Review Article

Trichoderma species as a Next-Generation Biofertilizer and Biocontrol Agent

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Abstract: *Trichoderma spp. have emerged as promising next-generation biofertilizers and biocontrol agents due to their dual role in plant growth promotion and pathogen suppression. They enhance nutrient solubilization, produce phytohormones, and improve plant stress tolerance, while also protecting crops through mycoparasitism, antibiosis, and induction of systemic resistance. Their application in agriculture reduces dependence on chemical fertilizers and pesticides, supporting sustainable and eco-friendly farming. This review highlights the mechanisms, agricultural applications, challenges, and future prospects of Trichoderma spp., emphasizing their potential as key components in integrated nutrient and pest management strategies.*

***Keywords: Trichoderma spp*., Biofertilizer, Biocontrol, Plant growth promotion, Sustainable agriculture**

1. Introduction

1.1 Sustainable Agriculture: The Challenge

Modern agriculture has become heavily dependent on chemical fertilizers and pesticides to meet the escalating demands of food production. However, this reliance comes at a cost—environmental degradation, declining soil health, groundwater pollution, and negative human health impacts are among the major concerns (1). Biofertilizers—live microbial inoculants such as nitrogen-fixing bacteria, mycorrhizal fungi, and phosphate-solubilizing organisms—offer a promising, eco-friendly alternative. Their use not only enhances nutrient uptake and soil biodiversity but also supports agricultural productivity without the collateral damage associated with synthetic inputs (2).

1.2 Role of Biofertilizers in Reducing Chemical Dependency

Biofertilizers foster soil fertility and crop yield through multiple mechanisms: improving microbial diversity, augmenting organic matter, facilitating carbon sequestration, and enabling nutrient mobilization and phytohormone production. Studies have shown yield improvements of 10–40% with microbial inoculant use, along with enhanced seedling survival and accelerated flowering (2). These benefits underscore the potential of biofertilizers to decrease reliance on chemical fertilizers while promoting soil health and sustainable farming practices (3,4).

1.3 Introduction to *Trichoderma* spp.: Ubiquity and Importance

The fungal genus *Trichoderma* (phylum Ascomycota, family Hypocreaceae) comprises over 500 species ubiquitously present in soils, plant roots, and decaying matter (5). These fast-growing fungi are celebrated for their dual role in plant growth promotion and biocontrol, making them invaluable in sustainable agriculture (6). Mechanisms underlying their functionality include the solubilization of soil nutrients, production of phytohormones (like auxins, gibberellins, cytokinins), secretion of antimicrobial metabolites, mycoparasitism, competitive exclusion of pathogens, and induction of systemic resistance in plants (5,7). *Trichoderma* not only enhances soil and plant health but is also ecologically adaptable and environmentally safe, positioning it as a versatile biofertilizer, biocontrol agent, and biostimulant (6,8).

1.4 Objective of This Review

Given the urgent need for sustainable and resilient agricultural systems, this review aims to explore the multifaceted potential of *Trichoderma* spp. Specifically, it will:

1. Illuminate primary mechanisms driving plant growth promotion and pathogen suppression.
2. Evaluate its agricultural applications across crop systems and formulation strategies.
3. Identify current limitations—such as variability in field performance and regulatory hurdles—and propose solutions.
4. Highlight future directions, including strain improvements, synergistic microbe consortia, and integration into climate-smart agriculture.

Through this comprehensive analysis, the review underscores *Trichoderma* spp. as powerful, dual-function biofertilizers and biocontrol agents—key allies in advancing eco-friendly and sustainable agriculture.

2. Taxonomy and diversity of *Trichoderma* spp.

2.1 Classification and commonly used species

The genus *Trichoderma* (Ascomycota: Hypocreaceae) has undergone major taxonomic revision over the last two decades due to the widespread adoption of molecular markers. Modern treatments recognize several hundred species (estimates typically range from ~380–500 names, with ongoing descriptions increasing species richness), replacing the earlier morphology-based handful of taxa. Species delimitation today relies primarily on multi-locus sequence data rather than solely on morphological characters (9).

