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Review Article

Multifaceted Roles of *Trichoderma* in Sustainable Agriculture: Mechanisms, Applications, and Future Perspectives

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Abstract

Modern agricultural practices have boosted crop yields but have also intensified pressure on the food system, along with environmental and health issues linked to overreliance on chemical fertilizers and pesticides. Soil degradation, loss of biodiversity, pesticide resistance, pollution, and human health hazards are the serious negative consequences imposed due to intensive agricultural practices, necessitating the shift towards biological agents to boost productivity and safeguard environmental and human health. Beneficial organisms, especially *Trichoderma* species, have emerged as effective beneficial fungi due to their versatile roles in sustainable agriculture for disease suppression through mycoparasitism, competition, production of secondary metabolites, and entomopathogenesis. In addition to pathogen suppression, *Trichoderma* spp. induce defence mechanisms in plants, produce growth hormones, mobilize unavailable nutrients, and increase nutrient uptake, making plants tolerant to biotic and abiotic stress and facilitating the bioremediation of toxic soil. However, problems related to strain specificity, field performance, environmental conditions and shelf-life stability limit its widespread adoption. Future studies should focus on producing stress-tolorent and highly efficient strains, *Trichoderma* strains that can tolerate broader environmental conditions, exploring synergetic effects with other beneficial micro-organisms, and application methods. Overall, this review presents the versatile function of *Trichoderma* spp. in increasing crop yield and preventing negative consequences on environmental and human health, and also highlights challenges and the need for advance future studies.

Keywords: Biocontrol, Biofertilizer, Plant Growth Promotion, Soil Microbiome Interactions, Sustainable Agriculture

1. Introduction

Modern agriculture has become increasingly dependent on intensive farming practices involving the excessive application of chemical fertilizers and pesticides to maximize crop productivity, and fulfill the growing food demand [1–3]. The rapid response, easy availability, and immediate effectiveness of these agrochemicals have contributed significantly to their widespread adoption among farmers [4]. Although these practices have substantially enhanced agricultural output, their prolonged and indiscriminate use has generated severe environmental, ecological, and human health concerns.

The continuous application of chemical fertilizers and pesticides has adversely affected soil fertility, biodiversity, and environmental quality. Excessive pesticide application contaminates soil and water bodies, leading to eutrophication, destruction of beneficial soil microflora, and mortality of non-target organisms [5, 6]. Similarly, the overuse of synthetic fertilizers contributes to the accumulation of toxic compounds and heavy metals in agricultural soils, negatively affecting soil health, crop quality, and food safety [7]. Furthermore, prolonged use of pesticides with similar modes of action has accelerated the development of resistant strains of pathogens and insect pests, reducing the effectiveness of chemical control measures [8]. These environmental and agronomic challenges highlight the urgent need for sustainable agricultural practices capable of maintaining crop productivity while minimizing ecological degradation.

In recent years, sustainable and eco-friendly agricultural approaches have gained considerable attention as alternatives to chemical-intensive farming systems. Among these approaches, the use of beneficial microorganisms as biofertilizers and biocontrol agents has emerged as a promising strategy for enhancing crop productivity and maintaining environmental sustainability [9, 10]. Unlike chemical pesticides, microbial biocontrol agents generally possess multiple mechanisms of action, exhibit target specificity, and pose minimal risk to human health and the environment [3, 11]. These characteristics reduce the likelihood of resistance development among plant pathogens and pests, making microbial-based technologies a sustainable option for long-term agricultural management.

Among the diverse groups of beneficial microorganisms, *Trichoderma* spp. have attracted significant scientific and commercial interest due to their multifunctional roles in sustainable agriculture. Species of *Trichoderma* are widely distributed soil fungi known for their rapid growth, high reproductive capacity, adaptability to diverse environmental conditions, and strong rhizosphere colonization ability [12]. They can exist as saprophytes in soil organic matter, endophytes within plant tissues, and opportunistic symbionts associated with plant roots [13]. Upon colonization, *Trichoderma* spp. produce a wide range of bioactive compounds, hydrolytic enzymes, and secondary metabolites that promote plant growth, suppress pathogens, improve nutrient uptake, and induce plant defense responses [14–16]. In addition to their role as biocontrol agents against fungal pathogens, nematodes, and insect pests, *Trichoderma* spp. contribute to nutrient solubilization, phytohormone production, abiotic stress tolerance, and bioremediation of contaminated soils [17, 18]. Their broad-spectrum activities make them valuable components of integrated and sustainable agricultural systems aimed at reducing dependency on synthetic agrochemicals.

