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How Trichoderma Enhances Plant Defense Enzymes in Food Crops: Current Insights and Future Perspectives in Asia

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Abstract

Food crops are plants grown for consumption by humans and animals. These crops face threats from both abiotic and biotic factors. Therefore, environmentally friendly alternative controls, such as enhancing plant resistance using *Trichoderma* spp, are needed. This systematic review provides information on the effects of *Trichoderma* spp. application on plant physiology, particularly focusing on defense enzymes in food crops in the Asian region. Articles on the effects of *Trichoderma* application on food crop defense enzymes in Asia were retrieved from PubMed and Scopus. The literature search yielded 3,022 articles from these databases. Four criteria were established for study inclusion: i) studies involving *Trichoderma* spp.; ii) studies using food crops as the subject; iii) studies conducted in Asia; and iv) studies evaluating at least one defense enzyme activity. In this systematic review, we found at least 100 isolates of *Trichoderma* spp. that can increase plant resistance, as indicated by the increase of plant defense enzymes in Asia. The studies were mostly reported in India and China. Rice is the most frequently studied crop. The most frequently used is *T. harzianum*. Meanwhile, the defense enzymes tested are peroxidase, polyphenol oxidase, phenylalanine ammonia-lyase, chitinase, and β-1,3-glucanase. The most commonly used inoculation method is seed treatment in a controlled environment such as a greenhouse. More research on changes in plant enzymes due to *Trichoderma* spp. application is recommended to assess its effectiveness in practical, real-world settings, especially in field conditions.

Keywords: Food crops, induce systemic resistance, plant defense enzymes, *Trichoderma* spp.

Introduction

Food crops are plants that are grown for the purpose of consumption by humans and animals (Aly and Borik, 2023). The growth and production of food crops are the main focus today (Guleria et al., 2023). In 2021, food crops such as corn and rice occupy the second and third positions as the most produced agricultural commodities in the world after sugarcane (Statista, 2023). Threats to food crops are inseparable from abiotic factors (water shortages, soil pollution, and climate change) and Biotic factors (pest and disease attacks) (Guleria et al., 2023).

Nowadays, the most common control methods are using resistant varieties and pesticides. However, we cannot always rely on this method of control. This is because pests ınd diseases are dynamic, persistent, and nardy. Therefore, they will adapt more easily to climate change than food crops. Meanwhile, excessive use of pesticides in agricultural production has a negative impact on the environment. Pesticide resistance is a major problem that is increasing rapidly, making previously applied pesticides ineffective (Kaur and Chauhan, 2023). Therefore, environmentally friendly alternative controls are needed, such as increasing plant resistance using *Trichoderma* sp.

Trichoderma sp. is a beneficial microorganism that improves soil fertility and plant development. *Trichoderma* has a mutualistic endophytic relationship with various plant species, promotes host plant growth, protects against pathogen attack, and increases the absorption and efficient use of micro and macronutrients (Awad-Allah et al., 2023). Evidence of the success of *Trichoderma* spp. in improving plant quality due to abiotic and biotic stresses has been widely reported (Zaidi et al., 2014) (Gangwar and Singh, 2018). Most induction of plant resistance is only seen from how badly the plant is attacked by abiotic or biotic factors. Changes in plant physiological aspects as a result of *Trichoderma* spp. application is still limited, especially changes in plant defense enzyme activity.

This systematic literature review will provide information on the effect of *Trichoderma* sp. application on plant physiology, especially food crop defense enzymes in Asia. The findings emphasize that the increase in plant resistance due to the application of *Trichoderma* sp. can be known in plant physiology. This information is expected to provide new insights related to the induction of food crop resistance so that researchers can develop further studies on applying *Trichoderma* sp. to maximize its potential as an environmentally friendly biological control agent.

Methods

Database Sources

Articles reviewed on the effect of *Trichoderma* application on food crop defence enzymes in Asia were retrieved from online databases at 21 September 2024. PubMed and Scopus were used as the databases. The search was limited to English-language journal articles with publication dates between 2014 and 2024.

Search Term

The following search strings were utilized in the selection of relevant articles in the title, keywords, or abstract: ("Boost*" OR "Enhanc*" OR "Increas*" OR "Improv*" OR "Stimulat*" OR "Promot*") AND ("Plant* defens* enzyme*" OR" Plant* Enzyme*" OR "Enzyme*") AND ("Trichoderma*") AND ("Agricultural field*" OR "Field*" OR "Farmland*"). The literature search yielded 3022 records from Scopus and Pubmed, which were imported into Rayyan AI (http://rayyan.qcri.org) to manage and screen the data.

Screening and data extraction

The screening process removed duplicates, conference proceedings, reviews, book chapters, and editorial material. The remaining records were retrieved in full text and reviewed in detail. Screening was carried out against the inclusion/exclusion criteria. Four criteria were set for study inclusion: i) studies with *Trichoderma* spp.; ii) studies using food crops as an object; iii) studies conducted in Asia; and iv) studies evaluating at least one increasing enzymes defense activity (β-1,3-glucanase, Phenylalanine ammonia-lyase, Peroxidase, Chitinase, Chitosanase, and Polyphenol oxidase). Study

exclusion criteria were: i) studies not examine plant defense enzymes; ii) there is no interaction between *Trichoderma* spp. and food crop plants; iii) studies not written in English; iv) Introduction of *Trichoderma* spp. in combination with other microbes (unable to see the effects of *Trichoderma* directly). This systematic review followed the PRISMA statement and checklist guidelines for screening publications (Moher et al., 2009). A checklist for the systematic review is provided in Figure 1.