Among the numerous taxa, a relatively small number of species have been intensively used in agriculture and commercial products. The most commonly applied species include *Trichoderma harzianum* (and its complex), *Trichoderma viride*, *Trichoderma atroviride*, *Trichoderma asperellum*, *Trichoderma virens*, *Trichoderma longibrachiatum*, and *Trichoderma koningii* (or members of the *koningii* clade) — species that have demonstrated consistent plant growth promotion and antagonism across crops. Commercial formulations such as *Trichoderma harzianum* T-39 (Trichodex) and *T. harzianum* RootShield illustrate how particular strains within these species complexes dominate the market (10,11).

2.2 Global distribution and ecological adaptability

Trichoderma spp. are globally ubiquitous in terrestrial ecosystems, commonly isolated from agricultural soils, rhizospheres, decaying plant material, and as endophytes in diverse plant hosts. Their broad distribution reflects remarkable ecological plasticity: many species tolerate a wide range of temperatures, pH values, and substrate types, and several lineages have adapted to specialized niches (e.g., wood, compost, disease lesions). This ubiquity underpins their repeated isolation as native biocontrol and biofertilizer candidates across geographies, from temperate to tropical agroecosystems (11,12).

Ecophysiological traits that contribute to persistence in soils and rhizospheres include rapid saprotrophic growth, prolific conidiation, ability to utilize diverse carbon sources, and robust sporulation under variable moisture regimes. These features facilitate formulation (e.g., solid carrier, granular, or liquid inoculants) and field application but also contribute to context-dependent efficacy — i.e., strains that perform well in one agro-ecological zone may be less effective in another (10).

2.3 Genetic diversity and population structure

Molecular studies reveal high intraspecific and interspecific genetic diversity within *Trichoderma*, with complex population structure shaped by geography, host association, and ecological history. Multi-locus phylogenies based on markers such as the translation elongation factor 1-α (tef1α), the RNA polymerase II second largest subunit gene (rpb2), and the internal transcribed spacer (ITS) region provide the best resolution for species delimitation and population analyses. Recent population surveys combining tef1α, rpb2 and ITS sequences uncovered cryptic lineages within widely used species (e.g., the *Harzianum* complex, *T. atroviride*, *T. hamatum*), indicating that some "species" used in agriculture likely represent species complexes with variable traits (13).

Phylogeographic analyses and population genetic work show that (i) many agricultural isolates cluster with cosmopolitan clades, while (ii) several endemic or regionally restricted lineages exist, particularly in biodiversity hotspots. The high degree of genetic variation has practical implications: strain selection for bioformulation should be guided by molecular identification and functional screening, since closely related isolates may differ substantially in enzymatic profiles, metabolite production, and biocontrol efficacy (13,14).

2.4 Taxonomic challenges and best practices for identification

Despite progress, taxonomic challenges remain. Morphological characters are often insufficient for reliable identification because many species share convergent colony and conidial traits. The fungal barcodes ITS, tef1α and rpb2 are now recommended as standard markers for robust species identification; integration of multilocus sequence typing with morphological and ecological data is the current best practice. International white papers and keys (and curated databases) advocate for sequence-based species hypotheses and deposition of type sequences in public repositories to stabilize nomenclature and support reproducible identification of strains used in applied research and commercial products (13).

3. Mechanisms of Plant Growth Promotion

3.1 Nutrient Solubilization (Phosphorus & Micronutrients)

Trichoderma spp. promote plant nutrient uptake through multiple mechanisms. These beneficial fungi secrete organic acids—such as gluconic, citric, and fumaric acids—that acidify the rhizosphere and solubilize insoluble forms of phosphate, iron (Fe), and other micronutrients, enhancing their bioavailability to plants (15). Experimental evidence from tomato plants treated with *T. harzianum* SQR-T037 demonstrated improved root development via enhanced uptake of Fe and Cu through acidification, redox activities, and chelation mechanisms (16). In chickpea and sugarcane, inoculation with *Trichoderma* spp. led to increased phosphorus uptake and consequent improvements in growth and yield parameters—root/shoot growth, chlorophyll content, and cane yield were significantly higher with inoculation (17).

