

ROLE OF TRICHODERMA HARZIANUM AND TRICHODERMA VIRIDE AS ECO-FRIENDLY BIOPESTICIDES IN SUSTAINABLE AGRICULTURE

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ABSTRACT

The increasing dependence on synthetic pesticides in modern agriculture has raised concerns regarding environmental contamination, pesticide resistance, disruption of beneficial soil microorganisms, and long-term soil health. In this context, biological control using beneficial microorganisms has gained considerable attention as a more sustainable approach to crop protection. The present review critically examines the potential of Trichoderma harzianum and Trichoderma viride as eco-friendly biopesticides in sustainable agriculture. The reviewed literature indicates that these fungi can suppress a wide range of plant pathogens through several complementary mechanisms, including competition for nutrients and space, mycoparasitism, production of hydrolytic enzymes and secondary metabolites, and stimulation of plant defence responses. Their benefits may extend beyond disease suppression, as suitable strains can contribute to root development, nutrient acquisition, plant growth, and tolerance to environmental stresses. However, their effectiveness is influenced by strain characteristics, crop type, soil properties, climatic conditions, pathogen pressure, formulation quality, and application methods. Therefore, these fungi should not be regarded as universal replacements for synthetic pesticides but as important components of integrated crop protection. Future efforts should emphasize well-characterized strains, reliable formulations, product quality, multi-location field validation, and compatibility with existing agricultural practices. Overall, T. harzianum and T. viride offer considerable potential for reducing pesticide dependence and supporting environmentally compatible and sustainable crop production.

Keywords: pesticide; Trichoderma; mycoparasitism; Sustainable Agriculture

1. INTRODUCTION

Modern agriculture faces a difficult balance: crop production must increase to meet growing food demand, while the environmental costs of intensive farming need to be reduced. Heavy and repeated dependence on synthetic pesticides has contributed to concerns related to environmental contamination, disruption of beneficial soil microorganisms, pesticide resistance, and long-term soil health. These challenges have increased interest in biological approaches that can protect crops without placing the same pressure on agricultural ecosystems. Among the microorganisms explored for this purpose, *Trichoderma* has attracted considerable attention because of its ability to suppress plant pathogens while also supporting plant growth and soil health [1].

Trichoderma harzianum and *Trichoderma viride* are particularly important species in agricultural biocontrol. In India, both species have been widely investigated and commercially used against soil-borne plant pathogens, mainly through seed treatment and soil application. Earlier Indian research reported their use across approximately 87 crops, with activity against around 70 soil-borne and 18 foliar pathogens, demonstrating their broad agricultural relevance [2]. More recently, *Trichoderma*-based products have continued to gain importance as components of integrated disease-management programmes; globally, *Trichoderma* species are estimated to form the basis of more than 60% of licensed fungal biofungicides.

The effectiveness of these fungi is not based on a single mechanism. *T. harzianum* and *T. viride* can compete with pathogens for nutrients and space, parasitize pathogenic fungi, and produce secondary metabolites and hydrolytic enzymes such as chitinases and glucanases that interfere with pathogen development [3]. They can also colonize plant roots and stimulate plant defence responses, thereby helping plants respond more effectively to subsequent stresses. In addition to disease suppression, selected strains can improve root development, nutrient acquisition, and tolerance to environmental stress [4].

The increasing demand for safer and more sustainable crop protection has encouraged researchers to explore microorganisms that can naturally suppress plant diseases. Among the

beneficial fungi, *Trichoderma harzianum* and *Trichoderma viride* have received considerable attention because of their ability to establish themselves in the plant rhizosphere and restrict the growth of several important phytopathogens [5]. Their effectiveness is associated with multiple biological activities, including competition for nutrients and space, production of antifungal compounds and enzymes, and direct interaction with pathogenic fungi. Unlike many conventional pesticides, these beneficial fungi can contribute to disease management while maintaining a more biologically active soil environment. Their broad applicability in different crops makes them important candidates for developing practical and environmentally compatible biopesticide strategies [6].

The agricultural importance of *T. harzianum* and *T. viride* extends beyond direct pathogen suppression. Several strains have been reported to enhance root development, improve nutrient availability, and stimulate natural defence responses in plants, thereby supporting overall plant growth and resilience [7]. However, their effectiveness can vary with fungal strain, crop, soil conditions, climate, pathogen pressure, and method of application. Therefore, simply considering *Trichoderma* as a substitute for chemical pesticides does not fully represent its potential or limitations. A critical evaluation of available research is needed to understand where *T. harzianum* and *T. viride* perform consistently, how they can be incorporated into integrated crop protection, and their broader contribution to sustainable agriculture.

1.1 Objective

- To critically review the potential of *Trichoderma harzianum* and *Trichoderma viride* as eco-friendly biopesticides in sustainable agriculture.