Therefore, this review aims to provide a comprehensive overview of the multifaceted roles of *Trichoderma* spp. in sustainable agriculture. The review focuses on their mechanisms of action, applications as biocontrol agents and biofertilizers, roles in plant growth promotion and stress tolerance, bioremediation potential, and the environmental factors influencing their effectiveness. Additionally, the review highlights current challenges and future prospects for the successful integration of Trichoderma-based technologies into sustainable crop production systems.

2. Taxonomy, Characteristics, and Ecology of *Trichoderma*

2.1. Taxonomy and Classification

Trichoderma is a filamentous fungal genus belonging to the kingdom Fungi, phylum Ascomycota, class Sordariomycetes, order Hypocreales, and family *Hypocreaceae* [19]. Species of *Trichoderma* are commonly associated with the sexual state Hypocrea, although many agriculturally important strains are primarily recognized and utilized in their asexual forms [20]. Traditionally, *Trichoderma* species were categorized under fungi imperfecti because of the absence or rarity of sexual reproduction; however, advances in molecular taxonomy and phylogenetic analyses have significantly improved species identification and classification [21, 22].

Trichoderma includes more than 500 species, and ongoing taxonomic studies continue to add new species [23]. Among them, *T. harzianum, T. virens, T. atroviride, T. asperellum, T. asperelloides, T. hamatum, T. longibrachiatum*, and *T. gamsii* are the most extensively studied species because of their strong biocontrol potential and plant growth-promoting properties [24–28]. Due to their multifunctional capabilities and adaptability, these species are widely utilized in agriculture as biological control agents, biofertilizers, and bio-stimulants [29].

2.2. Morphological and Physiological Characteristics

Species of *Trichoderma* are characterized by rapid growth, profuse sporulation, and efficient colonization ability. They produce fast-growing, branched, septate hyphae with green-colored conidia that serve as a distinguishing morphological feature of the genus [30, 31]. Colonies are generally green to dark green due to abundant conidial production and can grow on a wide range of nutrient media, including potato dextrose agar [PDA], malt agar [MA], and Czapek-Dox agar [CDA] [20, 32].

Trichoderma spp. are highly adaptable fungi capable of surviving under diverse environmental conditions. Most species exhibit optimal growth between 25–30°C and prefer slightly acidic conditions, although some strains can tolerate broader temperature and pH ranges [33, 34]. Their remarkable adaptability and rapid reproductive capacity contribute to their ecological success and effectiveness in agricultural systems. Physiologically, *Trichoderma* spp. possess strong enzymatic machinery and metabolic versatility. They produce several extracellular enzymes, including chitinases, glucanases, cellulases, and proteases, which facilitate decomposition of organic matter and antagonism against plant pathogens [29, 35]. In addition, these fungi synthesize a wide range of secondary metabolites, volatile organic compounds, phytohormones, and siderophores that contribute to plant growth promotion, nutrient mobilization, and disease suppression [9, 36].

2.3. Ecology and Rhizosphere Colonization

Trichoderma species are cosmopolitan fungi commonly found in agricultural soils, forest ecosystems, decaying wood, compost, and other organic substrates [1]. Due to their saprophytic nature and rapid rhizosphere colonizing ability, *Trichoderma* create a strong competition for space and mobilizing nutrient from soil in comparison to other soil organisms [29, 35]. Besides their saprophytic nature, many species can establish endophytic associations with plants by colonizing root tissues without causing disease symptoms [13]. One of the most important ecological characteristics of *Trichoderma* spp. is their exceptional rhizosphere competence. They effectively colonize plant root surfaces and surrounding soil through rapid spore germination, hyphal proliferation, and competition for nutrients and space [29]. During root colonization, *Trichoderma* interacts closely with plants through chemical signaling and secretion of bioactive compounds that influence plant physiology and defense mechanisms [15].

The successful establishment of *Trichoderma* in the rhizosphere enhances nutrient availability, stimulates root development, and improves plant resistance against biotic and abiotic stresses [16]. Moreover, their ability to survive under fluctuating environmental conditions and interact synergistically with other beneficial microorganisms makes them important components of sustainable agricultural ecosystems [37].