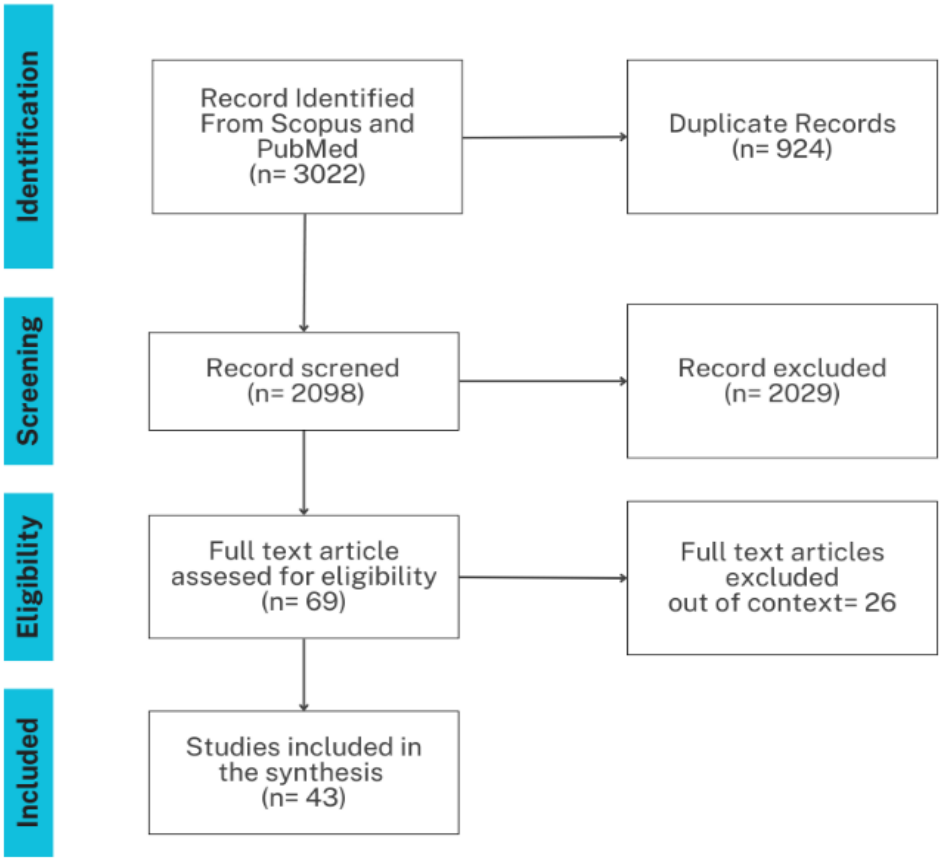


Figure 1. Preferred reporting items for systematic reviews and meta-analysis (PRISMA) diagram of systematic quantitative literature review selection process. Selection criteria are outlined under screening and data extraction represents the number of publications

Potentially relevant articles were downloaded and read in full. Information and data relevant to this review were extracted from eligible articles. The information included the Geographical distribution, the effect of *Trichoderma* sp. on plant defense enzymes, inoculation methods, and the study setting. The study settings used in each article were categorized into controlled and uncontrolled environments (e.g., greenhouse and field). All figures were constructed using Microsoft Excel 2021 and mapchart.net

Results

The geographical distribution of studies measuring the enhancement of defense enzyme activity in food crops using the biocontrol agent *Trichoderma* spp. in Asia reveals that India has conducted the most research on this topic, with a total of 26 studies. This is followed by China, Pakistan, Iraq, Iran, Thailand, and Malaysia (Figure 2). The most common inoculation method is seed treatment (Figure 3).



Figure 2. Geographical distribution of *Trichoderma* spp. application for enhancing food crops defense enzymes in Asia

A total of 100 isolates were identified across 43 reviewed articles. The most frequently used *Trichoderma* species was *T. harzianum*, appearing 43 times. Meanwhile, rice was the most commonly studied crop for enhanced defense enzyme activity. We also found that the defense enzymes tested were peroxidase, polyphenol oxidase, phenyl-alanine ammonia-lyase, chitinase, and β-1,3-glucanase (Table 1).

Table 1. *Trichoderma* species effect on plant defense enzyme

Trichoderma species	Plant species	Plant defense enzyme effected	References
T. harzianum T-14	Rice	Increasing 27.07 % POD activity than control	Datta et al., 2022
T. harzianum 94(A)		Increasing 23.29 % POD activity than control	
T. harzianum IRRI-2		Increasing 46.64 % POD activity than control	
T. asperellum OT-3		Increasing 27.30 % POD activity than control	
T. harzianum OT-8		Increasing 27.09 % POD activity than control	
T. harzianum	Chickpea	POD activities were significantly higher than the control	Javaid et al., 2021
T. viride		POD activities were significantly higher than the control	
T. asperellum	Maize	POD activities were significantly higher than the control treatment with meadow soil	Fu et al., 2017

