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Trichoderma-Based Biocontrol Strategies Against *Fusarium* Wilt: A Bibliometric Analysis and literature Review

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Abstract

***Fusarium* wilt is one of the most destructive soil-borne diseases threatening global food security. For decades, its control has relied heavily on synthetic chemical fungicides; however, their extensive use has led to pathogen resistance, environmental degradation, and risks to human health. *Trichoderma* has been widely investigated as a potential biological control agent due to its diverse mechanisms of action. This study aims to map the global research landscape on the application of *Trichoderma* in controlling *Fusarium* wilt through bibliometric analysis and literature review. Data were retrieved from the Scopus database (2015–2025) using selected keywords and analyzed with VOSviewer and Biblioshiny to identify publication trends, author collaborations, institutions, countries, and keyword clusters. The results indicate a marked increase in publications since 2020, with major contributions originating from India, China, and Egypt. The evolution of keywords indicates a shift in research focus from basic mechanistic studies to practical field applications. The literature review confirms the effectiveness of *Trichoderma* in suppressing disease and enhancing the productivity of agricultural commodities, although challenges persist in formulation, variability, and regulatory frameworks. These findings provide an important scientific basis for guiding future research, strengthening international collaboration, and supporting sustainable agricultural strategies that utilize biological control agents.**

Keywords: Bibliometric analysis, Biocontrol agents, Bio stimulant, Biotic stress, Plant defence

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Introduction

Wilt diseases is a serious soil-borne disease that causes substantial losses in crop production. It has been reported to significantly reduce plant growth and yield (Hadiwiyono *et al.*, 2020), thereby posing a major threat to agricultural sustainability. The disease is caused by *Fusarium*, which infects plants through the roots and colonizes the xylem vascular tissue, disrupting water and nutrient transport (Lal *et al.*, 2024). Infection is typically characterized by unilateral wilting that begins in the lower leaves and eventually leads to the death of the entire plant. Additional symptoms include brown discoloration of vascular tissues and stem rot. The pathogen also produces resting structures known as chlamydospores, which can persist in the soil for more than a decade, making effective control extremely challenging (Srinivas *et al.*, 2019).

For decades, the control of *Fusarium* diseases has relied heavily on synthetic chemical fungicides. However, their excessive use has led to several problems, including the development of pathogen resistance, disruption of soil microbiota, and negative impacts on both environmental and human health (Zhou *et al.*, 2025). Consequently, there is an urgent need for environmentally friendly, sustainable, and effective alternatives for pathogen management. One biological agent that has been widely studied and applied is the genus *Trichoderma*. In addition, this fungus promotes plant growth by producing phytohormones, hydrolytic enzymes, siderophores, ammonia, nitrogen-fixing compounds, and phosphatases

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(Abdenaceur *et al.*, 2022). he mechanisms by which *Trichoderma* suppresses *Fusarium* include mycoparasitism, the production of cell wall-degrading enzymes (CWDEs), secretion of volatile organic compounds (VOCs), and the induction of systemic plant resistance (ISR) (Yao *et al.*, 2023).

Although scientific publications on this topic continue to grow, comprehensive mapping of research trends, knowledge structures, and scientific evidence on the application of *Trichoderma* in *Fusarium* wilt control remains limited. Bibliometric analysis provides a systematic and quantitative approach to evaluating patterns in the scientific literature on *Fusarium* wilt biocontrol strategies, thereby offering strategic insights into field development, key contributors, and global research directions. This approach also enables the identification of knowledge gaps and shifts in research focus over time, which serve as a scientific basis for planning future studies and formulating strategies to develop more effective and sustainable biocontrol technologies. In contrast, literature reviews synthesize empirical evidence from multiple studies to assess effectiveness and methodological limitations. Integrating these approaches enables a more comprehensive and critical analysis by complementing quantitative bibliometric results with qualitative evaluation. Consequently, this combined approach not only maps research trends but also strengthens scientific interpretation and enhances practical relevance in the development of applicable biocontrol strategies in future.

Therefore, this study aims to: (i) map global research trends on the use of *Trichoderma* in controlling *Fusarium* wilt through bibliometric analysis, and (ii) synthesize experimental evidence from previous publications using a literature review approach. The findings of this study are expected to provide valuable scientific insights for researchers, policymakers, and agricultural practitioners in shaping more effective and sustainable research directions as well as biological control strategies.

