Review Article

The Role of Biofertilizers in Sustainable Agriculture: An Eco-Friendly Alternative to Conventional Chemical Fertilizers

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Abstract
Empirical observations and theory both discourage the production and use of chemical fertilizers as they can lead to environmental pollution, soil degradation and reduction in soil fertility in the long term. In certain cases, excess nutrients from chemical fertilizers such as nitrogen and phosphorus can leach into nearby water causing eutrophication. Also, the production process requires large amounts of energy, which often comes from burning fossil fuels contributing significantly to greenhouse gas concentration. Biofertilizers present a promising alternative to chemical fertilizers and improve agricultural sustainability and reduce environmental pollution. However, there is still more to learn about the potential benefits of biofertilizers based on factors such as soil type, crop species, and environmental conditions. This review shows the *Trichoderma* species as one of the most prominent biofertilizers that can help in plant growth promotion and serve as a biocontrol agent against plant pathogens. An extensive summary of scientific literature on *Trichoderma's* production, effectiveness in comparison to chemical fertilizers and its potential for use are discussed. *Trichoderma* species have been documented to possess numerous mechanisms to combat a wide range of plant pathogens, protect plants from biotic and abiotic stresses, reduce drought and salinity stress fungal attacks and promote root growth. *Trichoderma* is an ecofriendly organic fertilizer that can promote food security and enhance sustainable crop production. This article provides a comprehensive and up-to-date summary of the current state of knowledge on *Trichoderma* as a biofertilizer and indicates future research directions.

Keywords: Biofertilizer, Crop production, Formulation, Inoculant, Shelf life, *Trichoderma* species

1 Introduction

The excessive use of fossil fuels and production of synthetic fertilizer has led to environmental hazards which include greenhouse gas emissions (GHG). These emissions of GHG have negatively impacted the ecosystem causing air and water pollution [1]. Sustainable agronomy and environmental protection focus on practices that support long-term ecological balance, preservation of natural resources and promotion of sustainable development in agriculture in this millennium. The green revolution has led agricultural production to a great exploration that can improve the ecosystem thereby preventing pollution of the ecosystem, groundwater, and other contributory factors to the degrading environment [2], [3]. Fertilizer is a conventional nutrient booster, which has been extensively utilized in agricultural production for several decades. Conducting in-depth research, it has become widely acknowledged that the utilization of inorganic or chemical fertilizers can have adverse effects on ecosystems, groundwater and human health as compared to organic fertilizers. This is due to the long-term build-up of toxic substances of inorganic

Figure 1: The conventional chemical fertilizers widely used in the agricultural sector.

fertilizers in the soil which can contaminate soil, and water due to its accumulation leading to nutrient leaching and soil degradation [4]–[10]. Smith *et al.*, reported that chemical fertilizers such as nitrogen fertilizers increase denitrification which contributes significantly to global warming through the emission of nitrous oxide (N_2O) [11] and Khan *et al.*, have established that nitrogen fertilizers may degrade the soil's inorganic carbon [12]. According to Keana's findings, nitrates that do not adhere to soil components can permeate into groundwater and impede the growth of plants by accumulating excessively [13]. Figure 1 shows the conventional chemical fertilizer used for crop production by farmers. The focus needs to shift towards a biological control agent that can have a positive impact on the environment and improve the ecosystem. With the ongoing threat and menace, the use of biofertilizers is gaining recognition worldwide, and their applications are still prevalent. Biofertilizers are now receiving considerable attention from researchers and the agricultural industry because they can enhance crop production, improve nutritional quality, increase resistance to pathogens, and ultimately promote eco-friendliness [14]–[18]. The integration of organic fertilizer in agriculture provides a better sustainable environment for crop production [19], [20]. Organic fertilizer helps to reduce over reliance on chemical-based nutrient, conservation of energy, and efficient water use by crops. It also helps in recycling of agricultural waste [21], [22]. Biofertilizers include both plant extracts and manure, which contain living cells of different microorganisms commonly prepared microbiologically. The microorganisms in this blend are intended to inhabit the rhizosphere of plants thereby facilitating the delivery of soil nutrients to the crop with greater efficiency [15], [16], [23].

