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Enhancing Crop Yields using *Trichoderma* with Organic Amendment Integration

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Abstract

Trichoderma has been used in combination with a wide range of organic amendments such as vermicompost, farmyard manure, green manure, biochar, oil cakes, jivamrit (an organic formulation), essential oils and silicon based inputs as an important ecofriendly method to enhance the crop yield besides the health of the soil. The *Trichoderma* bio-organic fertilizer can also be used to promote the decomposition of organic matter and the abundance of beneficial bacteria to enrich the microbial community in the soil to ensure that more nutrients are released to crops with a better soil structure and resistance to biotic and abiotic stresses. Between field and horticultural and plantation crops, the two continued to improve germination, biomass, yield and quality parameters and to an impressive degree suppress soil-borne pathogens and nematodes by mycoparasitism, competition and antibiosis. Their mass production of *Trichoderma*-based bioformulations that can reduce the need to use chemical fertilizers and pesticides has also been made possible by recent developments of solid-state fermentation and bio-enriched substrates, thus forming a part of climate-smart and sustainable agriculture.

Keywords: *Trichoderma,* Biochar, Jivamrit, Mycoparasitism

Introduction

Food security has become a major challenge in modern agriculture because of the need to balance between the food security requirements and environmental sustainability. Although chemical fertilizers have played a crucial role in generating the productivity of the Green Revolution, they have caused major ecological issues such as soil degradation, groundwater pollution, greenhouse gas emissions and disturbance of soil microbiomes that are beneficial. Sustainability is more than a necessity like never before, especially in climate change and the decreasing natural resources.

Bio-organic fertilizers (BOFs) are another potential remedy that helps to unite the potential of organic matter to provide nutrients, as well as the biological activity of useful microorganisms. These formulations are usually combinations of organic matter as a result of agricultural wastes and animal excreta and plant refuse and other harmless microbial inoculants such as *Trichoderma*, *Bacillus*, *Pseudomonas*, nitrogen fixing bacteria among others. The manufacturing process encompasses an aerobic composting process and bioaugmentation methods that provide sustainability of the microbes and preserve organic matter. The combination of *Trichoderma* fungi with organic soil amendments is a game changer in turning to the sustainable farming concept, which has a high crop productivity with less reliance on chemical fertilizers.

Although BOFs have environmental advantages, they have a number of challenges encountered during implementation that restrict their use. The variability in performance by the various crops, the soils as well as the climatic area is a big issue. Some of the factors that are considered to have an impact on BOF efficacy are quality of raw materials, the selection of microbial strains, optimum dose and the environmental conditions during application and establishment.

There are various microbial components, which perform different functions in BOF systems. The *Trichoderma* species can best decompose organic matter, produce enzymes and suppress pathogens

using the bioavailability of mycoparasitism and antibiosis (Mukherjee *et al*., 2022). Nitrogen fixing bacteria lead to increased availability of nitrogen in the soil, which lowers the needs of synthetic fertilizer nitrogen. Phosphorus is enhanced by phosphate-solubilizing bacterium such as *Pseudomonas*. Microorganism consortia which are effective (EM) are known to help in the production of antioxidants and the synthesis of the plant growth hormone.

The basis of sustainable soil health management lies in organic amendments, which are used in conjunction with compost, vermiculite, manure, green manure, farmyard manure, crop residues and biochar. These substances replenish the soil organic matter levels, increase the capacity to hold nutrients, improve the soil texture and water-holding ability and provide the environment in which favourable conditions for beneficial microbial growth. Organic amendments offer the necessary substrates to microbial colonization and metabolism when added together with *Trichoderma* inoculants. The complementary interaction of organic matter and useful microorganisms produces a self-maintaining ecosystem, which supports the soil over the long term and soil health.

Trichoderma: Characteristics and Agricultural Applications

To realize the optimum efficiency of the microbial inoculants, farmers should be aware of the particular working mechanisms of the microbial inoculants. The choice of methods to be used by the farming microorganisms has been volatile to majority of farmers as they lack information regarding the kind of needs they need.

Species	Morphology & Colour	Key Features	Ecological/Practical Use
Trichoderma hamatum	Colonies white-cottony initially, later light green/yellow colour; highly branched conidiophores; concentric zones	Produces antimicrobial, antioxidant compounds.	Biocontrol of soil-borne pathogens, plant growth promotion.
Trichoderma viride	Rapid growth; colonies white to bright green with concentric rings; smooth to rough green	Highly branched conidiophores, saprophytic and mycoparasitic abilities, enzyme secretion like cellulases	Biocontrol; seed treatment; organic waste composting; industrial enzyme production
Trichoderma asperellum	Milky white to dark green colonies, sigmoid/hooked phialides	Moderate branching of conidiophores; efficient enzyme producer; induces systemic resistance in plants	Effective biocontrol of soil pathogens; plant growth promotion; root colonizer
Trichoderma afroharzianum	Colonies green with white aerial mycelium; ellipsoid, smooth green conidia	Root colonizer; produces multiple bioactive metabolites	Enhances root development and plant vigor; biocontrol in crops such as maize and wheat