Methods

This bibliometric study was conducted using the Scopus database, accessible via https://www.scopus.com/. The search strategy employed the following query: TITLE-ABS-KEY (Trichoderma AND ("biocontrol" OR "biological control" OR "disease management" OR antagonist) AND ("*Fusarium oxysporum*" OR "*Fusarium* wilt")), with a publication time span from 2015 to 2025. The objective of this search was to analyze the annual evolution of publications and identify the most frequently studied research areas. All retrieved data were exported in a compatible format and analyzed using VOSviewer© and Biblioshiny bibliometric software. The analysis included keyword mapping, author collaboration networks, and research trend visualization. Furthermore, a literature review of relevant articles was performed to synthesize empirical evidence on the role of *Trichoderma* in controlling *Fusarium*, thereby providing a more comprehensive evidence base.

Result and discussion

Publication trends on *Trichoderma* in the control of *Fusarium*

Bibliometric analysis reveals that publications related to *Trichoderma* have increased substantially since 2015, reaching a peak in 2022 with 70 articles (Figure 1). This growth pattern is more consistent than that observed for several other biological control agents, indicating a strong and sustained research preference for *Trichoderma* due to its multifunctional mechanisms, including mycoparasitism, antibiosis, and induction of plant resistance. The surge in publications also parallels global trends promoting sustainable agriculture and reduced reliance on synthetic fungicides. However, despite the expanding body of literature, challenges remain in translating laboratory and greenhouse findings into reliable field applications. Variability in strain performance, environmental dependency, formulation stability, and regulatory barriers continue to limit large-scale adoption. Future research is therefore expected to shift toward comparative field trials, strain optimization, advanced formulation technologies, and integrative approaches using multi-omics tools to enhance efficacy and consistency under diverse agroecosystem conditions.

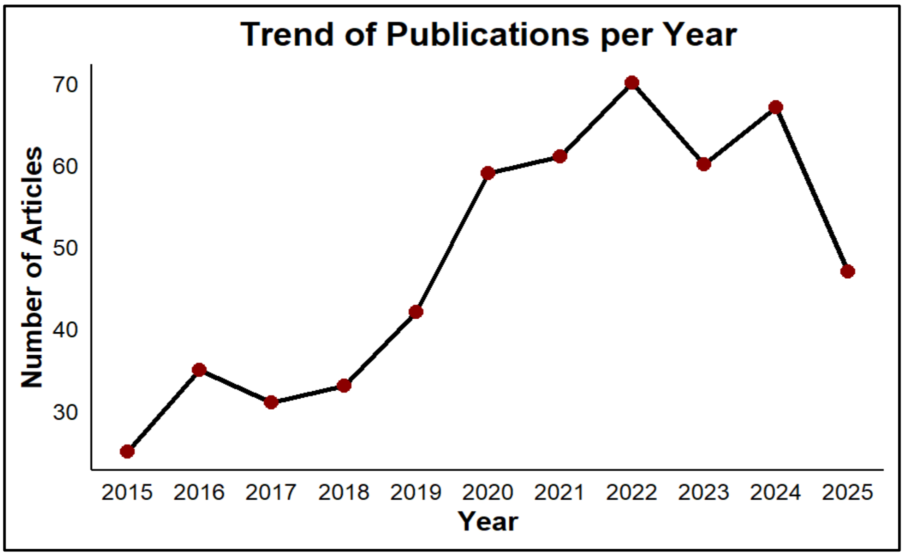

Figure 1. Trends in scientific publications on *Trichoderma*-mediated control of *Fusarium* during 2015–2025

