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Comparative Efficacy of Different *Trichoderma* Species in Suppressing Soil-Borne Pathogens of Major Food Crops

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Abstract

Soil-borne pathogens cause severe yield losses in many economically important crops. In the search for sustainable and eco-friendly plant protection strategies, *Trichoderma* species have emerged as prominent biocontrol agents. This review compares the efficacy of various *Trichoderma* species, including *T. harzianum*, *T. viride*, *T. asperellum*, and *T. atroviride*, against major soil-borne pathogens such as Fusarium oxysporum, Alternaria brassicae, Rhizoctonia solani, Sclerotium sclerotium, Sclerotium rolfsii, and Pythium spp. The review looks at antagonism mechanisms like mycoparasitism, antibiosis, enzyme production, and induced systemic resistance. It also investigates the role of species-specific characteristics in pathogen suppression, focussing on host specificity, rhizosphere competence, and environmental adaptability. Field trial data and laboratory studies are combined to determine the comparative effectiveness and applicability of these biocontrol agents.

Keywords*:* *T. harzianum, T. viride, T. asperellum, and T. atroviride*

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Introduction

Soil-borne fungal pathogens pose an ongoing and serious threat to global agricultural productivity. These pathogens have the unique ability to survive in the soil for long periods of time, often in the form of resilient spores or resting structures, making them extremely difficult to eradicate. Their widespread presence and adaptability enable them to infect a wide range of host plants across various agroecological zones. Prominent genera such as *Sclerotinia, Fusarium, Rhizoctonia, Pythium,* and *Alternaria* are known for causing a range of devastating diseases including stalk rot, root rot, vascular wilt, and damping-off. These infections affect vital crop groups like cereals (e.g., wheat and rice), pulses (e.g., chickpea and lentil), vegetables (e.g., tomato and brinjal), and various horticultural crops (e.g., pepper and cucumber). The impact of these diseases is multifaceted leading to poor seedling emergence, suppressed plant growth, and ultimately, significant reductions in yield and crop quality.

The damage caused by these soil-borne fungi is frequently exacerbated by favourable environmental conditions such as high soil moisture, dense planting, and poor drainage. Furthermore, because these pathogens can survive in soil organic matter or plant debris for many seasons, they contribute to recurring infections that test even intensive crop management systems (Agrios, 2005). Their economic implications are far-reaching, threatening not only food security but also raising cultivation costs due to the need for frequent chemical interventions and crop losses. Given these challenges, developing effective and long-term strategies for managing soil-borne fungal pathogens is a top priority in agricultural research and practice.

For decades, chemical fungicides have been the primary defence against a wide range of soil-borne fungal pathogens in agriculture. Because of their rapid action and broad-spectrum efficacy, farmers prefer them for managing diseases caused by genera such as Fusarium, Rhizoctonia, Sclerotinia, Pythium, and Alternaria. However, the long-term and indiscriminate use of these agrochemicals has had a number of unintended and concerning consequences. One of the most pressing issues is the development of fungicide resistance among pathogens. Continuous exposure to specific chemical classes enables pathogenic fungi to adapt and evolve mechanisms that render these fungicides ineffective, thereby diminishing their control efficacy (Kumar, D., 2020). For example, the repeated use of certain systemic fungicides in cauliflower fields of Agra has contributed to reduced sensitivity in Alternaria brassicae, the causative agent of Alternaria blight (Bhooshan & Kumar, D., 2022). This pathogen, known for its adaptability, continues to be a challenge despite multiple fungicidal interventions.

Another major concern is the accumulation of fungicide residues in soil and aquatic ecosystems. Persistent chemical residues not only contaminate natural resources, but they also disrupt the delicate balance of beneficial soil microbiota, which are essential for nutrient cycling, plant growth promotion, and natural disease suppression (Kumar, D., 2020). These non-target effects harm soil health and cause long-term ecological imbalances. Furthermore, the presence of fungicidal residues in food products poses significant risks to food safety and public health. Prolonged dietary exposure to chemical residues has been linked to a variety of health issues in humans and livestock, raising regulatory concerns and consumer awareness (Kumar, D., 2020).

