strains is due to the presence of volatile substances that inhibit pathogen growth. These metabolites, which include harzianic acid, alamethicins, tricholin, peptaibols, and various antibiotics, highlight the wide range of compounds utilized by *Trichoderma* for antibiosis [15].

Mycoparasitism

Mycoparasitism stands out as a key mechanism underlying the antagonistic behavior of *Trichoderma spp*. as biocontrol agents. The chemotropic growth of *Trichoderma* towards the host fungus is the first step in this process. Once the mycoparasites recognize the host, they coil and penetrate the host hyphae, which eventually results in host lysis [16] The host fungus is recognized, attacked, and eventually killed by *Trichoderma* as a result of its capacity to detect signals from the fungus. The fungal cell wall is broken down by this complex process, which depends on the successive synthesis of pathogenesis-related proteins, mainly glucanase, proteases, and chitinase [17]. About 20 to 30 proteins and metabolites are directly involved in the complex interaction of mycoparasitism, which involves many different factors. In *Trichoderma spp*., the functions of various glucanases and chitinases in this process have been thoroughly investigated. through gene-for-gene studies, offering important new information about the molecular processes underlying mycoparasitism [18].

Induced resistance

Induced resistance has become an important area of study within *Trichoderma* research, alongside its direct impacts on other fungal species, including mycoparasitism and antibiosis (Table 1). A key research finding demonstrated that *T. harzianum* strain T-39 can induce resistance, as evidenced by soil treated with this strain providing protection against fungal pathogens like *B. cinerea* and *C. lindemuthianum* in bean plants, even when T-39 was applied only to the roots without any foliar interaction [19]. This induced resistance has been noted across a variety of dicots and monocots, shielding plants from multiple pathogens including fungi, bacteria, and even certain viruses such as CMV. Further studies have shown that *T. harzianum* strain T-39 is effective against additional fungal pathogens across several dicot species. Research involving different *Trichoderma* species and strains on a range of plant types has supported these observations. Importantly, *T. harzianum* strain T-22 was recognized as the only microorganism capable of instigating systemic resistance to pathogens in model plants and maize, highlighting its distinctive potential [20]. Induced systemic resistance is viewed as a vital mechanism driving the biocontrol capabilities of *Trichoderma,* with several strains of *T. virens, T. asperellum, T. harzianum*, and *T. atroviride* triggering physiological changes that improve plant resilience against a variety of pathogens, including viruses [21]. At the molecular level, induced resistance is characterized by the enhancement of defensive processes, resulting in increased levels of associated metabolites and enzymes such as chalcone synthase (CHS), phenylalanine ammonio lyase (PAL), chitinase, glucanase, and proteins from the cerato-platanin (CP) family [22,23]. These include pathogenesis-related proteins (PR) and enzymes that assist in the response to oxidative stress, all contributing to the improved resistance of plants against various pathogens [24].

Such revelations regarding the molecular mechanisms of induced resistance provides the diverse role of *Trichoderma* in enhancing plant defenses and countering pathogenic threats.

Endophytes

The endophytic activity of various microorganisms, characterized by their ability to grow inside plant tissues without causing harm, holds promise for host plants by stimulating growth, delaying the onset of drought stress, and providing protection against pathogens [25]. Endosymbiotic species can colonize plant roots, prompting the expression of numerous plant genes involved in stress responses. Recent reports have highlighted *Trichoderma* isolates acting as endophytic plant symbionts in certain woody plants, where strains forming associations with roots induce changes in gene expression patterns in shoots [26,27]. These alterations play an important role in modifying plant physiology and can be utilized to enhance crucial traits such as nitrogen fertilizer uptake, resistance to abiotic and biotic stressors, and photosynthetic efficiency, ultimately leading to increased yields [28].

Phylogenetic analysis has revealed that all known endophytic species form distinct taxa, with few exceptions like *T. koningiopsis, T. stilbohypoxyli*, and *T. stromaticum* within their respective clades at terminal positions. This suggests that endophytism may not be an ancient trait but rather a recently evolved characteristic among *Trichoderma* species [27,29]. This evolutionary perspective sheds light on the dynamic nature of endophytic relationships within *Trichoderma* and evaluates their potential for applications in plant enhancement strategies.