Trichoderma species	Plant species	Plant defense enzyme effected	References
T. viride, *T. harzianum,* *T. harzianum* Th14, *T. harzianum* Th19, *T. harzianum* ThR, *T. asperellum* TUK42	Sorghum	POD, PPO, PAL activities were significantly higher than the control	Yadav et al., 2023
T. harzianum	Cowpea	Increasing activity of POD, PPO, and PAL than the control with 41%, 45%, and 39% respectively	Shoaib et al., 2018
T. viride		Increasing activity of POD, PPO, and PAL than the control with 15%, 30%, and 32% respectively	
T. longibrachiatum	Wheat	POD activities were significantly higher than the control	Zhang et al., 2016
T. erinaceum T51 *T. viride* T52	Bean	Significantly Increase activity of PAL after 24, 48, 96 hours after inoculation than the control	Kumar et al., 2024
T. afroharzianum IIPRTh-33	Pigeonpea	POD, PPO, PAL activities were significantly higher than the control	Mishra et al., 2023
T. asperellum IIPRTh-31		POD, PPO, PAL activities were significantly higher than the control	
T. harzianum IIPRTh-10		POD and PAL activities were significantly higher than the control	
T. harzianum IIPRTh-23		PAL activities were significantly higher than the control	
T. harzianum IIPRTh-12		PAL activities were significantly higher than the control	
T. asperellum IIPRTas-9		POD and PAL activities were significantly higher than the control	
T. asperellum IIPRTas-15		POD and PAL activities were significantly higher than the control	
T. asperellum IIPRTas-12		PAL activities were significantly higher than the control	
T. harzianum IIPRTh-38		POD and PAL activities were significantly higher than the control	
T. harzianum IIPRTh-22		PAL activities were significantly higher than the control	
T. asperellum IIPRTas-13		POD and PAL activities were significantly higher than the control	
T. harzianum IIPRTh-3		POD and PAL activities were significantly higher than the control	
T. longibrachiatum IIPRTg-3		PAL activities were significantly higher than the control	
T. asperellum IIPRTas-1		POD and PAL activities were significantly higher than the control	
T. harzianum IIPRTh-39		POD and PAL activities were significantly higher than the control	

Trichoderma species	Plant species	Plant defense enzyme effected	References
T. asperellum T4	Great millet	POD and PPO activities were significantly higher than the control	Manzar et al., 2021
T. harzianum T6		POD and PPO activities were significantly higher than the control	
T. asperellum T19		POD activities were significantly higher than the control	
T. asperellum T15		PPO activities were significantly higher than the control	
T. harzianum THU0816 ARS	Bean	POD, PPO, PAL activities were significantly higher than the control	Ram et al., 2015
T. erinaceum	Rice	PPO activities were significantly higher than the control	Shasmita et al., 2019
T. harzianum FCBP-SF-1277	Pea	POD activities were significantly higher with all metabolite concentrations (40, 50, 60%) than the control	Rauf et al., 2024
T. longibrachiatum	Wheat	POD, PPO, PAL activities were significantly higher than the control	Zhang et al., 2014
T. viride *T. harzianum* *T. harzianum* Th14, *T. harzianum* Th19, *T. harzianum* ThR, *T. asperellum* TUK42	Sorghum	POD, PPO, PAL activities were significantly higher than the control	Yadav et al., 2023
T. hamatum UoM 13	Pearl Millet	POD, PPO, PAL, and β -1,3-glucanase activities were significantly higher than the Untreated Plant	Siddaiah et al., 2017
T. harzianum	Broad bean	PAL activities were significantly higher than the control	Al-Ameri, 2023
T. viride BHU-2953	soybean	*T. viride* BHU-2953 with addition of recommendation of fertilizer was significantly increasing the activity of POD enzymes than the control	Paul and Rakshit, 2022
T. harzianum IIPRTh-3	Pigeonpea	POD and PAL activities were significantly higher than the control	Mishra et al., 2024
T. aureoviride FCB 691	Mungbean	Soil application with *T. aureoviride* + biomass of *Coronopus didymus* and inoculated wih *Macrophomina* phaseolina can increased POD, PPO, and PAL significantly than the control	Javaid et al., 2018
T. viride	Potato	POD activities were significantly higher than the control after 72 and 96 hours after pathogen inoculation PPO activities were significantly higher than the control after 48, 72, and 96 hours after pathogen inoculation PAL activities were significantly higher than	Kumar et al., 2023

Trichoderma species	Plant species	Plant defense enzyme effected	References
		the control after 48, 72, and 96 hours after pathogen inoculation	
T. asperellum T42	Rice	POD and PAL activities were significantly higher than the Untreated Plant in Drough or Non-Drought conditions	Singh et al., 2020
T. paraviridescens	Rice	PPO activities were significantly higher than the Untreated Plant	Islam et al., 2023
T. erinaceum		PPO activities were significantly higher than the Untreated Plant	
T. asperellum		PPO and POD activities were significantly higher than the Untreated Plant	
T. harzianum CRRI-T1 *T. erinaceum* CRRI-T2 *T. atroviride* CRRI-T3 *T. atroviride* CRRI-T5 *T. atroviride* CRRI-T9 *T. atroviride* CRRI-T13	rice	PPO activities were significantly higher in shoot and root than the Untreated Plant	Swain et al., 2018
T. harzianum Th9	Potato	Chitinase and β -1,3-glucanase activities were significantly higher than the control	Singh et al., 2020
T. harzianum UPMT1	Rice	POD, PPO, and PAL activities were significantly higher in shoot and root than the Untreated Plant	Ng et al., 2015
T. virens UPMT2		POD, PPO, and PAL activities were significantly higher in shoot and root than the Untreated Plant	
T. harzianum	Maize	PPO activities were significantly higher than the untreated plant	Afrouz et al., 2023
T. harzianum 56 *T. harzianum* 69 *T. harzianum* 75 *T. harzianum* 82 *T. harzianum* 89	Wheat	PAL activities were significantly higher than the untreated plant after 13 days treated with drought stress	Shukla et al., 2014
T. harzianum CRRI-T1 *T. erinaceum* CRRI-T2 *T. artroviride* CRRI-T3 *T. hebeiensis* CRRI-T15 *T. parareesei* CRRI-T16 *T. longibrachiatum* CRRI-T22 *T. reesei* CRRI-T27	Rice	POD and PPO activities were significantly higher than the control	Swain et al., 2021
T. harzianum *T. viride*	Rice	POD activities were significantly higher than the control	Ghosh, 2017
T. asperellum GDFS1009	Maize	POD and PPO activities were significantly higher than the control 0 and 72 hours after inoculation	Batool et al., 2020