In response to these challenges, researchers and practitioners are increasingly turning to biological and environmentally friendly disease management approaches. The use of biotic and abiotic elicitors has gained popularity as part of integrated disease management (IDM) strategies. For example, recent research has shown that certain biotic agents (such as *Trichoderma* spp.) and abiotic inducers (such as salicylic acid and potassium phosphates) can induce systemic resistance (ISR and SAR) in cauliflower against A. brassicae (Bhooshan & Kumar, D., 2023). These methods activate the plant's natural defence mechanisms without relying on chemical toxicity, providing a safer and more sustainable alternative.

Further investigation by Bhooshan and Kumar, D., (2024) revealed that the application of these resistance-inducing compounds not only reduced disease severity but also enhanced the activity of key defense-related enzymes like peroxidase, polyphenol oxidase, and phenylalanine ammonia-lyase in the host plant. These biochemical changes contributed significantly to the reinforcement of the plant's immune response, emphasizing the potential of non-chemical agents in managing soil-borne pathogens.

Among the various biological control agents, *Trichoderma* species have emerged as highly effective alternatives for controlling soil-borne pathogens. *Trichoderma* spp. is free-living filamentous fungi that can be found in soils and root ecosystems. Biocontrol mechanisms include mycoparasitism, competition for space and nutrients, induction of systemic resistance in host plants, and production of cell wall-degrading enzymes like chitinases and glucanases, as well as antifungal secondary metabolic products (Benítez *et al*., 2004; Vinale *et al*., 2008).

Importantly, different *Trichoderma* species and strains have varying levels of efficacy against specific pathogens, which are determined by their genetic makeup, environmental adaptability, and colonisation potential. For example, *Trichoderma harzianum* is known for its strong root colonisation and enzyme production, whereas *Trichoderma viride* and *Trichoderma atroviride* have been shown to be effective against a variety of fungal pathogens. Comparative studies show that strain-specific traits such as the ability to produce volatile organic compounds (VOCs), lytic enzyme profiles, and compatibility with rhizosphere conditions have a significant impact on biocontrol performance (Mukherjee *et al*., 2013).

Therefore, identifying and selecting the most effective *Trichoderma* species and strains tailored to specific crops and pathogens is essential for maximising their biocontrol potential. Such comparative analysis serves as the foundation for integrated disease management programs that aim to reduce chemical inputs while also promoting sustainable agricultural practices.

Major Soil-Borne Pathogens of Crops

Soil-borne fungal pathogens are one of the most persistent and damaging threats to agricultural productivity across the globe. Their ability to survive in soil as resistant structures such as sclerotia, chlamydospores, and oospores allows them to persist over multiple growing seasons, making control difficult. Several major pathogens are frequently associated with devastating diseases in a wide range of economically important crops.

Fusarium oxysporum is one of the most commonly encountered and damaging pathogens, causing vascular wilt in a variety of host plants. The fungus invades xylem tissues, obstructing water transport and causing wilting, yellowing, and eventual plant death. This pathogen infects crops like tomato, chickpea, banana, and brinjal, and its host-specific strains complicate resistance breeding and management efforts (Kumar, D., 2020).