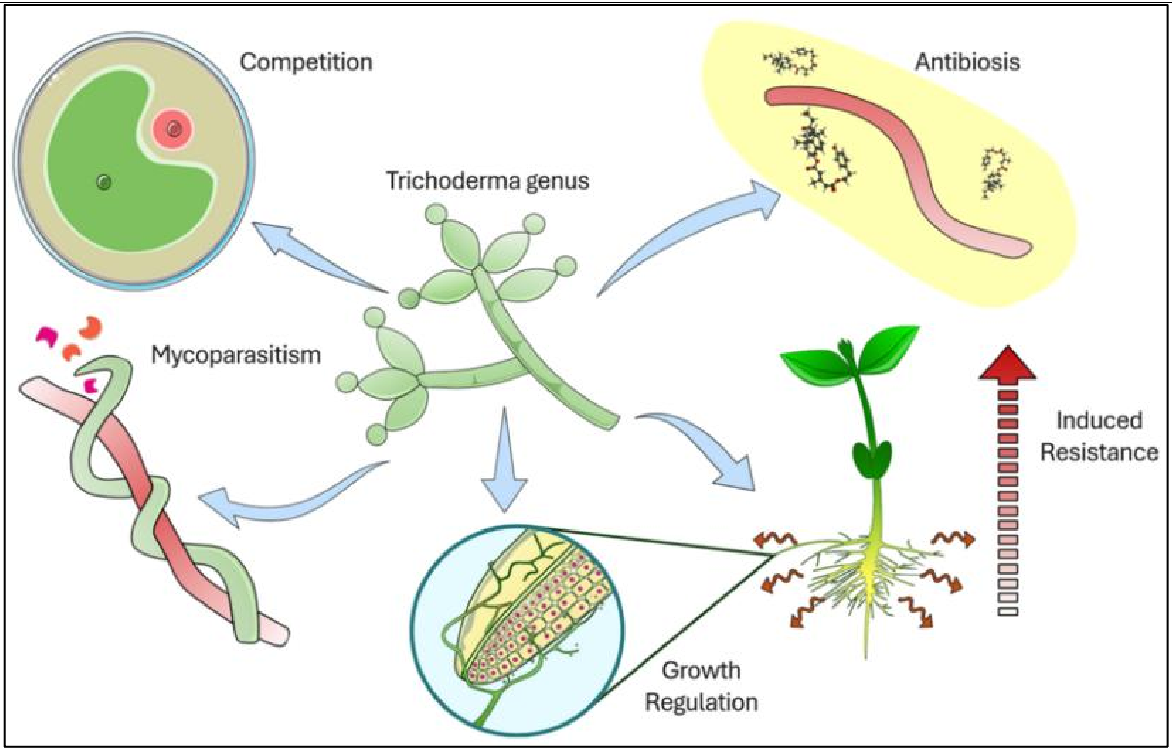

Figure 1. Mechanism of action for biocontrol exhibited by *Trichoderma spp. Reproduced from* [38].

3. Mechanisms of Action of Trichoderma

The effectiveness of Trichoderma spp. in sustainable agriculture is primarily attributed to their diverse and synergistic mechanisms of action against plant pathogens and environmental stresses. These mechanisms involve both direct and indirect interactions with pathogens, insects, nematodes, and host plants. Depending on the species, strain, host plant, and environmental conditions, Trichoderma may exhibit antagonistic activities through competition, mycoparasitism, antibiosis, induction of plant defense responses, and entomopathogenic or nematicidal actions [39–41].The multifunctional nature of these mechanisms contributes significantly to the broad-spectrum efficacy of Trichoderma in crop protection and plant growth promotion. The mechanism of action for biocontrol exhibited by *Trichoderma spp*. is illustrated in figure 1.

3.1. Competition for Nutrients and Space

One of the primary mechanisms by which *Trichoderma* suppresses plant pathogens is through competition for nutrients and ecological niches in the rhizosphere. Due to their rapid growth rate, high reproductive capacity, and strong rhizosphere colonization ability, *Trichoderma* spp. effectively occupy root surfaces and surrounding soil regions, thereby limiting the availability of space and nutrients for pathogenic microorganisms [29, 35]. Iron is one of the most critical micronutrients involved in microbial competition within the soil environment [42]. *Trichoderma* spp. produce siderophores, which are low molecular weight iron-chelating compounds that efficiently mobilize iron from the surrounding environment [43]. These siderophores deprive competing pathogens of available iron, restricting their growth and [36, 44]. In addition, rapid nutrient uptake and efficient carbon utilization further enhance the competitive advantage of *Trichoderma* over pathogenic fungi [45].