Trichoderma species	Plant species	Plant defense enzyme effected	References
T. harzianum	Pea	PAL activities were significantly higher than the control when measured 24 & 48 hours after inoculation PPO activities were significantly higher than the control when measured 96 hours after inoculation POD activities were significantly higher than the control when measured 24 hours after inoculation	Pandey et al., 2021
T. hamatum UoM 13	Pearl Millet	POD, PPO, PAL and β -1,3-glucanase activities were significantly higher than the control	Lavanya et al., 2017
T. harzianum	Wheat	POD activities were significantly higher than the control	Younis et al., 2022
T. artroviride	Pearl Millet	POD activities were significantly higher than the control	Nandini et al., 2017
T. asperellum T42	Pea	PAL activities were significantly higher than the control	Patel et al., 2017
T. asperelloides PSU-P1	Rice	POD activities in shoots and roots plant treated with *T. asperelloides* were significantly higher than the control PAL activities in roots plant treated with *T. asperelloides* were significantly higher than the control	Wonglom et al., 2024
T. harzianum UBSTH-501	Wheat	POD and PAL activities were significantly higher than the control	Singh et al., 2019
T. harzianum T891	kidney bean	POD activities were significantly higher than the control	Guo et al., 2024
T. longibrachiatum TG1	Wheat	POD and PAL activities were significantly higher than the control	Boamah et al., 2021
T. longibrachiatum TG1	Wheat	POD and PAL activities were significantly higher than the control	Boamah et al., 2022
Trichoderma CRRIT-5	Rice	POD activities in roots were significantly higher than the control	Sarangi et al., 2021
Trichoderma CRRIT-13		POD activities in shoots and roots were significantly higher than the control	
Trichoderma NRRIT-26		POD activities in shoots and roots were significantly higher than the control	
Trichoderma NRRIT-27		POD activities in shoots and roots were significantly higher than the control	
T. viride	Potato	PAL activities were significantly higher than the control after 0, 24, 48, and 72 hours after pathogen inoculation β -1,3-glucanase activities were significantly higher than the control after 24, 48, and 72 hours after pathogen inoculation	Kumar et al., 2021
T. harzianum		PAL activities were significantly higher than the control after 0, 24, 48, and 72 hours after	

Trichoderma species	Plant species	Plant defense enzyme effected	References
		pathogen inoculation β -1,3-glucanase activities were significantly higher than the control after 0, 24, 48, and 72 hours after pathogen inoculation	
T. reesei	Rice	PPO and PAL activities in shoots and roots were significantly higher than the control	Singh et al., 2019

Note: POD= Peroxidase, PAL= Phenylalanine ammonia lyase, and PPO= Polyphenol oxidase

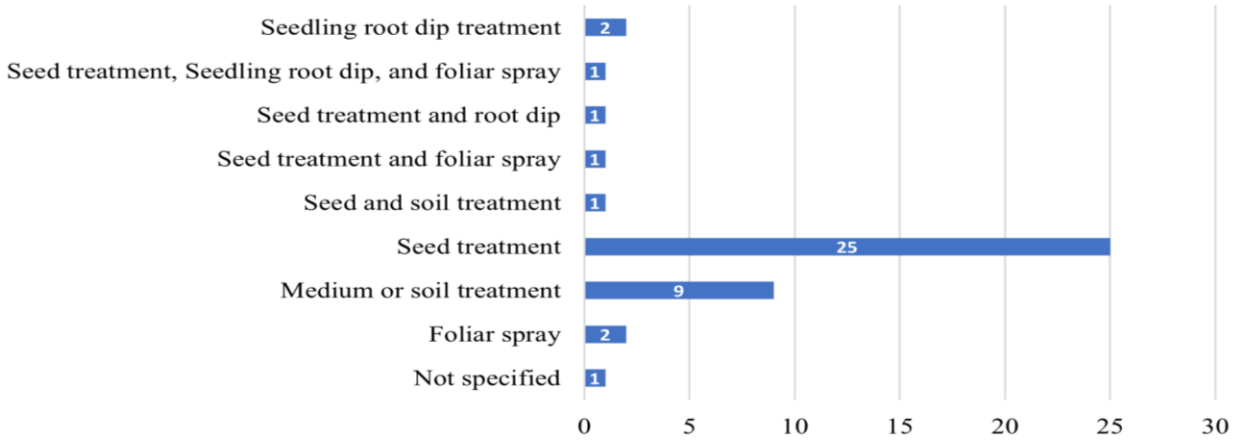


Figure 3. Inoculation methods of *Trichoderma* spp.

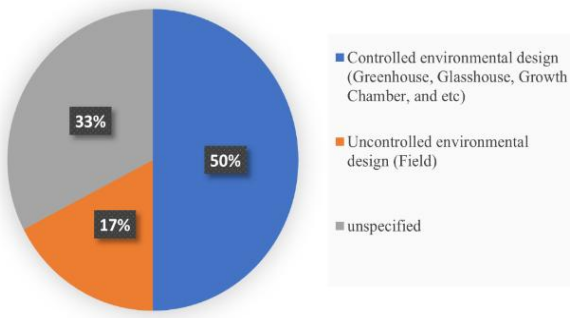


Figure 4. Study setting of *Trichoderma* spp. affecting plant defense enzyme

Discussion

Studies measuring the increase of defense enzyme activity in Asian food crops using *Trichoderma* spp. have been mostly reported in India and China (Figure 2). This is closely related to their superior research capabilities compared to other Asian countries. According to Scimago (2024), data on scientific publications in 2023 show that India and China rank among the top three countries with the highest number of scientific publications worldwide.