3.2 Production of Phytohormones (IAA, Gibberellins, Cytokinins)

Certain *Trichoderma* strains produce a diverse array of phytohormones that directly influence plant development. For instance, *Trichoderma virens* T49, *Trichoderma longibrachiatum* T68, *Trichoderma spirale* T75, and *Trichoderma harzianum* T115 generate gibberellins (GA_1, GA_4), abscisic acid (ABA), salicylic acid (SA), auxin (IAA), and cytokinins (dihydrozeatin, isopentenyladenine, trans-zeatin), with production levels varying by strain and culture conditions (18). Additional isolates from olive rhizosphere produced notable levels of IAA (1.30–21.15 µg/mL) and gibberellic acid (0.53–7.87 µg/mL), reinforcing their plant growth–promoting potential. In cucumber, *T. asperellum* Q1 produced IAA, gibberellin, and ABA, facilitating improved root colonization and growth (15).

3.3 Siderophore Production and Iron Availability

Trichoderma spp. often synthesize siderophores—primarily hydroxamate types like ferrichromes—that chelate iron (Fe^{3+}) in iron-limited environments, aiding plant iron acquisition and outcompeting pathogens for iron (15). *Trichoderma asperellum* T6, a high siderophore producer, enhanced Fe^{2+} levels in soil and increased Fe^{3+}-chelate reductase activity in cucumber, facilitating plant growth through improved iron nutrition. The strain's organic acids and extracellular reductase enzymes further aided Fe^{3+} solubilization. Similarly, *T. asperellum* Q1's siderophores increased endogenous IAA levels in *Arabidopsis* roots under iron-deficient conditions, suggesting a dual role in nutrient mobilization and hormone-mediated growth enhancement (19). In sorghum, *T. harzianum* inoculation under Fe deficiency upregulated plant Fe uptake genes (SbTOM2), auxin synthesis (SbSAURX15), nicotianamine synthase (SbNAS3), and siderophore transporter (SbYS1), while increasing both fungal siderophore and IAA levels—facilitating iron acquisition even in high pH soils (20).

3.4 Induction of Systemic Resistance in Plants

Trichoderma spp. can prime plant defenses via both MAMP-triggered immunity (MTI) and induced systemic resistance (ISR). Fungal cell wall and membrane components—such as chitin, β-glucans, and sterols—are recognized as MAMPs by plant receptors, initiating basal immune responses. Additionally, secreted molecules like xylanase EIX, LysM effectors (Tal6), ceratoplatanin (Sm1), peptaibols, and volatiles activate SA- and JA-ET–dependent ISR, reinforcing resistance against necrotrophic pathogens, herbivores, and nematodes. ISR activation is also facilitated via "priming," whereby

Trichoderma colonization heightens SA, JA, and ethylene responsiveness, as well as defense gene transcription—including small-RNA-mediated regulation and systemic signaling through volatile organic compounds (VOCs). These pathways help plants better withstand both biotic and abiotic stresses, including drought and salinity, by modulating ROS scavenging, phytohormone balance, and transcriptional "memory" of stress responses (21).

4. Biocontrol Potential of *Trichoderma* spp.

Trichoderma spp. exhibit significant mycoparasitic activity, enabling them to parasitize a wide range of phytopathogenic fungi. This interaction involves the secretion of hydrolytic enzymes such as chitinases, glucanases, and proteases, which degrade the cell walls of host fungi, leading to their lysis and death. For instance, *Trichoderma harzianum* produces endochitinase (Ech42), which plays a crucial role in the degradation of fungal cell walls during mycoparasitism (22). Additionally, *Trichoderma harzianum* has been shown to effectively control *Sclerotinia sclerotiorum* by producing cell wall-degrading enzymes that disrupt the pathogen's structure (23).

Trichoderma spp. are prolific producers of bioactive secondary metabolites that exhibit antifungal properties. These include peptaibols, gliotoxin, and trichokonins, which inhibit the growth of various plant pathogens. The production of these metabolites is influenced by environmental conditions and the presence of competing microorganisms. For example, *Trichoderma harzianum* has been reported to produce volatile organic compounds (VOCs) that not only suppress pathogen growth but also induce systemic resistance in plants (24).