As a Biocontrol agent

Trichoderma was originally noted for its mycoparasitic abilities against notable pathogens like *Rhizoctonia solani,* but later on it was found that it can work against many other pathogens. This fungus holds a prominent status among commercial biological control agents, featuring in various crop and disease management strategies either independently or in conjunction with other components (Figure 2). With a catalogue of over 80 *Trichoderma* species documented, key varieties such as *T. harzianum*, *T. virens*, and *T. viride* are commonly employed for biocontrol purposes (Table 2). In regions like India, only a selected few species, such as *T. viride* and T. *harzianum*, have received commercial approval, notwithstanding the recognized effectiveness of others like *T. virens* and *T. asperellum.* However, challenges relating to toxicity assessments, environmental impact evaluations, and the scale-up of production technologies have hindered the registration of these highly beneficial species. Unregistered biocontrol products claiming plant disease management benefits flood the market, threatening the recognition of established agents like *Trichoderma*. Despite their proven biocontrol activities, the lack of comprehensive toxicity and efficacy data risks the safe deployment of *Trichoderma* species. Some strains, like *T. afroharzianum*, have been identified as pathogenic to maize, highlighting the need for careful strain selection [30,31].

Plant Growth Promotion

The combination of *Trichoderma* species and Plant Growth-Promoting *Rhizobacteria* (PGPR) has shown promising potential in enhancing plant resistance and growth, offering an eco-friendly alternative to chemical treatments in agriculture. *Trichoderma* spp. are known for their ability to induce plant resistance against various diseases, while PGPR enhances plant growth and soil fertility. Together, they form a synergistic relationship that can significantly improve plant health and yield. This combination has been studied across different crops, demonstrating varying degrees of success in disease control and growth promotion. *Trichoderma brevicompactum* TB2 has shown significant growth-promoting effects, increasing fresh and dry weights of various plants and enhancing root development. The production of growth hormones like indole-3-acetic acid (IAA) and siderophores contributes to improved nutrient absorption and overall plant health. *Trichoderma* spp. and PGPR have been effective in controlling downy mildew in sweet corn, reducing disease incidence by 66.53% and severity by 89.84% when used in combination with rhizobacteria at a concentration of 60 mL L-1[32].

Formulation and Application

Various formulations have been explored for pilot production of *Trichoderma*, each designed to enhance the stability and efficacy of the fungal cultures. These formulations aim to maintain the viability and effectiveness of the biocontrol agents, as demonstrated by research on liquid compositions of *T. asperellum* in mineral or vegetable oils. Additionally, the use of cost-effective growth media like sugarcane molasses and brewer's yeast further enhances biomass production and quality by offering control over key variables like pH, temperature, and nutrients, thereby minimizing contamination risks. Advances in micro and nanotechnology have improved the formulation of *Trichoderma* for agricultural use, enhancing its viability and effectiveness [33].

Liquid Formulations

Liquid formulations of biological control agents (BCAs) vary in their composition, but they typically include microbial cultures or suspensions mixed with water, oils (mineral or organic), polymers, or combinations of these. For microbial inoculants, suspension concentrates are usually prepared by dispersing solid active ingredients—either free or immobilized microbial cells—into water or aqueous solutions using standard methods. Such liquid formulations are widely used in biopesticides [34-35].

For instance, *Pseudomonas fluorescens* has been successfully formulated in coconut water enriched with glycerol or polyvinylpyrrolidone (PVP). Similarly, [36] developed an oil dispersion containing soybean oil, glucose, and other stabilizing agents with conidia of *Trichoderma asperellum*. [37] designed water-in-oil emulsions of *P. fluorescens* using coconut, rice bran, or castor oils blended with glycerin, polyethylene glycol, and Tween 20. More recently, [37] demonstrated that oil-based formulations of *T. asperellum* TV190, using mineral or vegetable oils, significantly improved microbial viability (37–43% for mineral oils and 56–63% for vegetable oils) compared to untreated controls (8–12%). Patil et al. also reported that liquid oil-based formulations of *T. asperellum* effectively controlled Fusarium wilt in chickpeas. Oil-based systems are often preferred because they help maintain the microbes in a state of physiological dormancy, thereby extending shelf-life and stability. Carrier oils such as paraffin, soybean, and groundnut oil are frequently used for this purpose [38-39]. To further enhance biomass yield and formulation quality, low-cost growth media like sugarcane molasses and brewer's yeast have been employed, offering better control over pH, temperature, and nutrient supply.