Rice is the most frequently studied crop (Table 1). This is linked to the cultural habits of India and China, where rice is a staple food. In 2023–2024, China and India were the largest consumers of rice globally (Statista, 2024). Rice is the most researched commodity and as approximately 90% of global rice production and consumption happens in Asia (Bandumula, 2017).

The most frequently used *Trichoderma* species was *T. harzianum*, appearing 43 times. Meanwhile, defense enzymes tested were peroxidase, polyphenol oxidase, phenylalanine ammonia-lyase, chitinase, and β-1,3-glucanase (Table 1). Plant induced resistance is linked to these defense enzymes. Every plant defence enzyme has its own mechanism for enhancing resistance. For example, the enzyme peroxidase. Pathogen or biocontrol agent infection in host plant tissues stimulates peroxidases, a well-known class of PR

proteins. They are able to limit the cellular spread of infection by forming structural barriers or by creating highly toxic environments by massive ROS and RNS generation (Appu et al., 2021).

There is a strong correlation between increased plant defense enzyme activity due to *Trichoderma spp.* application (Kumar et al., 2023; Gashash et al., 2023). *Trichoderma* spp. increases plant defence enzymes with its ability to be symbiotic with plants. *Trichoderma* spp. acts as an elicitor that can make plants respond to the stimulus given to them, thus this *Trichoderma* treatment enhances plant defence enzymes that will lead to the formation of jasmonic acid, salicylic acid and other defence metabolites such as phenol, lignin, phytoalexins, and others. Therefore, the plants are more resistant if there is infection from pathogens afterwards (Islam et al., 2023) (Yao et al., 2023).

The most common inoculation method is seed treatment (Figure 3). The method plays a vital role in its effectiveness in influencing plant resistance. It also considers factors such as the type of biocontrol agent, the pathogen, and the specific plant species studied (Lavanya et al., 2017). It is regarded as easier compared to other methods like root soaking or inoculation in the growing medium (Kumar et al., 2014). This suggests that treating seeds with *Trichoderma* spp. can enhance plant resistance, evidenced by increased plant defense enzyme activity. Therefore, for future applications of *Trichoderma* sp. it is highly recommended to apply it to seeds.

Most studies have been conducted in controlled environments such as greenhouse (Figure 4). The place where research is conducted also plays a crucial role in the outcome of the research. Research conducted in a controlled environment tends to provide better results than research in an uncontrolled environment. In addition, data bias is also more common in studies in uncontrolled environments than in controlled environments (Kandi and Vadakedath, 2023). However, research on uncontrolled environments in agriculture must still be conducted by following proper research principles in order to provide many benefits to farmers who generally carry out agricultural practices in the field (Dechassa et al., 2022).

Conclusion

In this systematic review, we found at least 100 isolates of *Trichoderma* spp. that can increase plant resistance, as indicated by the increase of plant defense enzymes in Asia. The studies were mostly reported in India and China. Rice is the most frequently studied crop. The most frequently used is *T. harzianum*. Meanwhile, the defense enzymes tested are peroxidase, polyphenol oxidase, phenylalanine ammonia-lyase, chitinase, and β-1,3-glucanase. The most commonly used inoculation method is seed treatment in a controlled environment such as a greenhouse. More research on changes in plant enzymes due to *Trichoderma* spp. application is recommended to assess its effectiveness in practical, real-world settings, especially in field conditions.

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Declaration

Author contribution

Hasan Albana is the main contributor for this paper. Nurbailis is corresponding

author and Darnetty is co-author. All authors read and approved the final paper.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Afrouz M, RZ Sayyed, B Fazeli-Nasab, R Piri, W Almalki, BN Fitriatin. 2023. Seed bio-priming with beneficial *Trichoderma harzianum* alleviates cold stress in maize. PeerJ 11: e15644. DOI: 10.7717/peerj.15644

Al-Ameri HA. 2023. Estimation of phenyl alanine ammonialyase (PAL) and some phytoalexins in *Vicia faba* plants infected with spot disease caused by *Alternaria alternata*. Journal of Applied Natural Science 15(4): 1499-1504. DOI. 10.31018/jans.v15i4.4811

Aly AA, ZM Borik. 2023. Food crops, growth and productivity as an important focus for sustainable agriculture. In: Plant Small RNA in Food Crops. Academic Press. London. DOI: 10.1016/B978-0-323-91722-3.00006-3

Appu M, P Ramalingam, A Sathiyanarayanan, J Huang. 2021. An overview of plant defense-related enzymes responses to biotic stresses. Plant Gene 27: 100302. DOI: 10.1016/j.plgene.2021.100302

Awad-Allah EF, AH Shams, AA Helaly, and EI Ragheb. 2022. Effective applications of *Trichoderma* spp. as biofertilizers and biocontrol agents mitigate tomato Fusarium wilt disease. Agriculture 12 (11): 1950. DOI: 10.3390/agriculture12111950

Bandumula N. 2018. Rice production in Asia: Key to global food security. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences 1323-1328. DOI: 10.1007/s40011-017-0867-7