Publishers and journals

A bibliometric analysis of publishers and scientific journals reveals notable variation in productivity, reputation, and relevance to the topic of *Fusarium* control using *Trichoderma* (Table 1). Frontiers in Microbiology ranks first, with an H-index of 259 and a CiteScore of 8.5, reflecting its strong global visibility and high citation impact. This journal is particularly suitable for manuscripts focusing on molecular aspects, biocontrol mechanisms, and biotechnological innovations involving *Trichoderma*. Similarly, the Journal of Fungi, which has a dedicated focus on mycology, demonstrates strong bibliometric performance (Impact Factor 4.8; CiteScore 8.4). It provides an excellent platform for studies exploring the interactions between *Trichoderma* and *Fusarium,* including metabolite production, signaling pathways, and microbial dynamics. Biological Control also offers a highly relevant outlet, especially for research on field applications and biological product formulations, with an H-index of 130 and a CiteScore of 7.9. In contrast, Indian Phytopathology and Archives of Phytopathology and Plant Protection show comparatively lower bibliometric indicators, reflecting more limited international coverage and a predominantly regional scope. Nevertheless, these journals may still serve as strategic venues for publishing preliminary findings or context-specific applied research. Overall, journal selection should be carefully aligned with the methodological depth, intended audience, and dissemination goals of the research to maximize its scientific impact.

Table 1. Top ten journals publishing the most articles on *Fusarium* control using *Trichoderma*, including the number of articles, H-index, publisher, impact factor (IF), CiteScore, and online ISSN

Journal	No article	H index	Publisher	IF	Cite score	ISSN (online)
Frontiers in Microbiology	27	259	Frontiers Media SA	4.5	8.5	1664302X
Indian Phytopathology	21	20	Springer	0.9	1.3	0367973X
Biological Control	17	130	Elsevier	3.4	7.9	10499644
Journal of Fungi	17	78	MDPI	4.0	8.4	2309608X
Archives of Phytopathology and Plant Protection	16	35	Taylor & Francis	1.0	1.3	03235408

Fundamental articles

Bibliometric results indicate that several highly cited articles have made significant contributions to advancing the use of *Trichoderma* as a biological agent against *Fusarium* wilt disease (Table 2). The most cited publication, with 174 citations, highlights resistance mechanisms mediated by *Trichoderma virens* through the jasmonic acid and salicylic acid pathways, providing a fundamental basis for understanding plant defense responses. In addition, other influential studies emphasize the role of antifungal metabolites, cell wall-degrading enzymes, volatile compounds, and root exudates in enhancing the effectiveness of biocontrol. The diversity of research foci demonstrates that investigations on *Trichoderma* extend beyond the identification of superior species or strains, encompassing a deeper understanding of the complex interactions among plants, pathogens, and biological agents. The high citation rates of these studies confirm the continuing evolution of *Trichoderma* research and underscore its importance as a foundation for developing more sustainable biological control strategies.

Table 1. Most cited articles related to *Trichoderma* in controlling *Fusarium* based on bibliometric analysis

Title	Year	Source article	Citation	Ref (Doi)
Different mechanisms of *Trichoderma virens*-mediated resistance in tomato against Fusarium wilt involve the jasmonic and salicylic acid pathways	2018	Molecular Plant Pathology	174	(Jogaiah *et al.*, 2018)
Synergistic effect of *Trichoderma*-derived antifungal metabolites and cell wall degrading enzymes on enhanced biocontrol of *Fusarium oxysporum* f. sp. cucumerinum	2016	Biological Control	165	(Saravanakumar *et al.*, 2016)
Characterization of novel *trichoderma asperellum* isolates to select effective biocontrol agents against tomato fusarium wilt	2015	Plant Pathology Journal	161	(El Komy *et al.*, 2015)
Root exudates of stressed plants stimulate and attract *Trichoderma* soil fungi	2018	Molecular Plant-Microbe Interactions	154	(Lombardi *et al.*, 2018)
Identification of a novel fungus, *Trichoderma asperellum* GDFS1009, and comprehensive evaluation of its biocontrol efficacy	2017	PLOS ONE	135	(Wu *et al.*, 2017)
Inhibition of plant pathogenic fungi by endophytic *Trichoderma* spp. through mycoparasitism and volatile organic compounds	2021	Microbiological Research	147	(Rajani *et al.*, 2021)