The *Trichoderma* species, which mainly reside in soil and plants, are widely employed as biocontrol fungi, which are increasingly gaining acknowledgment among modern researchers [24]. *Trichoderma* not only enhances plant growth and nutrient absorption but also boosts the ability of plants to withstand abiotic stress and fortify their defense mechanisms [25]–[27]. Different species of *Trichoderma* have demonstrated the ability to inhibit *Pythium*, *Fusarium*, *Rhizoctonia*, *Sclerotium*, and *Macrophomina* [24], [28], [29]. Among the notable species are *T. harzianum*, [30], [31], *T. viride* [32], [33], T. reesei [34], [35], *T. koningii* [36], [37], *T. atroviride* [38], [39] and many more. The goal of sustainable crop production is to offer an environmentally friendly substitute for conventional farm inputs like chemical fertilizers. As a result, biofertilizers are more sustainability-oriented than chemical fertilizers. This review aims to demonstrate that biofertilizers are a crucial component of sustainable agriculture, which employs microorganisms, organic manure, and eco-friendly fertilizers to enhance crop growth and yield.

2 Biofertilizers and Functions of Biofertilizers

Biofertilizer has been identified as an alternative to chemical fertilizer to increase soil fertility and crop production for sustainable agricultural production. These potential biological fertilizers would facilitate productivity and sustainability of soil and also protect the environment as eco-friendly biofertilizers and cost-effective inputs for the farmers [40]. The application of biofertilizer to the soil increases the biodiversity, which constitutes all kinds of useful bacteria and fungi including the arbuscular mycorrhiza fungi (AMF) called plant growth-promoting rhizobacteria (PGPR) and nitrogen fixers. There are so many microorganisms thriving in the soil, especially in the rhizosphere of the plant. A considerable number of these microorganisms possess a functional relationship and constitute a holistic system with plants. They have beneficial effects on plant growth [41]. In Bangladesh *Trichoderma* species are mainly used as biocontrol of soil and seed-borne pathogens [42]. Biofertilizers have shown great potential as a renewable and environmentally friendly source of plant nutrients. More so, they are an important component of Integrated Nutrient Management (INM) and Integrated Plant Nutrition System (IPNS) [43]. Biofertilizers are used as a live formulation of beneficial microorganisms, when amended to seed, root, or soil. It mobilizes the availability and utility of the microorganisms and thus improves soil health. The use of naturally grown biofertilizers results in higher crop yields, poses no harm to humans, and promotes sustainable economic development for farmers and their countries [44]. Biofertilizers produce better yield of crop and are also harmless to humans thereby leading to a better sustainable economic development for the farmers and their country [45]. It has also been reported that the application of biofertilizers increases yield and reduces environmental pollution [46]. Biofertilizers are used in the live formulation of beneficial microorganisms. Their application to seed, root, or soil, mobilizes the availability of nutrients, particularly by their biological activity, and improves the build-up of lost microflora and in turn, improves the soil health in general [47]. The use of biofertilizers in agricultural practices started about six decades ago and it is now evident that these beneficial microbes can also enhance plant resistance to adverse environmental stresses such as water and nutrient deficiency and heavy metal contamination [48]. Biofertilizers keep the soil environment rich in all kinds of macro and micronutrients via nitrogen fixation, phosphate, and potassium solubilization or mineralization, the release of plant growth regulating substances, production of antibiotics, and biodegradation of organic matter in the soil [17]. Biofertilizers when applied as seed or soil inoculants, tend to multiply and participate in nutrient cycling leading to crop productivity. Generally, 60%–90% of the total applied fertilizer is lost and the remaining 10%–40% is taken up by plants. Due to this, biofertilizers have become an important component of integrated nutrient management systems for sustaining agricultural productivity and providing a healthy and conducive environment [49]. Biofertilizers are efficient in the supply of nutrients, amelioration of toxic effects in soils, root pests, disease control, improving water usage, and soil fertility [50]. Table 1 shows the different types of biofertilizer with different microorganisms present. *Trichoderma* and other microorganisms are known to break down soil pollutants. These microbes can be used in creative ways to reduce soil pollution, like bioremediation and phytoremediation. In addition, *Trichoderma* is useful in bioremediation to enhance the degradation of pollutants, due to its ability to produce enzymes that can degrade a wide range of pollutants such as polycyclic aromatic hydrocarbons (PAHs) and chlorinated solvents [51], [52]. For example, a study conducted in India found that the use of *Trichoderma* in combination with vetiver grass enhanced the removal of heavy metals from contaminated soil [53]. Different strains of *Trichoderma* can be used for both agricultural and industrial purposes [54]. *Trichoderma* is capable of enhancing soil quality by breaking down chemicals and metals through the use of enzymes. In addition to this, *Trichoderma* species can withstand and store heavy metals like Ni, Cd, Zn, Pb, and As [55], [56]. Studies conducted by Lopez Errasqun and Vázquez [55] and Tripathi *et al.*, [54] suggest that soil quality and crop productivity have been negatively impacted by the overuse of agrochemicals. However, introducing *Trichoderma* to soil can help break down these chemicals and make the nutrients more accessible for crops. Table 2 demonstrates that *Trichoderma* species can remediate agrochemicals and pollutants in the environment.