Batool R, MJ Umer, Y Wang, K He, T Zhang, S Bai, Z Wang. 2020. Synergistic effect of Beauveria bassiana and *Trichoderma asperellum* to induce maize (*Zea mays* L.) defense against the Asian corn borer, *Ostrinia furnacalis* (Lepidoptera, Crambidae) and larval immune response. International Journal of Molecular Sciences 21(21): 8215. DOI: 10.3390/ijms21218215

Boamah S, S Zhang, B Xu, T Li, A Calderón-Urrea. 2021. *Trichoderma longibrachiatum* (TG1) enhances wheat seedlings tolerance to salt stress and resistance to Fusarium pseudograminearum. Frontiers in Plant Science 12: 741231. DOI: 10.3389/fpls.2021.741231

Boamah S, S Zhang, B Xu, T Li, A Calderón-Urrea, RJ Tiika. 2022. *Trichoderma longibrachiatum* TG1 increases endogenous salicylic acid content and antioxidants activity in wheat seedlings under salinity stress. PeerJ 10: e12923. DOI: 10.7717/peerj.12923

Datta D, AK Senapati, L Behera, NW Zaidi, S Kumar, P Dey. 2023. Alleviating drought stress in rice plant through intervention of *Trichoderma* spp. Journal of Environmental Biology 44(3): 373-379. DOI: 10.22438/jeb/44/3/MRN-4084

Dechassa N, N Keneni, S Bediye, G Alemayehu. 2022. Research methods: A Handbook for Agricultural Researchers. Ethiopian Institute of Agricultural Research. Addis Ababa. Ethiopia.

Eman AA, IA Mohamed, SF Allah, AH Shams, IH Elsokkary. 2023. *Trichoderma* species: An overview of current status and potential applications for sustainable agriculture. Indian Journal of Agricultural Research 57(3): 273-282. DOI: 10.18805/IJARe.AF-751

Fu J, Z Liu, Z Li, Y Wang, K Yang. 2017. Alleviation of the effects of saline-alkaline stress on maize seedlings by regulation of active oxygen metabolism by *Trichoderma*

asperellum. PLoS One 12(6): e0179617. DOI: 10.1371/journal.pone.0179617

Gangwar OP and AP Singh. 2018. *Trichoderma* as an efficacious bioagent for combating biotic and abiotic stresses of wheat—A review. Agricultural review 39(1): 48-54. DOI: 10.18805/ag.R-1770

Gashash EA, SA El-Sayed, WM Kamel, EA Sarhan. 2023. Evaluation of the potential of native *Trichoderma* spp. against root-rot diseases of soybean. Archives of Phytopathology and Plant Protection 56(16): 1282-1299. DOI: 10.1080/03235408.2023.2279943

Ghosh SK. 2017. Study of effects of antagonistic soil microbes on rice early stand establishment, prevention of seedling mortality and induction of peroxidase and catalase enzymes. In: Plant Cell Biotechnology and Molecular Biology. Society for Biology and Biotechnology. India

Guleria P, V Kumar. 2023. Plant small RNA in food crops. Elsevier. London. DOI: 10.1016/B978-0-323-91722-3.00006-3

Guo Z, J Zhang, Z Liu, Y Li, M Li, Q Meng, M Yan. 2024. *Trichoderma harzianum* prevents red kidney bean root rot by increasing plant antioxidant enzyme activity and regulating the rhizosphere microbial community. Frontiers in Microbiology 15: 1348680. DOI: 10.3389/fmicb.2024.1348680

Islam MR, R Chowdhury, AS Roy, MN Islam, MM Mita, S Bashar, MA Latif. 2023. Native *Trichoderma* induced the defense-related enzymes and genes in rice against *Xanthomonas oryzae* pv. *oryzae* (Xoo). Plants 12(9): 1864. DOI: 10.3390/plants12091864

Javaid A, A Ali, A Shoaib, and IH Khan. 2021. Alleviating stress of Sclerotium rolfsii on growth of chickpea var. Bhakkar-2011 by *Trichoderma harzianum* and *T. viride*. JAPS: Journal of Animal and Plant Sciences 31(6): 1755-1761. DOI: 10.36899/JAPS.2021.6.0378

Javaid A, IH Khan, A Shoaib. 2018. Management of charcoal rot of mungbean by two *Trichoderma* species and dry biomass of *Coronopus didymus*. Planta Daninha 36: e018182795. DOI: 10.1590/s0100-83582018360100124

Kandi V, S Vadakedath. 2023. Clinical trials and clinical research: a comprehensive review. Cureus 15(2): e35077 DOI: 10.7759/cureus.35077

Kaur S, BS Chauhan. 2023. Challenges and opportunities to sustainable crop production. In: P Guleria and V Kumar (eds). Plant Small RNA in Food Crops. Elsevier. DOI: 10.1016/B978-0-323-91722-3.00006-3

Kumar S, R Chandra, L Behera, C Keswani, E Sansinenea. 2022. Dual *Trichoderma* consortium mediated elevation of systemic defense response against early blight in potato. European Journal of Plant Pathology: 1-16. DOI: 10.1007/s10658-021-02431-4

Kumar S, R Chandra, L Behera, I Sudhir, M Meena, S Singh, C Keswani. 2023. Microbial consortium mediated acceleration of the defense response in potato against *Alternaria solani* through prodigious inflation in phenylpropanoid derivatives and redox homeostasis. Heliyon 9(11): e22148. DOI: 10.1016/j.heliyon.2023.e22148

Kumar S, V Shukla, YN Tripathi, M Aamir, K Divyanshu, M Yadav, RS Upadhyay. 2024. Biochemical changes, antioxidative profile, and efficacy of the bio-stimulant in plant defense response against *Sclerotinia sclerotiorum* in common bean (*Phaseolus vulgaris* L.). Heliyon 10(1): e23030. DOI: 10.1016/j.heliyon.2023.e23030