Alternaria brassicae is a prominent soil- and air-borne necrotrophic fungal pathogen that primarily infects members of the Brassicaceae family, including economically important crops such as cauliflower, cabbage, mustard, and broccoli. The disease it causes, known as Alternaria blight, is recognized for its ability to cause significant damage at both vegetative and reproductive stages of plant growth. This pathogen typically produces dark brown to black necrotic lesions with concentric rings on leaves, stems, and pods. In severe infections, lesions coalesce, leading to premature leaf senescence and defoliation. On pods, the fungus can cause shriveling and darkening, which directly affects seed quality and yield. The disease substantially reduces the photosynthetic capacity of the plant, thereby impacting overall productivity. Being necrotrophic, A. brassicae derives nutrition from dead plant tissue, actively killing host cells through the production of phytotoxins and cell wall-degrading enzymes. This mode of pathogenesis makes it particularly challenging to control through conventional methods. It has been isolated and characterized from infected cauliflower fields in Agra, Uttar Pradesh, highlighting its regional economic relevance (Bhooshan & Kumar, 2022). Sclerotium sclerotiorum (Lib.) de Bary is a highly destructive, necrotrophic fungal pathogen with a wide host range, making it polyphagous and cosmopolitan in distribution. It thrives in a variety of agroclimatic conditions and survives in the soil for extended periods through resilient structures called sclerotia, which contribute to its persistence and epidemiological success. Being both ubiquitous and soil-borne, it affects numerous broadleaf crops, particularly under favourable conditions of high humidity and moderate temperatures (Rathi *et al*., 2014). One of the most economically significant diseases caused by S. sclerotiorum is Sclerotinia stem rot, especially in oilseed crops like Indian mustard (Brassica juncea). This disease has emerged as a major constraint in mustard production in India, leading to widespread concern among farmers and agricultural researchers. The pathogen infects the stem tissues, often resulting in water-soaked lesions that turn brown and dry, causing the stem to collapse. In severe cases, the disease leads to premature plant death and drastic yield losses.

Sclerotium rolfsii Sacc., an alarming soil-borne fungal pathogen, is well known for its wide host range and the severity of the diseases it causes in several major agricultural crops. The fungus is the cause of collar rot, stem rot, and southern blight, all of which impacts plant basal regions, causing wilting, lodging, and, eventually, plant death. The fungus has key survival strategies is its ability to produce sclerotia, which are small, hard, spherical structures that act as overwintering propagules in the soil. These sclerotia are highly resistant to environmental extremes and can survive for long periods of time, allowing the pathogen to persist in infested fields and resurface in subsequent crop seasons.

The fungus thrives under warm and humid soil conditions, which accelerate the germination of sclerotia and the initiation of infection. Such climatic conditions are particularly prevalent in tropical and subtropical regions, making crops highly vulnerable during the rainy or irrigated growing seasons. S. rolfsii is notably damaging to groundnut (Arachis hypogaea), where collar rot is a major yield-limiting factor. In tomato and various legume crops, the pathogen attacks the stem base and roots, causing lesions, girdling, and plant collapse. The disease often progresses rapidly, especially in densely planted or poorly drained soils, leading to significant crop losses if not managed promptly.

Rhizoctonia solani Kuhn is a highly virulent, soil-borne fungal pathogen with a wide host range and a significant impact on crop productivity, particularly in intensive farming systems. It is well known for causing root rot, collar rot, and damping-off diseases, especially during the early growth stages of crops. These conditions contribute substantially to seedling mortality, poor crop stand, and eventually reduced yields. The pathogen is particularly destructive in rice, tomato, and brinjal (eggplant)—crops widely cultivated across diverse agroecological zones. In rice, it is responsible for sheath blight, while in tomato and brinjal, it infects the hypocotyl and root regions, leading to lesions, stem girdling, and collapse of seedlings. R. solani causes both pre-emergence damping-off—where seedlings decay before breaking through the soil surface—and post-emergence damping-off, where young seedlings rot at the base and topple over shortly after emergence.

Ability of R. solani s to survive as saprophytic mycelia or sclerotia on plant debris and organic matter contributes significantly to its persistence in soils used for farming. These survival structures remain dormant until favourable environmental conditions cause germination and infection. The pathogen does not produce asexual spores, so its epidemiology is heavily dependent on soil-borne inoculum. The disease is frequently exacerbated in monoculture systems and fields with poor drainage, where successive cropping and high soil moisture promote the accumulation of inoculum. Once established, R. solani can persist in the soil for years, posing a constant threat to subsequent crops. Its management is particularly difficult due to the lack of effective chemical treatments and the absence of strong genetic resistance in most crop cultivars.