3.2. Mycoparasitism

Mycoparasitism is considered one of the most important direct antagonistic mechanisms of *Trichoderma* against phytopathogenic fungi. In this process, *Trichoderma* recognizes, attacks, and parasitizes the hyphae or resting structures of pathogenic fungi [46]. The initiation of mycoparasitism involves chemotropic growth toward the host fungus, followed by attachment, coiling around the pathogen hyphae, and penetration of the cell wall [35, 47].

The penetration process is facilitated by the secretion of extracellular hydrolytic enzymes such as chitinases, β-1,3-glucanases, cellulases, and proteases, which degrade the structural components of the pathogen cell wall [39]. These enzymatic activities ultimately result in lysis and destruction of the target pathogen. Studies have demonstrated that *T. harzianum* exhibits strong mycoparasitic activity against several economically important pathogens, including *Alternaria porri, Fusarium oxysporum, Rhizoctonia solani,* and *Sclerotium rolfsii* [30, 35]. Representative examples of plant diseases controlled by Trichoderma spp. are presented in table 1.

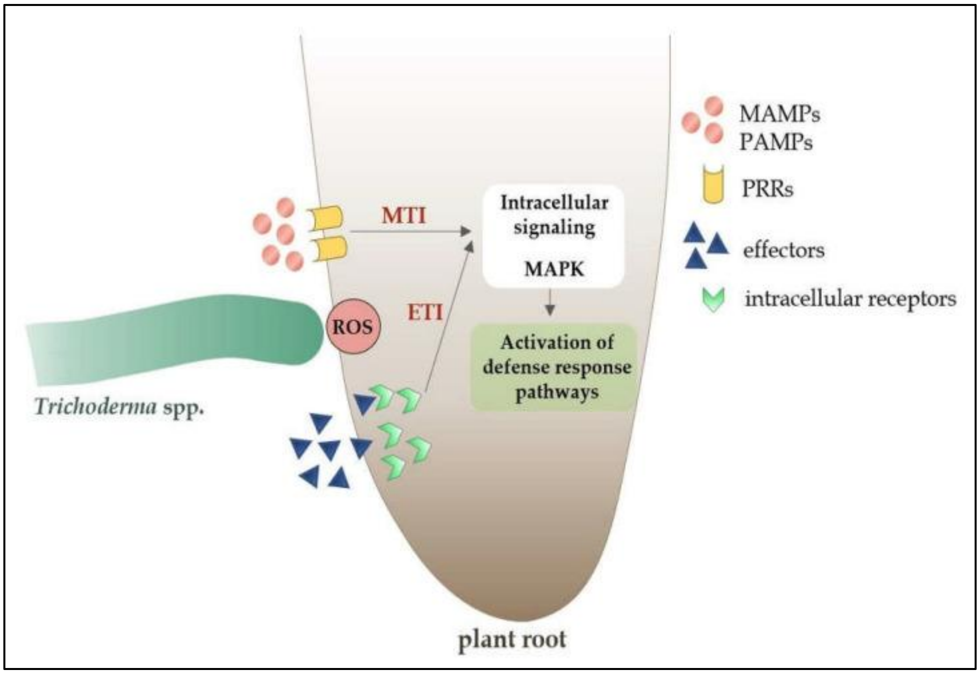

Figure 2. Plant defense response pathways triggered by microbe-associated molecular patterns (MAMPs) and effector molecules from *Trichoderma* spp. Reproduced from [48]. These pathways are consistent with recent reports demonstrating that *Trichoderma* spp. induce plant defense responses through complex mechanisms involving signaling molecules and pathogen suppression [49].

Table 1. Some examples of plant diseases controlled with *Trichoderma*.

Pathogen Species	Trichoderma Species	Mode of Action	References
Botrytis cinerea	*Trichoderma* spp.	Development of secondary metabolites	[50]
Phytophthora capsici	*T. virens*	Mycoparasitism and production of gliotoxin, a secondary metabolite.	[24]
Colletotrichum gloeosporioides	*T. asperelloides* *T. asperellum*	Competition and production of secondary metabolites	[25]
Meloidogyne incognita *Fusarium oxysporum*	*T. longibrachiatum*	Synthesis of Zinc nanoparticles, altering the expression of defense gene and destruction of hyphal growth.	[26]
Diplodia seriata	*T. harzianum* *T. carraovejensis* *T. gamsii*	Antibiosis through the production of bio active secondary metabolites and extra cellular enzymes.	[3]
Pyricularia oryzae	*T. harzianum*	Not mentioned	[4]
Phytophthora cinnamomi	*T. atroviride*	Competition	[51]
Fusarium avenaceum	*T. atroviride*	Growth inhibition of pathogen through the secretion of Volatile Organic Compound.	[52]
Fusarium oxysporum	*T. harzianum*	*Mycoparasitism*	[53]