Kumar S, M Thakur, A Rani. 2014. *Trichoderma*: Mass production, formulation, quality control, delivery and its scope in commercialization in India for the management of plant diseases. African Journal of Agricultural Research 9(53): 3838-3852. DOI: 10.5897/AJAR2014.%209061

Lavanya SN, S Niranjan-Raj, SC Nayaka, KN Amruthesh. 2017. Systemic protection against pearl millet downy mildew disease induced by cell wall glucan elicitors from

Trichoderma hamatum UOM 13. Journal of Plant Protection Research 57(3): 1-13. DOI: 10.1515/jppr-2017-0042

Manzar N, Y Singh, AS Kashyap, PK Sahu, MVS Rajawat, A Bhowmik, AK Saxena. 2021. Biocontrol potential of native *Trichoderma* spp. against anthracnose of great millet (*Sorghum bicolour* L.) from Tarai and hill regions of India. Biological Control 152: 104474. DOI: 10.1016/j.biocontrol.2020.104474

Mishra RK, S Pandey, KK Hazra, M Mishra, SS Naik, A Bohra, and NP Singh. 2023. Biocontrol efficacy and induced defense mechanisms of indigenous *Trichoderma* strains against Fusarium wilt [F. udum (Butler)] in pigeonpea. Physiological and Molecular Plant Pathology 127: 102122. DOI: 10.1016/j.pmpp.2023.102122

Mishra RK, S Pandey, M Mishra, U Singh Rathore, B Singh. 2024. Identification and characterization of high salinity tolerant *Trichoderma* harzianum strain, IIPRTh-3 for mitigating salt stress, wilt incidence and promoting plant growth in pigeonpea. Archives of Phytopathology and Plant Protection 57(9): 691-704. DOI: 10.1080/03235408.2024.2390212

Moher D, A Liberati, J Tetzlaff, DG Altman. 2009. Preferred reporting items for systematic reviews and meta-analyses: The Prisma statement. PLoS Medicine 6(7): e1000097. DOI: 10.1371/journal.pmed.1000097

Nandini B, P Hariprasad, HN Shankara, HS Prakash, N Geetha. 2017. Total crude protein extract of *Trichoderma* spp. induces systemic resistance in pearl millet against the downy mildew pathogen. 3 Biotech 7: 1-10. DOI: 10.1007/s13205-017-0816-4

Ng LC, M Sariah, O Sariam, O Radziah, MA Zainal Abidin. 2016. PGPM-induced defense-related enzymes in aerobic rice against rice leaf blast caused by *Pyricularia oryzae*. European Journal of Plant Pathology 145: 167-175. DOI: 10.1007/s10658-015-0826-1

Pandey P, KP Kushwaha, V Upadhyay, J Purohit. 2024. Synergistic effect of plant defense elicitors and biocontrol agents on induction of defense enzymes in pea against downy mildew. Indian Journal of Agricultural Research 58(1):1-14. DOI: 10.18805/IJARe.A-5798

Patel JS, RN Kharwar, HB Singh, RS Upadhyay, BK Sarma. 2017. *Trichoderma* asperellum (T42) and Pseudomonas fluorescens (OKC)-enhances resistance of pea against Erysiphe pisi through enhanced ROS generation and lignifications. Frontiers in Microbiology 8: 306. DOI: 10.3389/fmicb.2017.00306

Paul S, A Rakshit. 2022. Evaluating lignification, antioxidative defense, and physiochemical changes in soybean through bio-priming under graded soil fertilization. Journal of Soil Science and Plant Nutrition 22(2): 2295-2306. DOI: 10.1007/s42729-022-00809-9

Ram RM, AJ Akansha Jain, AS Akanksha Singh, HB Singh. 2015. Biological management of Sclerotinia rot of bean through enhanced host defense responses triggered by Pseudomonas and *Trichoderma* species. Journal of Pure and Applied Microbiology 9(1):523-532. https://microbiologyjournal.org/

Rauf A, MN Subhani, M Siddique, H Shahid, MB Chattha, AF Alrefaei, RS Lucas. 2024. Cultivating a greener future: Exploiting *Trichoderma* derived secondary metabolites for fusarium wilt management in peas. Heliyon 10(7): e29031. DOI: 10.1016/j.heliyon.2024.e29031

Sarangi S, H Swain, T Adak, P Bhattacharyya, AK Mukherjee, G Kumar, and ST Mehetre. 2021. *Trichoderma*-mediated rice straw compost promotes plant growth and imparts stress tolerance. Environmental Science and Pollution Research 28: 44014-44027. DOI: 10.1007/s11356-021-13701-3.

Scimagojr, 2024. Scimago Journal and Country Rank.https://www.scimagojr.com/countryrank.php?year=2023

Shasmita, H Swain, SK Naik, AK Mukherjee. 2019. Comparative analysis of different biotic and abiotic agents for growth promotion in rice (*Oryza sativa* L.) and their effect on induction of resistance against *Rhizoctonia solani*: a soil borne pathogen. Biological

Control 133: 123-133. DOI: 10.1016/j.biocontrol.2019.02.013

Shoaib A, M Munir, A Javaid, ZA Awan, M Rafiq. 2018. Anti-mycotic potential of *Trichoderma* spp. and leaf biomass of Azadirachta indica against the charcoal rot pathogen, *Macrophomina phaseolina* (Tassi) Goid in cowpea. Egyptian Journal of Biological Pest Control 28: 1-7. DOI: 10.1186/s41938-018-0031-6