Solid Formulations

Solid formulations offer an alternative method for the production of *Trichoderma* inoculum, utilizing agricultural wastes such as wheat straw, sugarcane bagasse, sawdust, corn cob meal, and rice bran either individually or in combination as substrates for fungal multiplication [40]. Both liquid and solid formulations require drying to ensure stability and extend shelf life. While solid formulations are cost-effective for small-scale production, they entail significant space and infrastructure for preparation, inoculation, and storage, drying, and milling. However, for large-scale production, spray drying emerges as a cost-effective technique, particularly for the production of dried microbial particles [41]. In research laboratories, solid fermentation serves as a common method for mass-producing *Trichoderma spp*. Cereal grains like wheat, bajra, and sorghum serve as common substrates for this purpose.

Talc Based Formulation

Talc-based formulations of *Trichoderma viride* have emerged as a promising solution for agricultural challenges, particularly in India, where they were developed at the Agricultural University of Tamil Nadu [42]. The manufacturing process involves culturing *Trichoderma* in a liquid medium, which is then blended with talcum powder in a precise ratio of 1:2. Subsequently, the mixture is dried under shade until it reaches an optimal moisture content of 8%. These formulations exhibit remarkable stability, having a shelf life of 3 to 4 months. It is estimated that the annual requirement of *Trichoderma* in India stands at about5000 metric tons, which is sufficient to cover approximately 50% of the country's agricultural land[43].Researchers have extensively explored the biocontrol potential of talc-based *Trichoderma* formulations across various crop diseases. Pradhan *et al.* (2022) conducted a study focusing on the efficacy of a talc-based formulation of *T. viride* against *Fusarium* wilt disease in chickpeas [44]. Their findings evaluated the effectiveness of the formulation, whether applied to seeds or soil, in mitigating the incidence of wilt in chickpeas. Similarly, Sundaramoorthy and Balabaskar (2013) ventured into developing talc-based formulations, this time targeting *T. harzianum* for combating wilt disease in tomatoes caused by *Fusarium oxysporum f. sp. lycopersici* [45]. Their greenhouse experiments revealed promising results, with *Trichoderma* application resulting in a minimal incidence rate of wilt disease, in the formulation's biocontrol efficacy in real-world scenarios.

Vermiculite-Wheat Bran-Based Formulation

The formulation of *Trichoderma* vermiculite-wheat bran-based formulation involves a meticulous process aimed at optimizing the growth and viability of the fungus. Initially, the fungus is cultivated in a specialized medium consisting of molasses and yeast, with a cultivation duration spanning 240 hours [46].Simultaneously, wheat bran (3.3g) and vermiculite (100g) undergo sterilization for three days at 70°C in an oven to eliminate any potential contaminants. Once sterilized, this substrate is meticulously mixed with 14 mL of the liquid culture derived from the fungal cultivation process, along with 17.5 mL of 0.05N hydrochloric acid (HCl). This precise mixture is then carefully allowed to dry in the shade until it reaches an optimal moisture content, ensuring the viability and stability of the formulation. Finally, the formulated product is packaged, ready for distribution and application in agricultural settings.

Oil-Based Formulations

Oil-based formulations represent a specialized category of liquid formulations designed to enhance the efficacy and viability of *Trichoderma* for agricultural applications. Various types of oil carriers, such as mineral oil, vegetable oil, and coconut oil, are utilized, chosen for their compatibility with *Trichoderma* and their ability to impart stability to the formulations [47]. Moreover, oil-based formulations exhibit superior adherence capacity to various surfaces, including seeds and plant leaves, thereby ensuring prolonged contact and efficacy against plant pathogens. To ensure the removal of bacteria and create a stable emulsion, surfactants are often incorporated into non-aqueous solvents such as diesel oil, mineral oil, and vegetable oil. Importantly, the formulation's longevity is crucial for its effectiveness, necessitating acceptance for foliar application in dry weather conditions and ensuring a prolonged storage life. Notably, Batta (2007) successfully developed an emulsion formulation of *T. harzianum*, demonstrating significant efficacy in reducing postharvest fruit rot caused by *Botrytis cinerea* [47].