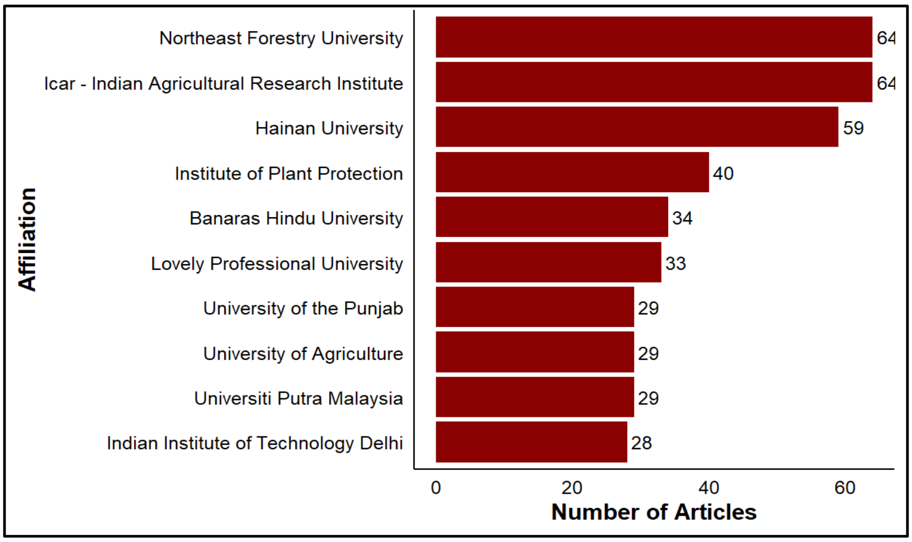

Figure 2. Top ten institutions with the highest number of publications on *Trichoderma* research for controlling *Fusarium*

Affiliations of the authors

An analysis of author affiliations reveals that the highest number of publications on *Trichoderma* and Fusarium wilt research originate from Northeast Forestry University and the ICAR–Indian Agricultural Research Institute, each contributing 64 articles. These are followed by Hainan University with 59 articles and the Institute of Plant Protection with 40 articles. Other notable contributors include Banaras Hindu University, Lovely Professional University, as well as several institutions in Pakistan and Malaysia, such as the University of the Punjab, University of Agriculture, and Universiti Putra Malaysia. This distribution indicates that research on *Trichoderma* is predominantly concentrated in Asia—particularly in China, India, and South Asia—reflecting the region's strong commitment to advancing biological control strategies for managing plant diseases.

Country of the authors

The bibliometric analysis reveals that India and China lead in both the number of publications and total citations related to the use of *Trichoderma* for controlling *Fusarium* wilt disease. However, when considering international collaboration, measured by total link strength, Saudi Arabia ranks highest (59), followed by Egypt (44), whereas India (36) and China (28) display comparatively lower values (Figure 3). These results suggest that, despite being centers of research productivity, India and China's publication activities are largely domestic or involve limited international partnerships.

Moreover, countries such as Egypt, Saudi Arabia, Pakistan, and several European nations, including Spain and Italy, make notable contributions through high citation counts, even though their overall publication volumes are lower (Table 3). The United States and Germany also participate in global collaboration networks, although their roles are comparatively smaller than those of Asian countries. Overall, this pattern highlights the dominance of Asia—particularly South and East Asia—in advancing *Trichoderma* research, while also reflecting the gradual expansion of international collaboration to include partners from Europe and North America.

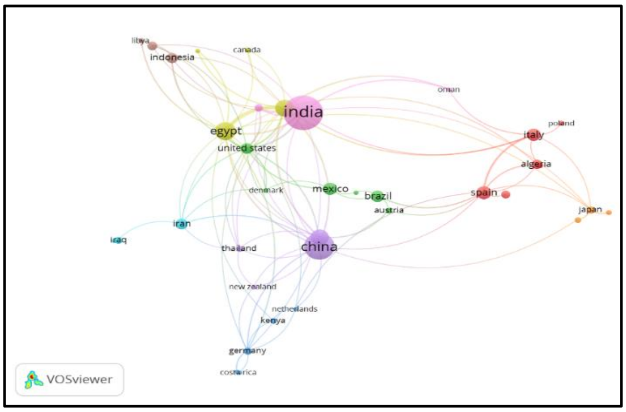

Figure 3. International collaboration map of research on Trichoderma in controlling Fusarium, visualized using VOSviewer.