Pythium spp. is destructive plant pathogens from the Oomycetes class. They are also known as water moulds or algal fungi. Although they resemble true fungi in appearance and lifestyle, they are phylogenetically distinct and have closer evolutionary ties to algae. These pathogens are well-known for causing damping-off disease, a serious condition that kills seeds and young seedlings, especially during the nursery stage of crop development. Pythium has a wide host range, including major vegetable crops (tomatoes, cucumbers, and peppers) and cereal crops (rice, maize, and wheat). The widespread occurrence and rapid disease progression can result in significant losses in nurseries and early crop stages, affecting both yield and transplant success (Kumar, D., 2020).

The traditional use of chemical fungicides to manage these pathogens has yielded short-term success, but it has also resulted in a number of issues, including the development of resistant pathogen populations, environmental pollution, and negative effects on beneficial soil microorganisms. These concerns have fuelled increased interest in biologically-based and environmentally friendly alternatives, such as the use of microbial antagonists, resistance-inducing agents, and integrated disease management approaches (Sharma & Singh, 2014; Bhooshan & Kumar, 2023).

The recent trend in plant pathology emphasises the importance of fostering systemic resistance in crops and utilising beneficial microbes such as *Trichoderma* spp. and Pseudomonas fluorescens to suppress soil-borne diseases while improving plant health and yield (Kumar, D., 2020; Bhooshan & Kumar, D., 2024). These approaches are safer, more environmentally friendly, and consistent with the principles of agricultural sustainability.

Overview of *Trichoderma* spp. as Biocontrol Agents

Trichoderma is a genus of filamentous, soil-dwelling fungi that have emerged as highly potent biological control agents against a broad spectrum of plant pathogens. *Trichoderma* species are frequently encountered in agricultural soils and plant rhizospheres. They are known for their rapid growth, high reproductive potential, and production of a variety of bioactive compounds. These characteristics allow them to compete for ecological niches and suppress phytopathogens using a variety of antagonistic mechanisms (Vinale *et al*., 2008). *T. harzianum*, *T. viride*, *T. asperellum*, and *T. atroviride* are the most well-studied and used species in agriculture. These species have broad-spectrum antagonism and have been commercialised in numerous bioformulations to control soil-borne pathogens such as *Fusarium*, *Pythium*, *Rhizoctonia*, and *Sclerotium*, which are major contributors to root rot, wilt, and damping-off diseases in economically important crops (Harman *et al*., 2004; Vinale *et al*., 2008).

The potency of *Trichoderma* spp. as biocontrol agents is determined by a number of factors. Spore viability is essential for rapid colonisation and establishment in the rhizosphere, which is required for pathogen competitive exclusion. Furthermore, rhizospheric colonisation ability is a distinguishing feature that enables *Trichoderma* strains to form long-term associations with plant roots, improving both disease resistance and plant growth (Hermosa *et al*. 2012). Environmental adaptability, particularly tolerance to a wide range of temperature, moisture, and soil pH, is also important in determining how well these fungi perform in the field. Furthermore, strain specificity has a significant impact on the spectrum and efficiency of biocontrol activity because different strains may vary in their enzymatic profiles, metabolite production, and interaction with the host plant (Verma *et al*., 2007).

Trichoderma spp. use mycoparasitism to suppress plant pathogens by recognising, coiling around, and penetrating pathogenic fungi's hyphae. They then degrade the fungi using lytic enzymes like chitinases and β-1,3-glucanases. They also demonstrate antibiosis by secreting secondary metabolites with antifungal properties, such as peptaibols, pyrones, and gliotoxins (Howell, 2003). They also compete with pathogens for space and nutrients in the rhizosphere, using a strategy known as competitive exclusion. Some *Trichoderma* strains may also trigger systemic immunity in host plants, activating defense-related pathways and providing resistance to future pathogen attempts (Shoresh *et al*., 2010). Due to their multifaceted mode of action and environmentally friendly nature, *Trichoderma* spp. have become essential components of sustainable and integrated pest management (IPM) strategies. Their use reduces reliance on chemical fungicides while also improving agroecosystem health in the long run.

Mechanisms of Biocontrol by *Trichoderma* spp.