The competitive saprophytic ability of *Trichoderma* spp. is a key factor in their biocontrol efficacy. They outcompete pathogens for essential nutrients and space, thereby reducing pathogen establishment and proliferation. Studies have demonstrated that *Trichoderma* spp. can utilize a broader range of carbon sources compared to many plant pathogens, giving them a competitive edge in nutrient acquisition (25). Furthermore, their rapid growth and colonization of the rhizosphere create an environment less conducive to pathogen survival.

Beyond direct antagonism, *Trichoderma* spp. can enhance plant defense mechanisms through the induction of systemic resistance. This phenomenon involves the activation of plant immune responses, leading to increased resistance against a broad spectrum of pathogens. The ISR elicited by *Trichoderma* spp. is associated with the modulation of plant hormones such as salicylic acid (SA) and jasmonic acid (JA), which play pivotal roles in plant defense signaling pathways (26). Moreover, *Trichoderma harzianum* has been shown to induce the expression of defense-related genes in plants, thereby enhancing their resistance to subsequent pathogen attacks (11).

5. Applications in Agriculture

Field applications of *Trichoderma* spp. have been developed in several formats—including seed treatment, soil inoculation, and foliar sprays—to exploit its biocontrol and growth-promoting properties under diverse cropping systems. Seed treatment or coating with *Trichoderma* helps establish early root colonization, enhance germination rates, and protect seedlings from soil-borne pathogens; for example, a novel dustable powder formulation of *Trichoderma viride* used as seed treatment significantly suppressed Fusarium wilt in chickpea under field conditions (27). Soil inoculation (or soil application), often with *Trichoderma*-based granules, pellets or biogranules, is applied at planting or during crop growth to suppress root rots or wet root rot; in mungbean, combining soil application of *Trichoderma virens* biogranules with seed treatment significantly reduced wet root rot incidence and increased yield (28). Foliar sprays (or root drench equivalent) are less common but have been demonstrated in studies where combining *Trichoderma* with other biocontrol agents improved seedling performance in cabbage, enhancing both seedling vigor and field performance (29).

Several case studies highlight *Trichoderma*'s success across cereals, pulses, vegetables, and fruits. In chickpea, seed + soil application of *Trichoderma viride*, *Trichoderma virens*, and *Trichoderma harzianum* lines managed wet root rot (caused by *Rhizoctonia solani*) and boosted yield (30). In lentil, *Trichoderma* strains suppressed wilt disease and improved germination when used as biocontrol agents in seed treatment or soil application (31). In tomato cropping systems, *Trichoderma spp.* suppressed Fusarium wilt and improved plant growth under greenhouse or field settings (32). A case study among pulse farmers in Bundelkhand (India) demonstrated that seed treatment of *Trichoderma harzianum* in chickpea, lentil, and pigeonpea under rain-fed conditions reduced root rot and wilt incidence by around 25-30 % and increased yield margins by 12-17 % compared to untreated controls.

On the commercial side, several formulations are available or under development. For example, biopolymer-based seed coatings of *Trichoderma harzianum* (strain Th4d) using chitosan/cellulose blends have been shown to reduce disease incidence in oilseed crops (e.g., safflower, soybean) with significant yield improvements. The aforementioned dustable powder formulation of *T. viride* for chickpea represents another commercial or semi-commercial product tailored for seed treatment (27). Additionally, field formulations such as "Pusa 5SD" (seed dressing) and soil-applied biogranules/pellets (e.g., Pusa Biogranule 6, Pusa Biopellet 16G) based on *T. virens* have been used successfully in mungbean to control wet root rot and enhance germination and vegetative growth.

Together, these applications illustrate that *Trichoderma* can be effectively integrated into field practices through seed treatment, soil inoculation, or foliar supplementation; success depends on matching formulation type, strain selection, crop type, and local environmental conditions. Choosing well-formulated commercial products (e.g., seed coatings, powder or granules) validated in local trials is crucial for achieving consistent performance in the field.

6. Limitations and challenges

Despite considerable promise, the practical deployment of *Trichoderma* spp. faces several persistent limitations that constrain consistent field performance. First, there is substantial variability in field efficacy: isolates that show strong biocontrol or growth-promotion in vitro or in controlled environments frequently perform inconsistently under diverse field conditions due to interactions among strain genotype, native soil microbiota, crop genotype, and local abiotic factors (soil type, moisture, temperature).