2.1 *Source of Trichoderma-enriched biofertilizer*

The most important sources of biofertilizers are nitrogen fixatives, phosphate solubilizers and mycorrhiza [47]. These microorganisms include *Bacillus*, *Pseudomonas*, *Lactobacillus*, photosynthetic bacteria, nitrogen-fixing bacteria, and a wide range of well-known genera of nitrogen-fixing bacteria [79]. The impact of *Azospirillum* species on plant growth can be attributed to various factors, including the synthesis of plant hormones, nitrogen fixation, enhancement of nitrate reductase activity, and facilitation of mineral uptake [80]. *Azospirillum* plant association has been shown to induce biochemical changes in roots. This improves crop and pasture growth, increases the adsorption of water and minerals from the soil, and biologically improves nitrogen fixation [81]–[83]. The application of organic and biofertilizers have been widely used in vegetable production which has enhanced the growth and high yield of such vegetables [84]. Research has

Table 1: Biofertilizers and their functions

S/N	Biofertilizer	Functions	Microorganisms	References
1	Nitrogen fixers	Enzymes such as nitrogenase, nitrate reductase, nitrite reductase, and glutamine synthetase, help convert nitrogen into organic compounds that are usable by plants, as they have been biologically fixed into forms that plants can readily absorb.	*Azolla pinnata, Rhizobium spp., Azotobacter chroococcum, Azospirillum lipoferum, Acetobacter diazotrophicus, Derxia gummosa*	[23]
2	Phosphorus solubilizing biofertilizer (PSB)	Provide better bioavailability and bioaccessibility for Phosphorus to promote plant growth.	*Bacillus circulans, Bacillus coagulans, Torulospora globasa, Pseudomonas fluorescens (siderophore), Thiobacillus (SOM), Aspergillus niger (avirulent), Trichoderma spp., Paecilomyces spp*	[16], [57], [23]
		Solubilization in plants occurs through the production of organic acids, which help to lower soil pH levels. This process enables the breakdown of phosphate compounds, thereby releasing phosphorus for plant use.	*Rhizobium, Mycorrhizae, Bacillus, Pseudomonas*	[58], [59], [60], [23]
3	Potassium solubilizers Biofertilizer	Move and disperse unavailable K for the growth of plants.	*Bacillus spp., Pseudomonas spp.*	[14],[23] [61], [62]
4	*Trichoderma*	Help in detoxification of fungi, pesticides and herbicide		[61], [62]
5	Zinc mobilizer		*Pseudomonas spp., Bacillus spp., Rhizobium spp.*	[23]

Table 2: *Trichoderma* species involved in pollutant bioremediation

S/N	Pollutants	T. spp	Results	References
1	Bromoxynil	*T. Viride* and *T. harzianum*	The amount of bromoxynil remaining was 0.63 ppm (99. 37%) and 1.56 ppm (98.44%) using *T. Viride* and T. harzianum at a concentration of 100 ppm (of the initial concentration)	[63]
2	Olive oil mill waste water	*T. viride*	50% removal of phenolic compounds and 66% of organic Carbon was removed	[64]
3	Copper (Cu)	*T. atroviride*	Adsorption of Cu in vitro between 50 and 85%	[65]
4	Carbendazim and Mancozeb	*T. spp.*	Carbendazim and mancozeb were degraded by 36% and 25%, respectively, during incubation for 15 days	[66]
5	Zinc (Zn)	*T. atroviride*	Bioremediator of copper pollution, the fungus has a Zn adsorption capacity ranging from 30.4% to 45% and 47.6% to 64%, respectively. 30.4–45% and 47.6–64% Zn adsorption	[65]
6	Cadmium (Cd)	*T. asperellum*	Cd is removed at a rate of 76.17%	[67]
7	Benzo [a] Pyrene	*T. reesei*	The amount of B [a] P removed during the incubation period was 54%	[68]
8	Lead (Pb)	*T. viride*	Lead (Pb) uptake of 9.14 mg/g was observed	[69]
9	Chromium (Cr)	*T. viride*	Uptake of 2.55 mg/g of Cr	[69]
10	Diesel oil	*T. reesei*	A 40-day incubation at 25°C resulted in 98.78% degradation of petroleum hydrocarbons	[70]
11	2,4,6- trinitrotoluene	*T. viride*	The degradation of Trinitrotoluene creates hydroxymethyl 5-furancarboxaldehyde and 4-propyl benzaldehyde, which are major compounds.	[71]

demonstrated that the use of compost in agriculture provides benefits to the soil, plants, and the environment, including the presence of essential nutrients such as nitrogen, phosphorus, and potassium. This highlights the advantages of compost application in agriculture [85]–[87].