Sodium Alginate Encapsulation of *Trichoderma*

The sodium alginate encapsulation method offers a sophisticated approach to incorporating *Trichoderma* into a protective matrix for enhanced stability and efficacy in agricultural applications. This formulation involves dissolving *Trichoderma* spores in a carefully prepared solution consisting of sodium alginate, a natural polymer derived from seaweed, at a precise ratio of 1:4 [48]. The resulting mixture is then meticulously dripped into a beaker containing a solution of 1.5 percent calcium chloride ($CaCl_2$) and allowed to undergo gelation for a duration of 30 minutes.

During this process, uniformly sized beads, approximately 3 mm in diameter, are formed, effectively encapsulating the *Trichoderma* within the sodium alginate matrix. These encapsulated *Trichoderma* beads are subsequently extruded through a sterile muslin cloth to remove excess solution and then subjected to aseptic air drying. The dried beads, now coated with the sodium alginate matrix, are carefully transferred into plastic bottles filled with sterile distilled water, where they are maintained at room temperature [48]. This encapsulation method not only ensures the protection of *Trichoderma* spores but also facilitates their controlled release and sustained activity in agricultural settings.

Formulations from Press Mud

Press mud, an organic residue produced during the sugar manufacturing process, emerges as a promising substrate for cultivating *Trichoderma,* offering a sustainable approach to biocontrol formulation development [49]. The press mud-based formulation process utilizes organic waste materials to cultivate *Trichoderma*, presenting an eco-friendly and economically viable approach to biocontrol formulation development. By utilizing press mud as a substrate, this method not only reduces waste from the sugar industry but also generates a sustainable solution for agricultural disease management.

Formulations from Coffee Husk

The utilization of coffee husk as a substrate for the mass production of *Trichoderma* presents a sustainable and economically viable approach to biocontrol formulation development, particularly in regions like Karnataka where coffee production is prominent.

Sawant and Sawant (1996) pioneered the use of coffee husk, a by-product of the coffee industry, for *Trichoderma* cultivation, tapping into a readily available resource [50]. This formulation has gained widespread adoption in regions like Karnataka and Kerala, where it has been effectively employed in the management of *Phytophthora* foot rot in black pepper crops. Moreover, some scientist explored the feasibility of utilizing various cost-effective solid substrates, including rice, corn, and wheat bran, for large-scale cultivation of *Trichoderma* [51]. Among these substrates, wheat bran emerged as particularly promising for the successful production of *Trichoderma* spores.

Formulations from Banana Waste

Banana waste, frequently ignored as a resource, presents itself as an interesting and valuable material for creating solid formulations based on *Trichoderma,* thus providing a sustainable solution for managing agricultural waste. Balasubramanian et al. (2008) were the first to develop a technique for cultivating Trichoderma using banana waste as the main substrate, supplemented with urea, rock phosphate, and a mixture of fungal and biocontrol agents [52].

Notably, the incorporation of a consortium of biocontrol agents, including *Bacillus polymixa*, *Pseudomonas sajorcaju,* and *Trichoderma viride*, enhances the formulation's effectiveness in combating plant pathogens and promoting plant health. This synergistic approach capitalizes on the complementary mechanisms of action exhibited by these beneficial microorganisms, resulting in a potent biocontrol formulation. Overall, the utilization of banana waste for *Trichoderma* based formulations represents a sustainable and environmentally friendly strategy for agricultural disease management. The repurposing agricultural waste materials and utilizing their inherent nutritional value, this approach contributes to the circular economy while promoting sustainable agriculture practices.