These countries play a central role in advancing research on biological control, whereas contributions from other regions remain relatively limited or, in some cases, scarcely represented. These findings highlight that global research activity is still largely dominated by countries with strong research capacity. Consequently, expanding international collaboration offers significant potential to broaden the scope, enhance knowledge exchange, and promote a more equitable application of biological control strategies worldwide. Figure 4 illustrates the worldwide distribution of scientific contributions. Countries such as the China and India are highlighted in dark blue, reflecting substantial research output. Countries shown in light blue indicate moderate levels of contribution, while regions in gray represent areas with no recorded publications

Table 2. The top ten countries with the highest number of publications and link strength on *Trichoderma* research for controlling *Fusarium*

No	Country	Article	Citation	Link strength
1	Saudi arabia	36	535	59
2	Egypt	44	954	44
3	India	159	2200	36
4	China	96	1956	28
5	United state	17	305	24
6	Pakistan	35	586	19
7	Spain	23	832	15
8	Italy	20	514	14
9	Germany	8	157	12
10	South korea	8	72	11

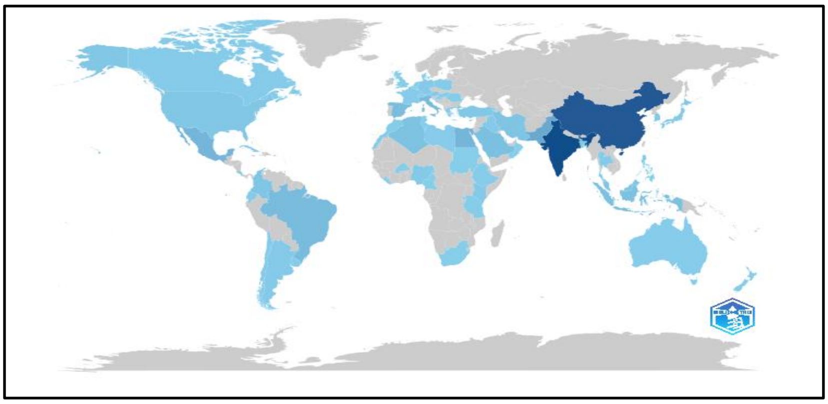

Figure 4. Geographical distribution of Corresponding Author's Countries on *Fusarium* control using *Trichoderma* by country

Co-occurrence networks and keyword clustering in *Fusarium* control research using *Trichoderma*

The bibliometric analysis demonstrates that research on *Trichoderma* as a biocontrol agent against *Fusarium* has evolved across diverse thematic approaches, which are visualized through network mapping using VOSviewer. The mapping divides scientific terms into four major interconnected clusters, each representing distinct yet overlapping research directions and focal areas within the field. Collectively, this bibliometric visualization offers a comprehensive overview of the research landscape, highlighting emerging themes and the most relevant journals for disseminating studies on *Trichoderma* and *Fusarium*. Accordingly, the choice of publication venue should be carefully aligned with the methodological framework, research depth, and intended scientific impact of the work.

The Role and Mechanisms of *Trichoderma* as a Biocontrol Agent against *Fusarium*

Trichoderma spp. is a group of soil fungi that has long been recognized as a biological control agent with great potential to enhance plant productivity and resistance. As a saprophytic microorganism that aggressively colonizes the rhizosphere, *Trichoderma* demonstrates a remarkable ability to interact with plant roots and stimulate growth through diverse biochemical mechanisms. For instance, *Trichoderma harzianum* AKH-5 can produce several plant-beneficial compounds, including indole-3-acetic acid (IAA), siderophores, ammonia, ACC deaminase, and hydrolytic enzymes (Hugar & Nayaka, 2025). milarly, *Trichoderma harzianum* T-A66 produces IAA, which promotes plant growth by stimulating root elongation and increasing overall biomass (Zhang *et al.*, 2020). Moreover, *Trichoderma pseudokoningii* has been shown to reduce the incidence of *Fusarium oxysporum* by 78.64% while simultaneously increasing cucumber yield by 33% (LI *et al.*, 2019).