Trichoderma combats pathogenic fungi by three fundamental biocontrol processes that comprise mycoparasitism, competition and antibiosis. The *Trichoderma* has several advanced biological processes of plant pathogen control and this makes them very useful and dependable biocontrol agents. *Trichoderma* protects plants via three processes that include the formation of antimicrobial compounds, increases cell wall strength by lignification and the activation of defense-related signal transduction that involves salicylic acid, jasmonic acid and ethylene. *Trichoderma* strain combined with various traits can be said to be an excellent biocontrol agent that can substitute the use of traditional agrochemicals in the sustainable farming practices.

Synergic reactions between *Trichoderma* and Organic Amendments.

When *Trichoderma* fungi are combined with the organic soil additives, there is a synergistic effect, which is more beneficial than the additives themselves. Such interactions increase both the fertility of the soil, stimulate positive microbial competence and develop sustainable agriculture models that limit the need to use synthetic inputs.

Vermicompost is one of the most efficient organic amendments of the *Trichoderma* integration because of balanced nutrient composition and useful microbial composition. The soil structure and the

quality of nutrients in the substrates are improved because decomposition by earthworms results in the formation of nutrient rich debris that is better at storing water and has a greater ability to retain it. The TBVC offers a slow release of essential macronutrients such as nitrogen (2.5-3.2%), phosphorus (1.8-2.5%) and potassium (1.5-2.1%) and micronutrients such as zinc, iron, manganese and copper. These nutrients are organically complexed giving them high bioavailability and limiting the amount of leaching losses. Application of TBVC leads to 41% weight gain of seed in potato farming and 130% germination rate of maize seedlings relative to the usual treatment. The synergistic nature of the organic matter of vermicompost and the enzyme production of *Trichoderma* are credited to the improvement in nutrient availability. Its capacity to enhance plant physiological activities, increase growth parameters and stimulate defense related enzymes and genes (Wonglom *et al*., 2024).

Farmyard manure is an excellent organic material to colonize with *Trichoderma* and it contains all necessary nutrients such as organic carbon (35-45%), nitrogen (1.52%), phosphorus (0.51%) and sulfur (0.3-0.5%) as well. The FYM application provides a desirable soil environment such as better buffering of soil pH, increased soil moisture and cation exchange capacity. The mixture of *T. harzianum* and FYM has been proven to be remarkably effective in the management of soil-borne diseases in all crops. There has been a total elimination of damping-off disease in tomatoes and chilli crops using field trials and there has been a markedly low occurrence rate of the disease relative to untreated controls. This combined method offers sustainable substitutes to fungicide chemicals and does not negatively affect the quality of crops.

Green manures will increase the nitrogen level and the organic matter in the soil. The green manure supplement is useful to the soil microbes by the way it promotes the diversity and activity of bacteria and fungi that enhance the process of carbon and nitrogen cycles. *Trichoderma* spp. in combination with green manure such as *Crotalaria juncea* improves the texture of the soil and its fertility. The soil structure is also improved to increase the movements of water, the ability of roots to penetrate the soil and gas exchange to provide an optimum environment in the soil to support the growth of plants and the activity of microorganisms. These are the physical traits mainly useful in heavy clay soils and poor agricultural land. The use of *T. harzianum* in combination with green manure was able to reduce the populations of *Meloidogyne javanica* nematodes by an extend of up to 60% in agricultural sites. The action of nematicidal effects is based on various mechanisms such as direct parasitism, synthesis of nematotoxic substances and promotion of plant resistance.

Biochar synergism is a new organic addition that has got some exclusive benefits to introduce *Trichoderma* integration owing to its carbon skeletal stability, high surface area and remarkable nutrient retention potential. The pyrolytic formation of biochar forms porous structures that offer the ideal environments to viable microorganisms besides enhancing the physical properties of the soils. The interaction of *Trichoderma* and biochar leads to canonic enzyme activity increment. The enzymatic enhancements are increasing the decomposition and cycling of nutrients of organic matter. The large surface area and functional groups of biochar have a good support for enzyme stabilization and adherence of microbes. The increased activity of the enzyme is translated to increased nutrient and better biological activity of the soils. The biochar composites containing *Trichoderma* are found to have enhanced pathogen suppression effects in several ways such as physical exclusion, production of antibiotics and competitive colonization (Kumari *et al*., 2025).