Mycoparasitism- Mycoparasitism is one of the most well-studied and important mechanisms by which *Trichoderma* species exert their antifungal activity against plant pathogenic fungi. This complex biological process involves *Trichoderma*'s direct interaction with the target pathogen, which results in its destruction via a series of coordinated steps such as recognition, attachment, penetration, and enzymatic degradation. Mycoparasitism begins with chemotropic growth, in which *Trichoderma* hyphae are attracted to pathogenic fungal hyphae via signalling molecules. Upon contact, *Trichoderma* species recognise and adhere to the host's hyphal surface, frequently forming coiling structures around it—a hallmark of mycoparasitic interaction. After adhesion, the mycoparasite enters the host hyphae mechanically and enzymatically (Harman *et al*., 2004).

Secretion of cell wall-degrading enzymes (CWDEs) is an important step in this process. Chitinases and β-1,3-glucanases are key hydrolytic enzymes that target chitin and glucans, the structural components of fungal cell walls. These enzymes degrade the pathogen's cell wall integrity, resulting in cytoplasmic leakage and death of the targeted fungus (Lorito *et al*. 2010). *T. harzianum* and *T. atroviride* are especially effective in mycoparasitism because of their high enzymatic activity and aggressive colonisation behaviour. These strains are known to produce a wide range of lytic enzymes and secondary metabolites that not only aid in parasitism but also inhibit spore germination and mycelial growth of pathogenic fungi. (Benitez *et al*., 2004).

Antibiosis–A Secondary Metabolite-Mediated Biocontrol Strategy by *Trichoderma* spp.

Antibiosis is an important biocontrol mechanism exhibited by several *Trichoderma* species, which involves the production and release of secondary metabolites that inhibit or kill plant pathogens. These bioactive compounds disrupt the growth, development, or metabolic functions of target fungi, reducing their ability to cause disease without direct physical contact. Several *Trichoderma* strains, particularly *T. harzianum*, T. virens, and *T. atroviride*, produce a diverse range of antifungal metabolites, including gliotoxin, viridin, peptaibols, trichodermin, and harzianic acid. These compounds act through a variety of biochemical pathways, including disrupting cell membrane integrity, inhibiting respiratory enzymes, and interfering with protein synthesis in pathogens (Vinale *et al*., 2008; Mukherjee *et al*., 2022). *Trichoderma* species are prolific producers of secondary metabolites with potent antifungal and antimicrobial activities. Among the well-characterized bioactive compounds are gliotoxin, viridin, and peptaibols, which contribute significantly to the biocontrol capabilities of various *Trichoderma* strains.

Gliotoxin-*Trichoderma* virens mainly produces gliotoxin, a sulfur-containing epipolythiodioxopiperazine compound. It has strong antifungal properties and is essential for combating phytopathogenic fungi. Gliotoxin's mode of action is to induce oxidative stress in target organisms. It disrupts normal cellular functions by producing reactive oxygen species (ROS) and inhibiting key enzymes by modifying thiol groups, particularly those containing cysteine residues. This results in protein dysfunction, mitochondrial damage, and, eventually, cell death (Mukherjee *et al*., 2022; Gardiner *et al*., 2004). Gliotoxin's antifungal properties make it particularly useful in the control of soil-borne pathogens such as Rhizoctonia solani and Fusarium oxysporum.

Viridin-Viridin, another significant metabolite produced by *Trichoderma* spp., particularly T. virens, is a furan-type antibiotic with broad-spectrum activity. Its mechanism of action involves the disruption of the mitochondrial electron transport chain, which interferes with cellular respiration in target fungal pathogens. This energy deficit severely limits pathogen growth and metabolic activity. Viridin inhibits ATP production and induces mitochondrial stress, causing the collapse of essential cellular processes in a variety of phytopathogens (Vinale *et al*., 2008; Singh *et al*., 2023).

Peptaibols- T. longibrachiatum and T. virens are the primary producers of peptidaibols, a type of linear peptide that contains α-aminoisobutyric acid. These peptides are amphipathic and membrane-active, with the primary antifungal action of forming transmembrane pores in pathogenic fungi's lipid bilayers. This pore formation leads to uncontrolled ion leakage, membrane potential loss, and, eventually, cell lysis (Sood *et al*., 2020). Peptaibols are dual-function metabolites with both protective and immunomodulatory roles, as they elicit defence responses in plants in addition to their direct antimicrobial action (Grigoletto *et al*., 2023).