3.3. Antibiosis

Antibiosis refers to the production of inhibitory compounds by one microorganism that adversely affect the growth or metabolism of another microorganism [54]. *Trichoderma* spp. are well known for producing a wide range of primary and secondary metabolites with strong antifungal, antibacterial, and insecticidal activities. These includes 390 metabolites such as such as gliotoxin, gliovirin, heptelidic acid, and viridin. Sepedonin, cathequin, caffeic acid, ferulic acid, 3, 4, 15-scirpenetriol and naematolin inhibits the growth and development of other fungal pathogens [9, 26, 55].

Table 2. Some examples of insects control by *Trichoderma.*

Pest Species	Trichoderma Species	Mode of Action	References
Macrosiphum euphorbiae	*T. atroviride*	Activation of Salicylic acid pathway which resulted on poor sap quality and attraction of parasitiod.	[56]
Spodoptera littoralis	*T. atroviride*	Activation of jasmonic acid pathway which resulted on inhibition of digestion and suppression of moth growth	[56]
Aphis gossypii	*T. harzianum*	Not mentioned	[57]
Brevicoryne brassicae	*T. harzianum*	Not mentioned	[27]
Ceratovacuna lanigera Zehntner	*T. hamatum*	Not mentioned	[58]
Aedes aegypti	*T. atroviride*	Direct infection through cuticle followed by production of secondary metabolites	[59]
Spodoptera littoralis	*T. hamatum*	Direct infection through natural openings	[60]
Locusta migratoria	*Trichoderma spp.*	Development of secondary metabolites	[50]
Diuraphis noxia *Tribolium castaneum*	*T. harzianum*	Development of secondary metabolites	[28]
Xylosandrus germanus	*T. harzianum, T. asperellum,* and *T. atroviride*	Mycoparasitism on the symbiotic fungus *Ambrosiella grosmanniae*	[61]

The antimicrobial compounds produced by *Trichoderma* interfere with cell membrane integrity, enzymatic activity, and metabolic pathways of pathogens, thereby inhibiting spore germination and mycelial growth [41]. Volatile organic compounds produced by certain strains of Trichoderma can also suppress pathogen growth without direct physical contact, thereby enhancing their effectiveness in the rhizosphere environment [62].

3.4. Induction of Plant Defense Responses

In addition to direct antagonistic effects on pathogens, *Trichoderma* spp. can enhance plant resistance by activating various defense mechanisms in host plants. Colonization of plant roots by *Trichoderma* triggers physiological and biochemical changes that stimulate both local and systemic defense responses [18, 63]

Several elicitors produced by *Trichoderma*, including hydrophobins, cellulases, glycoproteins, terpenoids, flavonoids, and polypeptides, function as signaling molecules that activate plant immune responses [64]. These elicitors stimulate the production of reactive oxygen species (ROS), phytoalexins, pathogenesis-related proteins, and defense-related enzymes such as chitinases and peroxidases [65, 66]. Trichoderma-mediated defense responses commonly involve induced systemic resistance [ISR] and systemic acquired resistance (SAR), which are regulated through jasmonic acid, ethylene, and salicylic acid signaling pathways [67]. For example, *T. harzianum* has been reported to induce jasmonic acid- and ethylene-mediated resistance in grapevine against *Plasmopara viticola* [68, 69]. Similarly, increased activities of defense enzymes in roots and leaves have been observed following *Trichoderma* colonization, indicating enhanced systemic resistance against pathogens [70]. The plant defence signalling pathways induced by *Trichoderma* is illustrated in figure 2.

3.5. Entomopathogenic and Nematicidal Activities

Besides suppressing plant pathogens, *Trichoderma* spp. also exhibit entomopathogenic and nematicidal properties against various agricultural pests. Entomopathogenic activity involves direct infection and colonization of insect hosts through the cuticle, followed by proliferation within the insect body and eventual death of the host [71].Certain strains of *Trichoderma* produce secondary metabolites and enzymes with insecticidal, antifeedant, and repellent properties that reduce pest survival and feeding activity [47].

For instance, culture filtrates of *T. harzianum* containing chitinase enzymes have shown antifeedant activity against *Helicoverpa armigera* in cotton [72]. Similarly, *T. atroviride and T. hamatum* have demonstrated pathogenic effects against insect pests such as *Aedes aegypti and Spodoptera littoralis* [59, 60].The examples of insects controlled by *Trichoderma* spp.are presented in table 2.