In addition, *Trichoderma* is a genus of fungi widely recognized as a biological control agent against various plant pathogens, including *Fusarium* spp., the main cause of wilt and root rot in many horticultural and food crops. *Trichoderma harzianum* has been proven effective in controlling *Fusarium oxysporum* f. sp. *pisi*, where its filtrate metabolites (60%) are able to suppress the disease while enhancing growth, yield, and physiological as well as biochemical activities related to plant resistance (Rauf *et al.*, 2024). The mechanisms involved in enhancing plant resistance to *Fusarium* disease by *Trichodermsa* include mycoparasitism (Correa-Delgado *et al.*, 2024), Volative Organic Compound (VOCs) (Joo & Hussein, 2022), cell wall degrading enzymes (Kumari *et al.*, 2024), nutritient competiion (Cui *et al.*, 2025), and induced systemic resistance (Cao *et al.*, 2025). Furthermore, *Trichoderma harzianum* AUMC 14897 exhibits multiple antagonistic mechanisms, including nutrient and space competition, mycoparasitism, VOC release, antioxidant enzyme production, and regulation of stress-related gene expression in oat plants infected with F. oxysporum (Zawawy *et al.*, 2025).

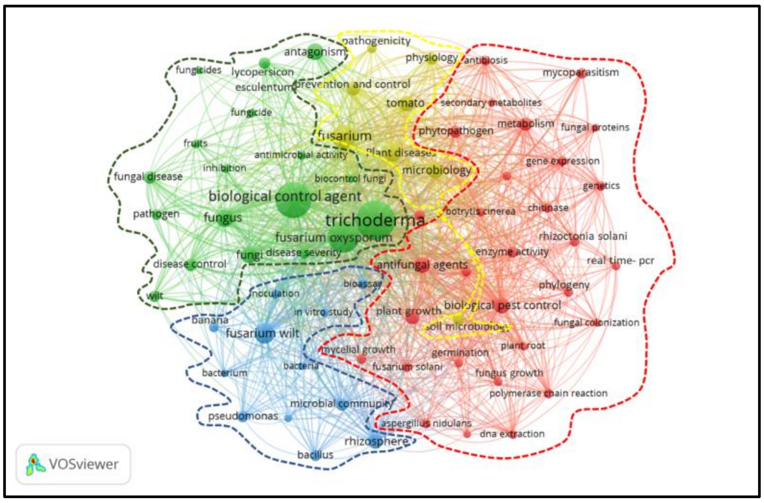

Figure 5. VOSviewer-Based Bibliometric Mapping of Author Keywords in Studies on *Trichoderma*-Mediated Control of *Fusarium*

Table 3. Analysis of keyword clusters in studies on *Trichoderma*-mediated control of *fusarium*

Cluster	Title	Keywords	Description
Green	Biological Control Agents for Plant Disease Suppression	*Trichoderma*, biological control agent, pathogen, *Fusarium oxysporum*, disease control, antagonism, inhibition, diseases severity	This cluster emphasizes the role of *Trichoderma* as a biological control agent in managing plant diseases. Research within this cluster highlights *Trichoderma* as a key antagonist against soil-borne pathogens, particularly *Fusarium*. The focus extends to practical applications, including inoculation methods, disease suppression in the field, and its potential as an alternative to chemical fungicides. This cluster therefore reflects a strong orientation toward evaluating the direct effectiveness of *Trichoderma* in plant disease management under applied agricultural conditions.
Red	Molecular Mechanisms and Enzyme-Based Antagonism	antifungal agents, biological pest control, Secondary metabolites, antibiosis, enzyme activity, gene expression, mycoparasitism, PCR, phylogeny	This cluster centers on the molecular and biochemical mechanisms underlying the antagonistic activity of *Trichoderma* against *Fusarium*. Research highlights the importance of hydrolytic enzymes such as chitinase, glucanase, and protease, which play a critical role in degrading fungal cell walls. In addition, secondary metabolites and antifungal proteins have been identified as key compounds that enhance the biocontrol potential of *Trichoderma*. Advanced molecular techniques, including real-time PCR and various omics approaches, are widely applied to investigate gene regulation, signaling pathways, and pathogen interactions. Recent trends point to the exploration of enzyme-encoding genes and secondary metabolite biosynthetic pathways as a foundation for breeding superior *Trichoderma* strains. A deeper understanding of these molecular mechanisms also provides essential support for the development of bioformulations with higher efficacy and consistent quality standards.
Blue	Rhizosphere Microbiome and Soil Microbiology	rhizosphere, microbial community, *Bacillus, Pseudomonas,* inoculation, bioassay, in vitro study	This cluster focuses on the interactions between Trichoderma and soil or rhizosphere microbial communities. Research in this area highlights how *Trichoderma* competes with, as well as synergizes alongside, beneficial bacteria such as *Bacillus* and *Pseudomonas* to improve soil health and promote root colonization. Traditional approaches, including in vitro assays and bioassays, are widely employed to evaluate the potential of these interactions. More recent studies increasingly utilize sequencing-based microbiome analyses to map shifts in microbial community composition following *Trichoderma* application. These findings are crucial for assessing the long-term ecological impacts of *Trichoderma*, particularly its role in sustaining soil microbial balance and enhancing agroecosystem resilience.