Conclusion

Trichoderma fungi have emerged as significant players in sustainable agriculture, primarily due to their biocontrol and plant growth-promoting properties. These fungi not only suppress various plant pathogens but also enhance soil health and plant growth through various mechanisms. The effectiveness of *Trichoderma* in controlling plant diseases is attributed to several biological control mechanisms. *Trichoderma* can alter the environment in ways that are unfavorable for pathogens. Which includes Antibiosis, the induction of plant defensive mechanism, and mycoparasitism. It also produces various secondary metabolites with antifungal properties, notable examples include Peptaibols, Gliotoxin and Trichokonins. *Trichoderma* also produces enzymes such as chitinases and β-1,3-glucanases. These enzymes can break down the cell walls of fungal pathogens, further enhancing its biocontrol capabilities, its role as a biocontrol agent, *Trichoderma* can form beneficial relationships with plants. It colonizes plant roots, promoting growth by improving nutrient uptake and enhancing the plant's resistance to diseases.

Utilizing *Trichoderma* as a biocontrol agent offers several benefits compared to traditional methods that rely on synthetic pesticides. These advantages include reduced chemical residues, lower environmental impact, and the promotion of sustainable agricultural practices. *Trichoderma,* acting as a green catalyst, offers sustainable solutions for agriculture and environmental biotechnology through its multifaceted roles in plant growth promotion, disease management, soil health improvement, and environmental remediation. Its integration into agricultural systems can reduce chemical inputs, enhance productivity and support environmental sustainability, contributing to the global objectives of achieving sustainable agriculture and environmental health.

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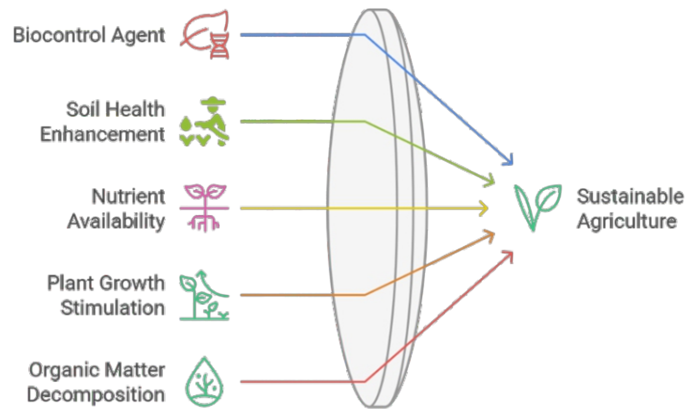