Trichoderma spp. are also effective against plant-parasitic nematodes [73]. Their nematicidal activity is mainly associated with the production of hydrolytic enzymes and toxic metabolites that degrade nematode eggs and inhibit larval development [74]. Studies have shown that *T. harzianum* can parasitize nematode eggs through chitinase production, significantly reducing nematode reproduction and survival [75]. In addition, non-volatile metabolites produced by *Trichoderma* spp. have been reported to cause substantial mortality in *Pratylenchus brachyurus* and *Meloidogyne incognita*, highlighting their potential as eco-friendly alternatives to chemical nematicides [55, 76].

4. Agricultural Applications of Trichoderma

4.1. *Trichoderma* as plant growth promoter

Trichoderma spp. produces various phytohormones ,and compounds that helps in growth promotion [77]. The phytohormones such as gibberellic acid (GA_3) and indole-3-acetic acid (IAA) increases the expression of growth -related genes which promote root development and biomass accumulation [78]. The inoculation of *Trichoderma* spp. increase biomass and root length of *A. euteiches*-infected plants [79]. Furthermore, *Trichoderma* application enhance fruit quality such as diameter, weight, circumference and TSS [80]. Especially, growth promoting effect is very beneficial when used to use with horticulture crops with week seed vigour [81].

4.2. Trichoderma as biofertilizer

Trichoderma serves as a natural substitute to synthetic fertilizers due to its ability to synthesis plant growth hormones, solubilize the insoluble phosphates, and increase the uptake of micro and macro nutrients [17]. *Trichoderma* spp. solubilize several soil nutrients that are present in an inaccessible form and convert them into plant available form, which increases the O_2 and CO_2 utilization [46]. When phosphorus binds with soil and form toxic complexes in acid soil, making the phosphorus unavailable to the plants [17]. *Trichoderma* strains can produce several enzymes which solubilize insoluble phosphates in acidic soil and micronutrients [9, 77] . For instance, *T. harzianum* can increase the various nutrient availability such as solubilize various plant nutrients, such as rock phosphate, iron, copper, manganese and zinc, especially in nutrient deficient soil [82]. Similarly, Application of Trichoderma-based-fertilizers at the rate of 9000 kg ha^{-1} significantly enhanced aboveground biomass in grassland system [83]. Due to the effective nutrient mobilization, roots in association with these fungi frequently are larger and more robust and consequently results in increased yield [84].

4.3. Trichoderma as bioremediator

Bioremediation is the process by which toxic chemicals from contaminated from soil and water are removed using biological agents, mainly microorganisms that are native to the contaminated sites [85, 86]. *Trichoderma* spp. can be used as myco-remediation of environmental contaminants of heavy metals such as lead [87]. They produce various organic acids including gluconic, fumaric and citric acid, and aids in lowering the pH of the soil, promoting the dissolution of phosphate, and micro and macronutrients like iron, magnesium which are essential for the plant metabolism. Additionally, they have extracellular enzymes within their system and catalytic reaction which promote the degradation of toxic aromatic compounds present in the soil [88]. The study conducted by Nykiel-Szymańska et al. [89] demonstrated that *Trichoderma* spp. help in the biodegradation of 80–99% of alachlor and 40–79% of metolachlor within a week.

4.4. Trichoderma as stress tolerant

Their colonization produces , auxin and GA which enhances tolerance to other abiotic stresses through improved water and nutrient uptake due to enhanced root and shoot growth and increased chlorophyll content, eventually increasing the crop yield [90–92]. *T. harzianum* inoculation improved drought tolorence in rice cultivation as it increases the activity of antioxidant enzymes, superoxide dismutase [SOD], catalase which eliminate the reactive oxygen species consequently preventing oxidative damage to rice due to drought [93]. Similarly, *T. asperellum* inoculation with reduced the adverse effect of drought and low temperature in tomato plant and increased the yield [94, 95]. During stress condition, it produced chlamydospores, which regulate oxygen utilization and withstand acidic condition [96]. The production of antioxidant and phenolic substances lower the leaf temperature and deal with heat stress [97].

5. Factors affecting the activities of *Trichoderma*

The efficacy of any biocontrol agent depends on the environment that they are subjected to. The full potential can only be exploited by studying the environmental conditions that favors its growth and colonization leading to proliferation [98]. Parameters such as species of *Trichoderma* and host plant and environmental conditions like temperature, pH, moisture ,salinity and nutrient availability significantly affects the effectiveness of *Trichoderma* in biocontrol mechanisms [34,39,99].