Table 4. *Continued*

Cluster	Title	Keywords	Description
Yellow	Applications of Trichoderma in Agricultural Systems	physiology, metabolism, microbiology, physiology, pathogenicity, prevention and control	This cluster represents research with a strong emphasis on applied science and plant ecology, characterized by dominant terms such as tomato, antagonism, disease suppression, and microbiology. Studies in this cluster focus on the direct application of *Trichoderma* within agricultural systems, particularly for the management of diseases in horticultural crops such as tomatoes. Research frequently involves field trials, the monitoring of disease symptoms, and the evaluation of plant growth parameters as key indicators of biocontrol success. In addition, classical microbiology and microbial ecology approaches are employed to examine the dynamics of rhizosphere microbial communities and to elucidate how *Trichoderma* interacts with other microorganisms in supporting plant health.

Table 5. The role and mechanism of *Trichoderma* in controlling *Fusarium*

Role	*Trichoderma* strain	Host	*Fusarium* species	Mechanism	Reference
Mycoparasitism	*T. harzianum*	chickpeas	*Fusarium oxysporum* f. sp. *Cicero*	The mycoparasitic mechanism of *Trichoderma* is characterized by the formation of spiral hyphae that entwine the pathogen, the development of appressoria, penetration through pores, and aggressive growth that leads to the degradation of host hyphae.	(Kumari *et al.*, 2025).
	T. atrovirde	Tomato	*F. oxysporum*	Scanning electron microscopy revealed the mycoparasitism of T. *atroviride* on *F. oxysporum* in dual culture, characterized by rapid hyphal coiling, the formation of appressorium-like structures on the pathogen surface, and subsequent lysis of *F. oxysporum* hyphae.	(Nofal *et al.*, 2021)
Induced systemic resistance	*T. asperellum M2RT4*	tomato	*Fusarium oxysporum* f. sp. lycopersici	*Trichoderma* can induce the expression of Pathogenesis-Related Protein-1 (TomPR1), β-1,3-glucanase (TomPR2), TomloxC, and SIWRKY4 genes, which play important roles in enhancing plant resistance to pathogen invasion, thereby improving both the quantity and quality of crop yields.	(Muhorakeye *et al.*, 2024)
	T. afroharzianum and *T. asperellum*	Pigeonpea	*F. udum*	Seed treatment with *Trichoderma* isolates has been shown to enhance the activity of defense enzymes, including peroxidase (173–244%), polyphenol oxidase (48–80%), and phenylalanine ammonia-lyase (147–178%), while reducing the incidence of *Fusarium* wilt by 78–85% in pea plants.	(Mishra *et al.*, 2023)
	T. asperellum	Castor	*F. oxysporum*	qPCR analysis revealed defense gene transcript reprogramming, while biochemical assays showed increased antioxidant enzyme activities (catalase, superoxide dismutase, and glutathione peroxidase) along with higher total phenol content.	(Pradhan *et al.*, 2023)
	T. asperellum + ascorbic acid	tomato	*Fusarium oxysporum* f. sp. *ly copersici*	*Trichoderma* enhances total phenol content, defense enzyme activities [phenylalanine ammonia-lyase (PAL), peroxidase (PO), chitinase (Chi), and polyphenol oxidase (PPO)], ROS (H_2O_2) accumulation, and the expression of defense-related genes [PAL, Chi, pathogenesis-related (PR) proteins, and lipoxygenase (Lox)]	(Singh *et al.*, 2020)
	T. harzianum	Cucumber	*F. oxysporum*	*T. harzianum* enhances the expression of cell cycle-related genes (CDKA, CDKB, CycA, CycB, CycD3;1, and CycD3;2). This mechanism contributes to maintaining low ROS accumulation and improving root cell viability in cucumber plants.	(Chen *et al.*, 2017)
Cell wall degrading enzymes	*T. harzianum*	Lentis	*Fusarium oxysporium* f. sp *lentis*	*Trichoderma* was found to produce two key cell wall-degrading enzymes, namely chitinase and β-1,3-glucanase.	(Javeria *et al.*, 2020)