2. REVIEW OF LITERATURE

The growing need to maintain crop productivity while reducing the environmental burden associated with intensive pesticide use has increased interest in biological approaches to crop

protection. Synthetic fungicides remain important in many production systems, but their repeated use has been associated with concerns such as resistance development, environmental contamination and effects on beneficial soil organisms. In this situation, *Trichoderma* has attracted considerable attention as a naturally occurring fungal resource with both disease-suppressive and plant-beneficial properties. Recent literature describes *Trichoderma* as an important component of sustainable agriculture because selected strains can interact with plant roots, suppress phytopathogens and contribute to improved plant growth and soil biological activity [8].

Among the agriculturally relevant species, *Trichodermaharzianum* and *Trichodermaviride* have received particular attention because of their antagonistic activity against several plant pathogens. Their importance does not arise from a single biological process. Instead, their effectiveness is associated with a combination of competition for nutrients and space, mycoparasitism, antibiosis, production of hydrolytic enzymes and secondary metabolites, and stimulation of plant defence responses. This combination gives *Trichoderma* a broader biological role than that of a conventional fungicide acting through one defined chemical target. Recent reviews continue to identify these mechanisms as central to the potential of *Trichoderma* in sustainable disease management [9].

The ability of *T. harzianum* and *T. viride* to colonize the rhizosphere is closely connected with their usefulness as biological control agents. The area surrounding plant roots is a highly active microbial environment where beneficial microorganisms, pathogens and the plant continuously interact. Once an effective *Trichoderma* strain becomes established around the roots, it can compete with pathogens for nutrients and available sites for colonization. This competition may be particularly useful during early plant development, when young roots are vulnerable to soil-borne pathogens. Recent studies emphasize that competition is not an isolated process but works together with other antagonistic activities to restrict pathogen establishment [10].

Mycoparasitism is another important feature associated with the biocontrol activity of *Trichoderma*. In this interaction, the beneficial fungus recognizes and grows towards the hyphae of a susceptible pathogen. It may attach to and coil around the pathogen and subsequently release enzymes capable of degrading fungal cell-wall components. Chitinases and glucanases are particularly relevant because chitin and glucans form important structural components of fungal cell walls. The resulting damage can interfere with pathogen growth and development. However, the strength of this interaction varies considerably between strains. Consequently, the biocontrol potential of *T. harzianum* or *T. viride* cannot be assumed to be identical for all isolates belonging to the same species [11].

The production of secondary metabolites adds another dimension to pathogen suppression. *Trichoderma* species are capable of producing a chemically diverse group of natural compounds, including terpenoids, alkaloids, polyketides, non-ribosomal peptides and other bioactive molecules. These compounds can interfere with pathogen growth and contribute to the antagonistic relationship between *Trichoderma* and phytopathogens. [12] emphasized that the diversity of *Trichoderma* natural products is closely linked with its biological control potential and represents an important area for future development of microbial-based crop protection.

Interaction with plants and improvement of plant health

The agricultural value of *T. harzianum* and *T. viride* extends beyond direct inhibition of pathogens. Certain strains can establish an association with plant roots and influence plant growth and physiological responses. Root colonization may improve root development and nutrient acquisition while also preparing the plant to respond more effectively to pathogen attack. This plant-mediated component of *Trichoderma* activity is important because disease resistance is not necessarily dependent only on the direct destruction of the pathogen. Instead, the beneficial fungus may influence the plant's own defence system and make it more responsive to subsequent stress [13].

Recent work has also highlighted the role of *T. harzianum* in improving plant tolerance to environmental stresses. A 2025 review reported that *T. harzianum* may influence phytohormone regulation, antioxidant responses, root development and nutrient uptake under conditions such as drought, salinity and high temperature. These effects are particularly relevant to sustainable agriculture because crop losses are not caused by pathogens alone; environmental stresses can also substantially reduce crop performance [14]. Thus, a suitable *T. harzianum* strain may provide benefits that extend beyond conventional biological disease control.

The plant-growth-promoting effect should nevertheless be interpreted carefully. Not every *Trichoderma* isolate produces the same response, and the interaction may depend on plant genotype, soil characteristics, environmental conditions and the compatibility between the fungal strain and its host. Recent literature increasingly stresses the importance of strain selection because broad statements about the benefits of the genus cannot necessarily be applied equally to every isolate [14].

Application in sustainable crop protection

The practical use of *T. harzianum* and *T. viride* includes seed treatment, soil application, root treatment and the use of formulated biological products. Seed treatment provides an opportunity for the fungus to establish close to emerging roots, while soil application can be useful when soil-borne pathogens are the major concern. Formulation is particularly important because biological efficacy depends not only on the intrinsic activity of the fungal strain but also on its survival during storage and its ability to remain viable after application. Recent research on *Trichoderma*-based formulations has therefore focused on improving stability, viability and field performance [15].