5.1. Temperature

Temperature significantly affects the growth and biocontrol efficiency of *Trichoderma*. Various studies have reported the efficiency temperature range between 25-30°C as the favourable range for the maximum antagonism and the temperature less than 20°C and more than 35°C retard the growth, colonization and biocontrol properties of Trichoderma [33]. For instance, antagonistic activity of *Trichoderma* spp. was decreased against *Macrophomina phaseolina* when temperature was increased from 25 to 35° C [100].

5.2. Soil pH

The biocontrol property is affected by pH condition as the production of secondary metabolites is greatly influenced by the pH range and its production is higher under optimum pH [3]. Although most of species can tolerant broad pH range, it has its optimum growth under acidic conditions, at the pH ranging from 5-7 [33, 34]. Moreover, pH 6.5 was favorable for the peak growth and sporulation of *Trichoderma* along with the highest maximum inhibition of five phytopathogen in chickpea rhizosphere i.e., 63.23%, 65.85%,53.33%, 53.84%, and 48.00% against *Fusarium oxysporum* f. *ciceri*, *Sclerotium rolfsii*, *Sclerotinia sclerotiorum*, *Pythium* spp. and *Rhizoctonia bataticola*, respectively [101].

5.3. Moisture Availability

Soil and surface moisture strongly affects the sporulation, germination, secretion of metabolites and survival of *Trichoderma* [1]. Sufficient water availability is crucial for hyphal contact, coiling and penetration. *Trichoderma* can withstand the relative humidity of 20-80%, however the maximum conidial formation and survival was obtained at

70%, demonstrating the role of irrigation for maintain optimum moisture level for field application. Under moist soils maintained at 25-35°C, *Trichoderma,* completely supressed *F. oxysporum* on chickpea over six months. On contrary, water logged and soil dry reduced its efficiency as pathogen survival is highest such condition [102]. The biocontrol efficiency increases at the moisture level between 8% against *Rhizoctonia solani* highlighting the role of optimum moisture level for disease control [103].

5.4. Soil organic matter and Nutrient Status

Organic matter improves soil physical, chemical and biological properties, thereby provide favourable micro environment conditions for *Trichoderma* growth and disease suppression [43]. Adequate organic matter and nutrient availability such as cow dung and compost manure in soil provides essential nutrient to *Trichoderma*, which facilitate its growth and survival, ultimately enhancing its activity [37]. For instance, the conjoint application of organic manure and increased nitrogen, phosphorus uptake, contributing to the maximum yield in wheat [104]. Additionally, incorporation of organic matter in soil promote the other beneficial microorganisms in soil, which synergistically enhance the efficiency of *Trichoderma* [105].

5.5. Host specificity and strain variability

Species and strain variability, and host specificity plays a significant role in the effectiveness of *Trichoderma*. *Trichoderma atroviride* was less effective than *T. harzianum* in promoting stem and canopy growth and controlling *Botrytis cinerea* in tomato plants [106]. On contrary, *T. atroviride* was found to be more effective than *T. harzianum* in controlling *Botrytis cinerea* in strawberry plants [107]. From these findings it can be inferred that the efficiency of *Trichoderma* is largely dependent on the crop species, suggesting that response to *Trichoderma* spp. is under genetic control. Therefore, it is evident to have molecular characterization of *Trichoderma* before making a general recommendation [92].

6. Challenges and Future Prospects

Despite the remarkable potential of *Trichoderma* spp. in sustainable agriculture, several challenges still limit their consistent performance and large-scale adoption under field conditions [29]. Although many studies have demonstrated promising results under laboratory and greenhouse environments, the effectiveness of Trichoderma-based products in open field conditions often varies due to environmental fluctuations, soil characteristics, host specificity, and interactions with native microbial communities [39, 99]. Therefore, improving the reliability and adaptability of Trichoderma formulations remains an important research priority.

One of the major limitations associated with Trichoderma-based bioinoculants is their relatively short shelf life and reduced survival under unfavorable environmental conditions such as extreme temperatures, low moisture, ultraviolet radiation, and fluctuating soil pH [33]. Environmental stress can significantly affect spore viability, rhizosphere colonization, metabolite production, and antagonistic activities, ultimately reducing field efficacy [98]. Consequently, future research should focus on developing stress-tolerant strains and improved formulations capable of maintaining stability and viability during storage and field application.