Recent research has demonstrated that the profile of secondary metabolites can differ significantly between *Trichoderma* strains and is frequently influenced by environmental conditions and substrate composition. Advances in metabolomics and genomics have enabled the discovery of novel antimicrobial compounds that contribute to *Trichoderma*'s antagonistic potential, opening up new possibilities for its use in sustainable agriculture (Kumar *et al*., 2021). Thus, antibiosis is a non-contact but effective mechanism by which *Trichoderma* suppresses a wide range of phytopathogens, playing an important role as a biocontrol agent in integrated pest and disease management systems.

Induced Systemic Resistance (ISR) Triggered by *Trichoderma* asperellum and T. virens

Non-pathogenic microbes, including beneficial fungi like *Trichoderma* asperellum and *Trichoderma* virens, activate induced systemic resistance (ISR), which is a plant-mediated defence strategy. Unlike localised immune responses, ISR does not involve the microbes directly attacking pathogens; rather, it primes the plant's immune system to respond more quickly and robustly to pathogen attack, even in distant tissues (Shoresh *et al*., 2010).

Trichoderma asperellum and T. virens colonise the rhizosphere or root surface and form a symbiotic relationship with the host plant. This interaction activates defense-related signalling pathways, particularly those regulated by jasmonic acid (JA) and ethylene (ET), which differ from SA-mediated systemic acquired resistance (SAR) (Pieterse *et al*., 2021). ISR activation increases the production of pathogenesis-related (PR) proteins, phenolic compounds, and antioxidant enzymes, preparing the plant for future pathogen encounters (Ghosh *et al*., 2022).

Recent studies affirm that *T. asperellum* and T. virens induce a "primed" state in plants, in which defence genes are kept at a low level of readiness, allowing for faster and stronger activation in response to biotic stress. This priming increases the plant's resistance to pathogens such as Fusarium oxysporum, Botrytis cinerea, and Rhizoctonia solani (Singh *et al*., 2023). Furthermore, ISR improves disease resistance, abiotic stress tolerance, plant growth promotion, and nutrient uptake, making *Trichoderma* spp. valuable components of sustainable agriculture (Manganiello *et al*., 2018).

Comparative Efficacy of Different *Trichoderma* Species

Several species in the *Trichoderma* genus act as effective biocontrol agents against a wide range of phytopathogens found in a variety of crops. Their modes of action, which include mycoparasitism, antibiosis, competition, and induced systemic resistance (ISR), vary by species and strain. Comparative studies have shown that the efficacy of these species varies depending on the target pathogen, environmental conditions, and crop system.

Trichoderma harzianum

Target Pathogens: Fusarium oxysporum, Rhizoctonia solani

Host Crops: Tomato, Chickpea

Biocontrol Efficacy: *T. harzianum* is one of the most extensively researched and commercially used species due to its aggressive root colonisation, ability to activate ISR, and production of hydrolytic enzymes. It exhibits strong antagonism via mycoparasitism and secondary metabolite production. In field trials, *T. harzianum* reduced Fusarium wilt in tomato and chickpea by more than 60% (Singh *et al*., 2016). Its ability to remain in the rhizosphere makes it ideal for field applications.

Trichoderma viride

Target Pathogens: Sclerotium rolfsii, Fusarium solani

Host Crops: Groundnut, Brinjal

Biocontrol Efficacy: *T. viride* is renowned for its strong enzymatic activity, particularly chitinases and glucanases, which break down fungal cell walls. It competes effectively for nutrients and space and has shown promising results in the prevention of collar and root rot diseases. Its spores also germinate quickly in the rhizosphere, allowing it to gain control over soil-borne pathogens (Kumar *et al*., 2021).