The commercial availability of *Trichoderma*-based products indicates that these fungi have moved beyond purely experimental use. However, commercialisation also brings the issue of product quality. [15], after examining commercially available *Trichoderma*-based products, reported considerable differences in viable fungal counts and found that the number of colony-

forming units in the tested products was lower than the declared values. The study also identified cases in which the taxonomic identity of recovered isolates did not correspond fully with the information provided on product labels. Such observations are important because inconsistent product quality can directly affect the reliability of biological control under practical farming conditions.

Field conditions present another limitation. Results obtained under laboratory or greenhouse conditions cannot always be reproduced in open agricultural environments. Soil pH, moisture, temperature, organic matter, pathogen population, crop variety and interactions with indigenous microorganisms can influence the establishment and activity of *Trichoderma*. Recent literature therefore identifies environmental variability and strain-specific performance among the major challenges limiting consistent field efficacy [16].

The significance of *T. harzianum* and *T. viride* in sustainable agriculture is perhaps best understood when they are considered as components of integrated crop protection rather than as universal replacements for synthetic pesticides. Their use can be combined with crop rotation, resistant cultivars, improved soil management and other biological or chemical measures. Such an approach allows disease management to rely on several complementary practices rather than placing continuous pressure on a single control method. Recent reviews have emphasized this integrated role of *Trichoderma* in reducing pesticide dependence while maintaining crop.

The use of *Trichoderma* is also being investigated beyond the management of diseases occurring during crop growth. Recent research has examined its potential in postharvest disease management, particularly for fungal decay of fruits and vegetables. [16] reviewed the use of *Trichoderma* against postharvest fungal deterioration and highlighted both its potential and the practical challenges associated with its application. This expands the possible contribution of *Trichoderma*-based biological control across different stages of crop production and handling.

Current research is increasingly moving from the simple identification of *Trichoderma* as a beneficial fungus towards the selection of specific strains with predictable agricultural

performance. Genomic, metabolomic and biochemical approaches are being used to understand the traits associated with antagonism, metabolite production and plant interaction. At the same time, formulation research is attempting to overcome problems related to shelf life, viability and establishment after application. Recent work has also explored combinations of *Trichoderma* with other beneficial microorganisms, although compatibility and consistency still require careful evaluation [17].

An important gap remains the difference between demonstrated laboratory potential and reliable field performance. A strain that strongly inhibits a pathogen on artificial media may not provide the same level of protection in soil or under fluctuating environmental conditions. Product formulation and quality control are equally important, particularly as the number of commercially available biological products increases. The findings of [14] demonstrate that the biological potential of *Trichoderma* must be supported by accurate strain identification, adequate viable counts and appropriate quality standards if farmers are to obtain consistent results.

Overall, the literature indicates that *T. harzianum* and *T. viride* have considerable potential as eco-friendly components of sustainable crop protection. Their value comes from the combination of pathogen suppression, plant-growth promotion and interaction with the rhizosphere rather than from any single mechanism. At the same time, the available evidence does not justify treating all strains or products as equally effective. Differences in strain characteristics, crop, environment, formulation and application method can substantially influence the outcome. For this reason, future work should place greater emphasis on well-characterized strains, multi-location field validation, formulation quality and their integration with existing crop-management practices. Such an approach would provide a more realistic pathway for using *T. harzianum* and *T. viride* as biological tools for reducing reliance on conventional pesticides while maintaining effective and practical crop protection [15].

3. TRICHODERMA HARZIANUM AND TRICHODERMA VIRIDE IN BIOLOGICAL CONTROL OF PLANT PATHOGENS

The search for practical alternatives to chemical fungicides has brought beneficial fungi such as *Trichoderma harzianum* and *Trichoderma viride* into greater focus. These fungi are naturally associated with soil and plant roots and are particularly useful against several soil-borne pathogens. Their importance in biological control comes from the fact that they do not depend on a single mode of action. Instead, they can interact with pathogens in different ways, which makes their use relevant to disease management under diverse cropping conditions. Both species have been reported to suppress important pathogens associated with diseases such as damping-off, root rot, wilt and stem rot in different crops [16].

One of the simplest ways through which *Trichoderma* limits pathogens is by competing with them for nutrients and available space around the plant root. Rapid colonization of the rhizosphere can reduce the opportunity for pathogenic fungi to establish themselves. This is particularly important in the early stages of crop growth, when young roots are more vulnerable to infection. *T. harzianum* and *T. viride* can also grow directly towards pathogenic fungi and establish close contact with their hyphae. In this interaction, *Trichoderma* may coil around or penetrate the pathogen and release enzymes such as chitinases and β -1,3-glucanases, which contribute to the breakdown of fungal cell walls.