Neem and castor oil cakes and other oilseeds processing used as organic substrates were found to offer the best *Trichoderma* substrates as well as provide nitrogen-rich organic matter and naturally occurring pest deterring compounds. The amendments are a combination of nutritional values and the natural bioactive compounds that help in increasing the protection of plants. A combination of *T. viride* with neem oil cage and garlic oil cage shows outstanding effectiveness in dealing with root-knot nematodes with enhancement of plant development and generation of large quantities of *Trichoderma* spores. This is a triple benefits solution to the intensively managed agricultural systems to offer sustainable solutions to pest management.

Jivamrit is an acid fermenting

microbial culture made of cow dung, cow urine, jaggery, gram flour, soil and water that provides the best conditions for *Trichoderma* proliferation. This conventional recipe offers equal nutrients and promotes positive microbial populations. Field experiments have shown that, in combination with biochar, *Trichoderma*-jivamrit gives spectacular results with maize seedlings developing 6.3-fold bigger root systems, 130% higher germination and 60% higher seedling length than controls.

Neem, castor, clove, eucalyptus and citronella essential oils improve the biocontrol effects of *Trichoderma* by synergizing the antifungal effect. The added properties of these natural compounds are the added pathogen suppression at the expense of environmental safety. A mixture of clove and thyme essential oils with *T. harzianum* is effective in inhibiting the growth of *Botrytis cinerea* and *Alternaria alternata* in fruits. A combination of the treatments provides sustainable options to the synthetic fungicides without compromising the quality of products.

Agricultural applications across crop systems

Trichoderma spp. combined with organic amendments is essential in the contemporary farming practice to improve crop production, improve soil health and facilitate sustainable farming. Its applications and uses are very diverse in a cross-cutting range of crops and agricultural systems.

Field crop uses: *Trichoderma* combined with organic amendments show outstanding results in the performance of the main field crops such as cereals, legumes and oilseeds. The use of *Trichoderma* bio-organic fertilizers leads to 20-30% growth in the yields of wheat and maize due to the increase in the diversity of microbial organisms in the soil and loss of pressure on the pathogen. *T. harzianum*-neem cake mixture in mungbean production enhances the mung bean germination rates and mortality due to disease, as well as improves the overall health of the plant.

Enhancement in horticultural crops: *Trichoderma*-organic amendment combinations are very useful in vegetable and fruit production systems. Inoculated Cucumber and tomato plants with the bio-agent exhibit 40% growths on roots and the shoots and enhance the efficiency of nutrient absorption. Strawberry fruit production has shown great improvement with 40% growth in weight of fruits per plant, 22% growth in the number of fruits per square meter with use of *Trichoderma*. There are fresh weight gains of 56% in 28 months of tomato planting with the *T. harzianum* that was planted using sheep manure. The quality of nutrition also shows improvements as the carotenoids and glucosinolates with the treated plants increasing by 60% and 39% respectively over the untreated controls. Such quality additions boost the nutritional content and the marketability.

Plantation crop management: Perennial plantation crops such as coffee, tea, cardamom and spice plants are given *Trichoderma* based biofertilizers which helps in boosting soil fertility and improving the health of plants. Sustainable production systems are formed through the stimulation of organic matter decomposition and the promotion of useful microbial communities. *T. harzianum* that is used together with organic amendments such as poultry manure, neem cake and coffee husk exhibit a very good performance in inhibiting *Phytophthora meadii* in cardamom and promoting the growth of the plant. These applications offer a viable alternative to the use of chemicals in the perennial crop system.

New Developments and Innovations

The synergistic effect between *Trichoderma* and the organic inputs has seen some biochemical manufacturing processes of the biofertilizers e.g. farmyard manure, crop residues and compost along with *Trichoderma* spp. The mixture leads to faster decaying of organic substances increased release of nutrients and the creation of more useful micro-organisms. The ultimate outcome is that the crops are receiving dependable nutrients in bio-available type; and the strain of disease can be thwarted organically making it an excellent match to organic and sustainable farming. Mass production capitalizes on solid-state fermentation technology where *Trichoderma* is cultivated on organic substances that lead to the viable spores that are covered with a nutrient carrier. These bioformulations involve control of pathogens and an increment in soil fertility, provide a feasible solution to reduce the use of chemical fertilizers and pesticides.

Conclusion

Trichoderma being a biological

product when mixed with organic compounds is the best natural product to be used in sustainable agriculture. This enhances the

fertility of the soil because of the enhanced recycling of nutrients, decomposition of organic materials and positive microbial activity. Combination of these measures has increased nutrient uptake of plants and crops and sturdiness or disease resistance. *Trichoderma* is a biocontrol agent, that minimises soilborne diseases in a number of ways. The joint application has shown great enhancement in the soil fertility, growth promotion, disease suppression and stress tolerance in a wide range of agricultural systems. This combination approach tackles the existing challenges in sustainable agriculture and leads to climate-resilient farming plans and the long-term preservation of soil health.

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