***Trichoderma* asperellum**

Target Pathogens: Pythium spp., Rhizoctonia solani

Host Crops: Rice, Vegetables

Biocontrol Efficacy: *T. asperellum* is particularly effective at inducing systemic resistance and producing antimicrobial metabolites such as peptaibols and polyketides. It has shown strong biocontrol potential in both greenhouse and nursery settings. Studies have shown that Pythium-induced damping-off is significantly reduced in rice and vegetable seedlings (Verma *et al*., 2017). Its ability to adapt to a wide range of environmental conditions makes it useful in a variety of agroecosystems.

Trichoderma atroviride

Target Pathogens: Fusarium oxysporum, Pythium spp.

Host Crops: Tomato, Onion

Biocontrol Efficacy: *T. atroviride* is widely recognised for its potent antibiosis properties. It produces several secondary metabolites, including trichodermin and atroviridin, which inhibit pathogen growth. It is well-adapted to acidic soils and performs well in low pH environments, making it ideal for areas with acidic soils. It also has high potential for suppressing vascular wilts and damping-off diseases (Mukherjee *et al*., 2022).

Factors Influencing Biocontrol Efficacy of Different *Trichoderma* spp.

The biocontrol effectiveness of *Trichoderma* species in agricultural systems is determined by a complex interaction of environmental, biological, and technological variables. While species diversity accounts for broad functional differences, specific traits like ecological adaptability, rhizosphere interactions, strain selection, and formulation type have greater effects on field performance and disease suppression capacity.

Soil Type and pH Tolerance

Soil characteristics, especially pH and texture, have a significant impact on *Trichoderma* spp. survival and activity. *T. atroviride*, for example, has superior colonisation and metabolic activity in acidic soils, which is due to its enzymatic adaptability and organic acid production at low pH levels. *T. viride*, on the other hand, thrives in neutral to slightly alkaline soils, making it ideal for crops grown in calcareous or loamy soils (Pandey *et al*., 2022). Recognising the soil environment aids in the selective application of compatible *Trichoderma* strains.

Crop Rhizosphere Compatibility

Different *Trichoderma* species and strains have selective compatibility with plant rhizospheres, which affects colonisation efficiency and biocontrol performance. For example, *T. harzianum* is known to associate well with solanaceous crops such as tomato and brinjal, whereas *T. asperellum* has a strong affinity for cereals such as rice and maize. These interactions are influenced by the composition of root exudate, which serves as a chemoattractant and nutrient source for fungal colonisation (Poveda, 2021). Enhanced rhizosphere compatibility not only improves pathogen suppression, but it also promotes plant growth and induces systemic resistance.

Strain Selection within Species

Biocontrol efficacy of *Trichoderma* is highly dependent on intraspecific variation. Even within a single species, such as *T. harzianum*, strains can differ significantly in their ability to produce hydrolytic enzymes, secondary metabolites, and compete in the rhizosphere. Mukherjee *et al.* (2013) emphasised the importance of strain-level selection based on antagonistic ability, sporulation rate, and environmental resilience in developing consistent and effective biocontrol agents. Advanced molecular tools and genomic screening now enable the precise selection of elite strains tailored to specific crop-pathogen systems.

Formulation and Delivery Methods- The success of *Trichoderma*-based biocontrol in the field is also heavily influenced by formulation technology and delivery strategies. Talc-based formulations are widely used because they are inexpensive, stable, and simple to apply. Meanwhile, liquid formulations have a longer shelf life and better microbial viability, especially for commercial strains of *T. harzianum* and *T. asperellum* (Sharma & Singh, 2014). Furthermore, innovations such as alginate beads, granules, and bio-priming techniques have increased application efficiency by boosting fungal survival in the field. The proper formulation ensures optimal colonisation, timely pathogen suppression, and long shelf life.

Challenges in the using *Trichoderma* spp. as Biocontrol Agents

Trichoderma species are widely recognised as effective biocontrol agents due to their antagonistic activity against a variety of plant pathogens and ability to stimulate plant growth. However, despite their demonstrated potential, several critical challenges prevent their widespread and consistent application in agricultural systems.