Shukla N, RP Awasthi, L Rawat, J Kumar. 2015. Seed biopriming with drought tolerant isolates of *Trichoderma harzianum* promotes growth and drought tolerance in *Triticum aestivum*. Annals of Applied Biology 166(2): 171-182. DOI: 10.1111/aab.12160

Siddaiah CN, NR Satyanarayana, V Mudili, VK Gupta, S Gurunathan, S Rangappa, RK Srivastava. 2017. Elicitation of resistance and associated defense responses in *Trichoderma hamatum* induced protection against pearl millet downy mildew pathogen. Scientific Reports 7(1): 43991. DOI: 10.1038/srep43991

Singh DP, V Singh, VK Gupta, R Shukla, R Prabha, BK Sarma, JS Patel. 2020. Microbial inoculation in rice regulates antioxidative reactions and defense-related genes to mitigate drought stress. Scientific Reports 10(1): 4818. DOI: https://www.nature.com/articles/s41598-020-61140-w

Singh N, A Singh, P Dahiya. 2020. Performance of potent isolate of *Trichoderma harzianum* (Th9) possessing mycoparasitic property against late blight-causing fungus *Phytophthora infestans* in addition to enhancing defensive enzymes activities in potato crop. Indian Journal of Agricultural Biochemistry 33(1): 99-101. DOI: 10.5958/0974-4479.2020.00016.7

Singh SP, S Pandey, N Mishra, VP Giri, S Mahfooz, A Bhattacharya, A Mishra. 2019. Supplementation of *Trichoderma* improves the alteration of nutrient allocation and transporter gene expression in rice under nutrient deficiencies. Plant Physiology and Biochemistry 143: 351-363. DOI: 10.1016/j.plaphy.2019.09.015

Singh UB, D Malviya, S Singh, M Kumar, PK Sahu, HV Singh, AK Saxena. 2019. *Trichoderma harzianum* and methyl jasmonate-induced resistance to Bipolaris sorokiniana through enhanced phenylpropanoid activities in bread wheat (*Triticum aestivum* L.). Frontiers in Microbiology 10: 1697. DOI: 10.3389/fmicb.2019.01697

Statista, 2024. Rice consumption worldwide in 2023/2024, by country (in 1,000 metric tons).https://www.statista.com/statistics/255971/top-countries-based-on-rice-consumption-2012-2013/

Statista. 2023. Production volume of the most produced food commodities worldwide in 2021, by product. https://www.statista.com/statistics/1003455/most-produced-crops-and-livestock-products-worldwide/

Swain H, T Adak, AK Mukherjee, PK Mukherjee, P Bhattacharyya, S Behera, M Jena. 2018. Novel *Trichoderma* strains isolated from tree barks as potential biocontrol agents and biofertilizers for direct seeded rice. Microbiological Research 214: 83-90. DOI: 10.1016/j.micres.2018.05.015

Swain H, T Adak, AK Mukherjee, S Sarangi, P Samal, A Khandual, NW Zaidi. 2021. Seed biopriming with *Trichoderma* strains isolated from tree bark improves plant growth, antioxidative defense system in rice and enhances straw degradation capacity. Frontiers in Microbiology 12: 633881. DOI: 10.3389/fmicb.2021.633881

Wonglom P, OU Ruangwong, W Poncheewin, S Arikit, K Riangwong, A Sunpapao. 2024. *Trichoderma*-bioenriched vermicompost induces defense response and promotes plant growth in Thai rice variety “Chor Khing”. Journal of Fungi 10(8): 582. DOI: 10.3390/jof10080582

Yadav SS, A Arya, V Singh, Y Singh. 2023. Elicitation of native bioprotective microbial agents associated systemic defense responses and plant growth promotion against bacterial stalk rot pathogen in sorghum (Sorghum

bicolor). Phytopathology Research 5(1): 47. DOI: 10.1186/s42483-023-00202-z

Yadav SS, A Arya, G Tondon, Y Singh. 2023. Antagonistic microbes mediated modulation of systemic resistance and defense related responses against *Dickeya dadantii* causing bacterial stalk rot in *Sorghum bicolor*. European Journal of Plant Pathology 167(4): 833-851. DOI: 10.1007/s10658-023-02769-x

Yao X, H Guo, K Zhang, M Zhao, J Ruan, J Chen. 2023. *Trichoderma* and its role in biological control of plant fungal and nematode disease. Frontiers in microbiology 14: 1160551. 10.3389/fmicb.2023.1160551

Younis HS, RM Abdullah, SA Hasan, AA Abdul-Sattar. 2022. Systemic resistance indicators study and seed gall nematode disease caused by *Anguina tritici* affecting of biological and varietal treatments on bread wheat (*Triticum aestivum* L.). International Journal of Agricultural Statistical Science 18(1): 289-296. DOI:

Zaidi NW, MH Dar, S Singh, US Singh. 2014. *Trichoderma* species as abiotic stress relievers in plants. in: Mukherjee PK, Babu S, Singh US, and Das SK (eds). Biotechnology and Biology of *Trichoderma*. Elsevier. Amsterdam.

Zhang S, Y Gan, B Xu. 2014. Efficacy of *Trichoderma longibrachiatum* in the control of *Heterodera avenae*. BioControl 59: 319-331. DOI. 10.1007/s10526-014-9566-y.

Zhang S, Y Gan, B Xu. 2016. Application of plant-growth-promoting fungi *Trichoderma longibrachiatum* T6 enhances tolerance of wheat to salt stress through improvement of antioxidative defense system and gene expression. Frontiers in Plant Science 7: 1405. DOI: 10.3389/fpls.2016.01405

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