Another important challenge is strain specificity and host-dependent performance. Different *Trichoderma* species and strains exhibit varying degrees of effectiveness depending on the crop species, pathogen type, and environmental conditions [106]. For example, certain strains may perform efficiently in one crop system but show limited effectiveness in another. Advances in molecular biology, genomics, transcriptomics, and metabolomics may facilitate the identification of highly efficient strains with enhanced biocontrol and plant growth-promoting capabilities [108]. The formulation and application methods of *Trichoderma* products also require further optimization. Inconsistent field performance is often associated with inappropriate carrier materials, low shelf stability, inadequate inoculum concentration, and inefficient delivery methods [29]. Future studies should therefore focus on developing advanced formulations such as encapsulated spores, nano-formulations, and slow-release carriers to improve shelf life, colonization efficiency, and persistence in soil environments [38, 109].

Commercialization and farmer adoption of Trichoderma-based products remain another important concern. Limited awareness among farmers, inconsistent product quality, lack of uniform registration process, and regulatory challenges often hinder widespread use of microbial biocontrol agents, particularly in developing countries [10, 110]. Therefore, establishing quality control standards, improving farmer awareness programs, and strengthening policy support for biological alternatives are essential for successful commercialization and adoption.

Future research should also explore the genetic improvement of *Trichoderma* strains through molecular breeding and genetic engineering approaches to enhance stress tolerance, antagonistic activity, nutrient solubilization, and environmental adaptability. Furthermore, understanding the molecular interactions between *Trichoderma*, plants, pathogens, and soil microbiomes will provide valuable insights into improving its agricultural applications [77]. Emerging technologies such as omics-based approaches, artificial intelligence-assisted strain screening, and microbiome engineering may further accelerate the development of next-generation Trichoderma-based bioinoculants.

Although microbial consortia involving *Trichoderma*, *Pseudomonas* spp., *Bacillus* spp., and arbuscular mycorrhizal fungi are reported to have synergistic interactions in enhancing plant growth and disease suppression, can enhance plant growth and disease suppression through synergistic interactions [111, 112], antagonistic relationships among consortium members have also been reported, underscoring the significance of compatibility assessment prior to application [113]. To achieve optimum field performance, future research should emphasize on understanding these interactions and developing optimized, crop-specific microbial consortia.

Overall, *Trichoderma* spp. hold enormous promise as multifunctional agents for sustainable agriculture. However, overcoming limitations related to environmental adaptability, formulation stability, field consistency, and commercialization will be crucial for maximizing their agricultural potential and promoting their large-scale integration into eco-friendly farming systems.

7. Conclusion

The increasing environmental and health concerns associated with the excessive use of chemical fertilizers and pesticides have accelerated the search for sustainable and eco-friendly agricultural alternatives. In this context, Trichoderma spp. have emerged as highly effective multifunctional microorganisms with significant potential to support sustainable crop production systems. Their versatile mechanisms, including competition, mycoparasitism, antibiosis, induction of plant defense responses, nutrient mobilization, phytohormone production, and biodegradation of toxic compounds, contribute substantially to plant health and productivity.

Beyond their role as biocontrol agents against fungal pathogens, nematodes, and insect pests, *Trichoderma* spp. also function as plant growth promoters, biofertilizers, stress alleviators, and bioremediation agents. Their ability to enhance nutrient uptake, stimulate root development, improve tolerance against abiotic stresses, and restore contaminated soils highlights their broad applicability in sustainable agriculture. Furthermore, the eco-friendly nature of Trichoderma-based technologies offers an effective approach to reducing dependency on synthetic agrochemicals while maintaining crop productivity and environmental safety.

However, despite their considerable potential, several challenges remain regarding field consistency, environmental adaptability, shelf stability, formulation development, and strain specificity. The effectiveness of *Trichoderma* is greatly influenced by environmental conditions, host plant interactions, and application methods, emphasizing the need for precise strain selection and improved formulation technologies. Future research should therefore focus on the development of stress-tolerant and highly efficient strains, advanced delivery systems, molecular characterization, and integration with other sustainable agricultural practices.

In conclusion, *Trichoderma* spp. represent promising biological tools for achieving environmentally sustainable and economically viable agriculture. Their multifunctional roles in crop protection, plant growth promotion, nutrient management, and stress mitigation make them valuable components of integrated farming systems aimed at improving food security while preserving environmental and human health.

Author contributions

Sujata Nepal: Conceptualization, literature review, writing—original draft preparation. Surakshya Sharma: Review and critical revision. Niraj Mahato: Review and editing. All authors read and approved the final manuscript.

Ethical approval

Not applicable.

Conflicts of Interest

The authors report no conflicts of interest.

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