Standardization of Formulations- One of the most pressing obstacles to the commercialisation of *Trichoderma*-based biopesticides is a lack of standardised, stable, and field-effective formulations. The performance of biocontrol agents varies greatly depending on formulation type (talc, liquid, granules), carrier materials, shelf life, and storage environment. These inconsistencies can affect spore viability, reducing biocontrol efficacy in the field (Sharma & Singh, 2014).

Strain Stability and Field Performance- Strain selection plays an essential role in determining the effectiveness of biocontrol applications. Even within a single species, strains can differ significantly in their ability to colonise the rhizosphere, produce secondary metabolites, and adapt to environmental stress. Furthermore, repeated sub-culturing or long-term storage can result in genetic drift and loss of beneficial traits, making strain stability a constant concern (Mukherjee *et al*., 2013; Pandey *et al*., 2022).

Integration into Existing Crop Management Systems

Another major obstacle is incorporating *Trichoderma* spp. into traditional crop management systems, which frequently rely heavily on chemical pesticides and fertilisers. Compatibility with other agrochemicals, appropriate application timing, and farmer awareness are all obstacles to widespread adoption (Poveda, 2021). Furthermore, regulatory approvals and quality control issues in some regions can cause delays or complications in biocontrol formulation market access.

Future Perspectives

Although *Trichoderma* spp. shows great promise for sustainable agriculture, overcoming current limitations necessitates a multidisciplinary approach that includes biotechnology, formulation science, field ecology, and precision farming. Future research should concentrate on strain optimisation using "omics" technologies, the development of next-generation formulations, and adaptive deployment strategies to maximise their impact across diverse agricultural landscapes.

Genomics and Metabolomics-Driven Strain Improvement

The use of genomics, transcriptomics, and metabolomics has created new opportunities for understanding the molecular basis of biocontrol activity. Whole-genome sequencing of *Trichoderma* spp. identifies genes involved in antifungal enzyme production, secondary metabolite biosynthesis, and plant signalling interactions. Such insights can help guide the development of elite strains that are more effective and adaptable to a wider range of environments (Mukherjee *et al*., 2022; Pieterse *et al*., 2021).

Microbial Consortia and Synthetic Communities

The formation of microbial consortia containing compatible *Trichoderma* strains and other beneficial microbes (e.g., Pseudomonas, Bacillus) is a promising strategy for increasing biocontrol spectrum and environmental resilience. These synthetic communities (SynComs) can enhance nutrient uptake, induce systemic resistance, and suppress a wider range of pathogens (Liu *et al*., 2022). However, more research is required to optimise strain compatibility and functional stability under a variety of field conditions.

Customized Formulations and Precision Agriculture

Advances in formulation technology, such as nanoencapsulation, biochar carriers, and smart delivery systems, are expected to improve persistence and targeted release of *Trichoderma* in soil. When combined with digital agriculture tools and AI-driven diagnostics, precision application of biocontrol agents may soon become a reality, ensuring efficient and cost-effective disease management tailored to specific agro-ecological zones (Jogaiah *et al*., 2023).

Conclusion

Although all four *Trichoderma* species—*T. harzianum*, *T. asperellum*, *T. viride*, and *T. atroviride*—exhibit considerable biocontrol potential, their field performance is shaped by specific host-pathogen interactions, environmental variables, and formulation compatibility. Notably, *T. harzianum* and *T. asperellum* demonstrate superior efficacy through induced systemic resistance and broad-spectrum antifungal mechanisms, making them highly effective against a wide array of soil-borne pathogens. In contrast, *T. viride* and *T. atroviride* are more specialized in enzymatic degradation and antibiotic production, respectively. A comparative analysis reveals that *Trichoderma* efficacy is both species- and pathogen-specific, necessitating strain selection based on the crop-pathogen interaction. Furthermore, advances in formulation technologies, as well as strategic integration with crop management practices, have the potential to significantly improve the performance and consistency of *Trichoderma* biocontrol agents. As a result, adopting a species and strain-specific approach, supported by ecological comprehension and agronomic alignment, becomes essential for the successful deployment of *Trichoderma* in sustainable agriculture.

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