This context-dependency has been documented across multiple cropping systems and is a major bottleneck for up-scaling biocontrol technologies (15). Second, shelf-life and formulation challenges limit product viability and farmer adoption: many *Trichoderma* formulations (powders, granules, liquids) lose viability during storage because of desiccation, temperature fluctuations, or osmotic stress; developing protective carriers (microencapsulation, polymer matrices) and stabilizing liquid formulations improves longevity but can increase production complexity and cost.

Encapsulation and biopolymer coatings have extended shelf life in some studies, yet optimized, low-cost formulations that maintain high CFU counts for 6–12 months under variable supply-chain conditions remain an industrial challenge. Third, environmental influence on efficacy is strong: soil pH, salinity, organic matter, temperature ranges and agricultural practices (tillage, pesticide use, fertilization) affect *Trichoderma* survival, colonization and mode-of-action (e.g., enzyme secretion, metabolite production).

Climate variability and extreme events (drought or flooding) can further reduce field performance, making long-term reliability difficult without site-specific validation (33). Finally, regulatory aspects create both hurdles and safeguards: in many jurisdictions registration of fungal biocontrol products requires ecotoxicology, toxicology, and environmental fate data (examples include EPA and EU regulatory frameworks), which increases time-to-market and development cost; meanwhile, divergent national regulations complicate international commercialization despite general recognition of *Trichoderma* as low-risk organisms. Regulatory harmonization and clear standards for strain identity, quality control and labeling are needed to streamline product approval while ensuring safety.

7. Future prospects

Several promising research and development avenues can address current limitations and expand the role of *Trichoderma* in sustainable agriculture. Integration into integrated pest and nutrient management (IPNM) — combining optimized *Trichoderma* strains with complementary agronomic practices and compatible microbial inoculants — offers the best route to consistent, context-adapted benefits; meta-analyses and field trials increasingly support *Trichoderma* as a component of multi-tactic IPM/IPNM packages (34). Advances in genetic improvement and precision breeding (including marker-assisted selection, targeted mutagenesis, and CRISPR-Cas editing) permit tailoring strains for enhanced enzyme production, stress tolerance, specific metabolite profiles or reduced production of undesirable metabolites; several studies highlight successful marker-free engineering and CRISPR applications in *Trichoderma* as realistic tools for next-generation biocontrol strains (35). Synergistic co-inoculation strategies — for example with arbuscular mycorrhizal fungi (AMF), *Bacillus* spp., or rhizobia — can combine complementary nutrient-mobilizing and disease-suppressive functions; recent greenhouse and field experiments show additive or sometimes synergistic effects on plant growth, stress tolerance and yield, although outcomes depend on strain compatibility and environmental context (36). Finally, *Trichoderma* is well-positioned to contribute to climate-smart agriculture: by improving root architecture, enhancing water- and nutrient-use efficiency, priming stress responses and reducing chemical input requirements, *Trichoderma* applications can increase resilience to abiotic stress while lowering greenhouse-gas footprints from fertilizer overuse. Recent reviews articulate a “toolbox” concept where *Trichoderma* strains are deployed in targeted ways to support adaptation and mitigation goals under changing climates (37).

Collectively, addressing formulation and regulatory constraints, applying precision strain improvement, validating co-inoculation and IPNM strategies under multi-site trials, and explicitly testing climate-resilience endpoints will be critical steps toward realizing the full potential of *Trichoderma* as a next-generation biofertilizer and biocontrol agent.

8. Conclusion

Trichoderma spp. represent next-generation biofertilizers and biocontrol agents with multifaceted roles in nutrient mobilization, plant growth promotion, and suppression of pathogens. Their integration into sustainable agriculture can reduce dependence on chemical inputs and enhance crop resilience under climate stress. Despite challenges of variable field performance, formulation stability, and regulatory hurdles, advances in strain improvement, co-inoculation strategies, and climate-smart applications highlight a promising future. With continued research and optimized formulations, *Trichoderma* holds great potential as a cornerstone of eco-friendly and resilient crop production systems.

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