Table 5. Continued

Role	*Trichoderma* strain	Host	*Fusarium* species	Mechanism	Reference
VOCs and antifungal	*T. koningiopsis*	Invitro	*Fusarium oxysporum*.	Volatile organic compounds (VOCs) produced by *T. koningiopsis* T-51 demonstrated strong growth-inhibitory effects against two plant pathogenic fungi and significantly reduced disease incidence in tomato fruits. A total of 24 compounds, including alkenes, alkanes, and esters, were identified in the VOCs of strain T-51.	(You *et al.*, 2022)
	Trichoderma harzianum	Invitro	*Fusarium oxysporum* f.sp. *cubense*	*Trichoderma* exhibited strong in vitro antagonistic activity against pathogens, with an inhibition rate of 76.9% after 10 days through direct confrontation and less than 40% after 7 days via volatile metabolites. In addition, UHPLC-ESI-MS/MS analysis identified seven low-molecular-weight phenolic compounds, including chrysophanol, fomarin, endocrocin, and trichophenol A.	(Hernández *et al.*, 2024)

Challenges and Future Prospects

Although *Trichoderma* has been proven effective in controlling *Fusarium* wilt through various mechanisms, its application in the field still faces several obstacles. First, the effectiveness of *Trichoderma* is strongly influenced by environmental factors such as temperature, humidity, soil pH, and interactions with native microbiota, often leading to inconsistent performance between laboratory, greenhouse, and field applications. Second, the genetic diversity within the *Fusarium* species complex poses an additional challenge, as different pathogenic strains may exhibit varying levels of susceptibility to *Trichoderma* antagonism. Third, the formulation and application technology of *Trichoderma*-based biopesticides require further development to ensure stability, viability, and shelf life. Moreover, regulations and policies regarding the registration of biocontrol products remain inconsistent across countries, limiting commercialization and broader adoption in the agricultural sector.

The use of *Trichoderma* in controlling *Fusarium* wilt holds highly promising prospects. Integrating *Trichoderma* with modern agricultural approaches—such as microbial consortia, omics technologies (genomics, transcriptomics, metabolomics), and nanotechnology—has the potential to enhance both the effectiveness and resilience of biocontrol strategies. The development of plant varieties that are responsive to *Trichoderma* colonization may further strengthen the synergy between host genetic resistance and biological control. Moreover, the global shift toward sustainable agriculture and the reduction of chemical fungicide use provide significant opportunities for *Trichoderma*-based products to become a key component of Integrated Diseases Management (IDM) systems.

Conclusion

This study confirms the growing scientific interest in *Trichoderma* as an innovative and sustainable strategy for controlling *Fusarium* wilt disease. A bibliometric analysis covering the period 2015–2025 shows a significant increase in publications, particularly since 2020, with India, China, and Egypt identified as the main contributors, along with a clear shift in research focus from basic mechanisms to practical field applications. These findings confirm the potential of *Trichoderma* as both a biocontrol agent and a plant growth promoter through multiple mechanisms, including mycoparasitism, antibiosis, competition, and the induction of systemic resistance, which have been demonstrated across a wide range of agricultural commodities. The main contribution of this review is the comprehensive mapping of global publication trends and existing knowledge gaps in research on *Trichoderma*-based control of *Fusarium.* However, widespread field adoption continues to face challenges related to strain performance variability, environmental influences, formulation limitations, and regulatory constraints. Therefore, future research should prioritize the standardization of evaluation methods, the implementation of multi-location field trials, the development of stable formulations, and the integration of multi-omics approaches to enhance application effectiveness and reliability. Overall, this study provides a strong scientific basis for guiding future research and supporting sustainable plant disease management policies.

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