Another important aspect is the production of secondary metabolites and other inhibitory compounds. Depending on the strain, these substances can slow pathogen growth or interfere with spore germination and other stages of the pathogen's life cycle. This helps explain why different *Trichoderma* strains can show varying levels of effectiveness even when they belong to the same species. The interaction is also influenced by crop type, soil characteristics, temperature, moisture and the population of the target pathogen [17].

The usefulness of these fungi becomes more interesting when their direct effect on pathogens is considered together with their association with plant roots. Root colonization by compatible *Trichoderma* strains may stimulate the plant's own defence mechanisms, allowing the plant to respond more effectively when exposed to pathogens. Thus, biological control by *T. harzianum* and *T. viride* is better viewed as a combination of pathogen suppression and support for plant health rather than as a simple replacement for synthetic fungicides. Their relatively broad activity and compatibility with integrated disease-management approaches make them important candidates for more sustainable crop protection.

4. ROLE OF *TRICHODERMA HARZIANUM* AND *TRICHODERMA VIRIDE* IN SUSTAINABLE CROP PROTECTION

Sustainable crop protection is no longer limited to finding ways of controlling a particular disease. It also involves maintaining soil quality, protecting beneficial organisms and reducing unnecessary dependence on synthetic agrochemicals. In this context, *Trichodermaharzianum* and *Trichodermaviride* have become useful biological resources because their role can extend beyond direct suppression of plant pathogens. These fungi are naturally found in soil and around plant roots, where suitable strains can establish themselves and interact with the plant and its surrounding microbial community. Their use therefore fits well with the broader concept of biological and integrated crop protection [18].

An important advantage of *Trichoderma* is its potential to support plant growth while providing protection against disease. When certain strains colonize the root region, they may influence root development and improve the plant's ability to obtain nutrients from the surrounding soil. Better root development can be particularly valuable during the early growth stages, when plants are establishing themselves and are more sensitive to environmental stress. Some studies have also shown that *T. harzianum* and *T. viride* can stimulate natural defence responses in plants. In such cases, the plant itself becomes better prepared to respond to pathogen attack rather than relying entirely on an external chemical treatment.

The contribution of these fungi to sustainable agriculture also lies in their potential to reduce the frequency or intensity of chemical fungicide use. This does not mean that synthetic pesticides can be completely replaced under every agricultural condition. Disease pressure, crop variety, soil conditions, weather and the characteristics of the particular *Trichoderma* strain can all affect the outcome. However, when effective strains are incorporated into an integrated disease-management programme, they can provide an additional biological means of protecting crops and may help reduce excessive dependence on conventional fungicides [19].

Practical application remains an important consideration. Seed treatment, soil application, root dipping and the use of formulated *Trichoderma* products are among the approaches used for introducing these fungi into crop production systems. Their success depends on maintaining viable fungal populations and selecting strains that are compatible with the crop and local environmental conditions. Thus, *T. harzianum* and *T. viride* should be viewed not simply as biological substitutes for chemical pesticides, but as useful components of a broader approach to sustainable crop protection. Their combined contribution to disease management, plant health and reduced chemical dependence provides a sound basis for their continued consideration in sustainable agriculture.

5. CONCLUSION

The present review highlights the important role of *Trichodermaharzianum* and *Trichodermaviride* as promising biological resources for sustainable crop protection. Their value lies not only in their ability to suppress plant pathogens, but also in their close association with plant roots and their contribution to overall plant health. The reviewed literature shows that these fungi can act through several complementary mechanisms, including competition for nutrients and space, mycoparasitism, production of hydrolytic enzymes and secondary metabolites, and stimulation of plant defence responses. These combined activities make *Trichoderma* different from conventional fungicides that generally depend on a specific mode of action.

The review also indicates that the benefits of these fungi can extend beyond disease control. Suitable strains may support root development, nutrient acquisition and plant tolerance to environmental stresses, thereby contributing to healthier and more resilient crops. Their use through seed treatment, soil application, root treatment and formulated products provides practical possibilities for incorporating biological control into existing agricultural systems. At the same time, the evidence suggests that their performance is not uniform under all conditions. Strain characteristics, crop type, soil properties, temperature, moisture, pathogen pressure and application methods can strongly influence their effectiveness.

Therefore, *T. harzianum* and *T. viride* should not be considered universal replacements for synthetic pesticides. Their greater value lies in their integration with crop rotation, resistant varieties, improved soil management and other biological or chemical measures. Such an integrated approach can help reduce unnecessary dependence on conventional fungicides while maintaining effective disease management. Future research should give greater attention to well-characterized strains, reliable formulations, product quality, multi-location field trials and compatibility with different crops and environments. With these improvements, *T. harzianum* and *T. viride* can make a meaningful contribution to reducing pesticide dependence and promoting a more balanced, biologically active and sustainable agricultural production system.

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