Figure 1: Trichoderma as Green Catalyst for sustainable Agriculture

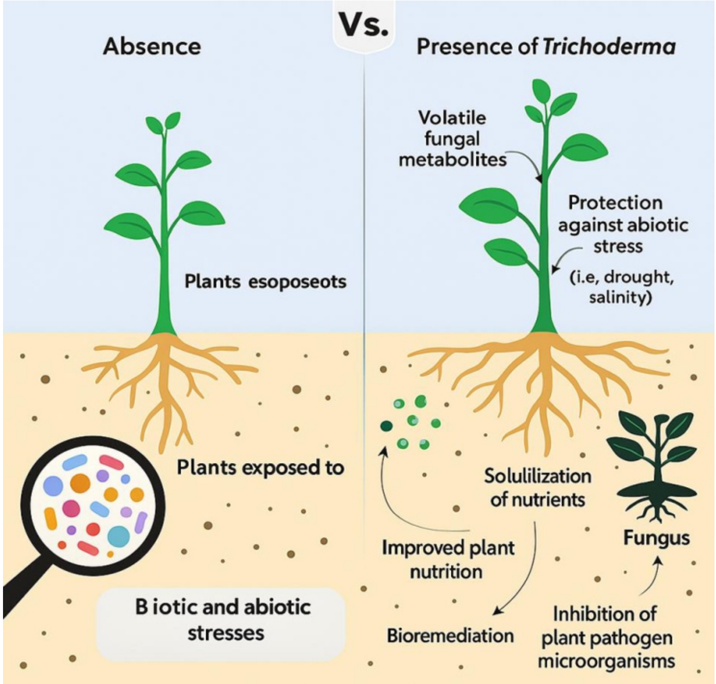

Figure 2: Trichoderma as biocontrol agent

Table 1: Induced Systemic resistance elicited by *Trichoderma* species

Species Plant and strain	Plant species	Pathogens	Outcome	References
T. virens G-6, G- 6-5 and G-11	Cotton	*Rhizoctonia solani*	Protected plant by inducing terpenoid	[53]
T. harzianum B-77	Fruits and vegetable	*Botrytis cinerea Pers.*	Post-harvest protection	[56]
T. atroviridae	*Vitis vinifera*	*Plasmopara viticola*	Activation of defense related mechanism	[56]
T. harzianum T-39	Bean	*Colletotrichum lindemuthianum, Botrytis cinerea*	No infection on leaves when T-39 was applied only on roots	[19]
	Tomato, pepper, tobacco, lettuce, bean	*B. cinerea*	No infection on leaves when T-39 was applied only on roots	[54]
	A. thaliana (L.) Heynh.	*Botrytis cinerea Pers.*	Ecotype Colombia-0 (Col- 0) showed resistance leading to reduced grey mold symptoms	[55]
	Tomato	*Botrytis cinerea*	0.4% T39 drench showed 84% decline in disease severity	[57]
	Cucumber, bean, tomato, and strawberry	*Botrytis cinerea* and *Podosphaera xanthii*	Protected from foliar diseases by direct or indirect effect via stimulation of beneficial microorganisms in the rhizosphere	[58]
T. harzianum T-22; T. atroviride P1	Bean	*B. cinerea* and *Xanthomonas campestris pv. phaseoli*	Activation of pathways related to antifungal compounds in leaves when present on roots	[2]
T. harzianum T-1 & T22; T. virens T3	Cucumber	*Green-mottle, mosaic virus*	No infection on leaves when strains were present only on roots	[59]
T. harzianum T-22	Tomato	*Alternaria solani*	No infection on leaves when T-22 was applied only on roots	[60]
*Trichoderma G*T3-2	Cucumber	*C. orbiculare, P. syringae pv. lachrymans*	Induction of defense related genes related to lignifications and superoxide generation	[61]
T. harzianum	Pepper	*Phytophthora capsici*	Improved production of the phytoalexins capsidiol toxic to pathogen	[62]
T. asperellum (T203)	Cucumber	*Pseudomonas syringae pv. lachrymans*	Modulated expression proteins related jasmonic acid/ethylene signaling the of to	[72]
T. asperellum SKT-1	*A. thaliana* (L.) Heynh.	Pseudomonas syringae pv. tomato DC3000	Induced systemic resistance to colonization by SKT- 1 and its cell-free culture filtrate	[20]
	A. thaliana	Cucumber virus mosaic	Improved defense mechanism against infection of CMV	[71]
T. harzianum Tr6, and Pseudomonas sp. Ps14	*T. harzianum* Tr6, and *Pseudomonas sp.* Ps14	In cucumber-*Fusarium oxysporum* f. sp. *radicis cucumerinum* and in A. thaliana against B. cinerea.	Ps14 and Tr6 activated the set of defense-related genes	[70]
T. virens and T. atroviride	Tomato	*Alternaria solani, B. cinerea*, and *Pseudomonas* syringae pv. tomato (Pst DC3000)	Secreted proteins- Sm1 and Epl1 both induced systemic acquired resistance	[63]

Table 2: *Trichoderma* as biocontrol agent

Name of *Trichoderma* Species	Name of Plant Pathogens	Crop Name	Inhibition/Efficienc cy (%)	Experime nt Condition	References
T. hamatum	*Sclerotium rolfsii and Rhizoctonia solani*	Ryegrass	42–47	Greenhous e and field condition	[64]
T. harzianum	*Phytophthora cinnamon*	Pine	28.5–37.5	Greenhouse	[65]
T. hamatum and T. harzianum	*P. cinnamomi*	Avocado		Greenhous e	[66]
T. viride, T. virens T. harzianum, T. pseudokoningii T. koningii	*Aspergillus niger, Rhizoctonia solani and Geotrichum candidum*	Sapodilla (Manilka ra zapota L.)	54–74	Laboratory	[67]
T. harzianum Ths97 strain	*F. solani*	Olive trees	25–50	Laboratory	[68]
Trichoderma 1433 viride Mutant strains	*Pythium aphanidermat um*	Mustard	85	Lab and field	[69]

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