2.2 *Comparison of biofertilizer with chemical fertilizer*

Despite their benefits, there are many negative perceptions about organic fertilizers. It has some drawbacks. Due to insufficient skill and technology to produce biofertilizers from sufficient quantities of agricultural waste, biofertilizer is often considered more expensive than chemical fertilizers. In addition, the effect is faster than chemical fertilizers. In order to use the microbial inoculum effectively, it is importance to take attention to its storage and mixing with powder. Since biofertilizers contain living organisms, the surrounding environment plays a vital role in determining their performance thereby producing a diverse result [88]. Table 3 compared microorganisms and chemicals used in crop production. Biofertilizer production faces several challenges, including short shelf life, insufficient base material, sensitivity to high temperatures, as well as storage and transportation issues. These factors play a significant role in limiting efficient production, and they need to be addressed to overcome the bottlenecks associated with biofertilizers. This is highlighted in various studies [89]–[93]. The viability of fungal preparations can be affected by various factors, including substrate contamination and oxidative stress [91]. Chemicals such as pesticides, fertilizers, glue, and antibiotics are widely used in agriculture due to their practicality, effectiveness, and market availability [94]. Pesticides, for instance, are utilized to eliminate crop pests and diseases [95]. Pesticides are heavily employed throughout the entire production process of crops, from planting to storage, in various types of agriculture, including food crops, horticultural crops, forest crops, and plantations. These pesticides leave residues on plants and soil after application, which can be harmful to soil organisms [96].

2.3 *Biofertilizers and carrier materials properties*

According to Anubrata and Rajendra [97], Figure 2 below demonstrates the five key steps involved in creating carrier-based bio-fertilizers. Commercial use of *Trichoderma* improves plant health and conversely

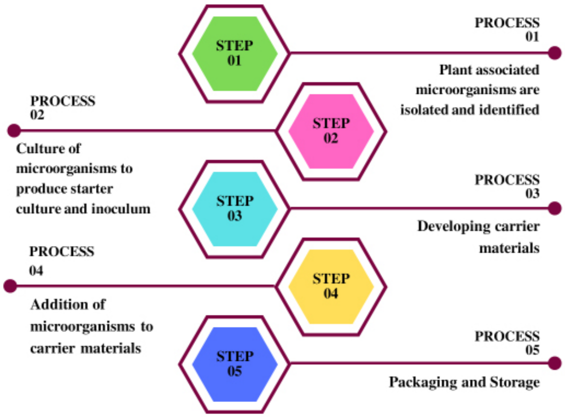

Figure 2: The general procedure in formulation carriers based biofertilizer.

controls plant disease, depending on the production of commercial formulations containing appropriate carriers that promote the long-term survival of the microorganism [98]. Most often, biofertilizers are made as carrier-based inoculants containing active microorganisms. Microorganisms are introduced into the carrier materials, which help to bring about easy handling, allow for long-term storage, and increase biofertilizer quality. Sterilization of the carrier material is important for durability and lasting storage of large numbers of inoculum on the carrier. Gamma irradiation or autoclaving has become the preferred sterilization method [99]. Seed or soil inoculation can be done with a variety of materials. The quality of effective carrier materials for seed inoculation must be affordable and readily available in sufficient quantity. It must not be dangerous to the plant nor the microorganisms used as inoculum. As a medium for seed inoculation, it should have strong seed adhesion and hygroscopicity. A good support material should be easy to prepare, have a high

Table 3: Microorganisms and agro chemical

S/N	Microorganisms	Agro Chemical	References
1	*T. atroviridae*	Organophosphate pesticide dichlorvos	[72]
2	*T. harziunum*	PGPR in metal-contaminated soil	[73]
3	*Trichoderma spp.*	Soil and water pollutants	[74]
4	*Trichoderma spp.*	Heavy metals, organometallic compounds, agrochemicals, tannery effluents, and harmful chemicals like cyanide	[75]
5	*Trichoderma spp.*	Pesticide-polyresistance cyanide	[76]
6	*T. harziunum*	Agrochemicals viz. DDT, dieldrin, endosulfan, penta-chloro-nitro-benzene, and penta-chloro-phenol	[77]
7	*T. harziunum*	Chlorpyrifos and photodieldrin (pesticides)	[78]

pH buffering capacity, and be gamma or autoclave sterilized [40]. The utilization of biofertilizer carriers enhances the efficacy of handling, storage and the shelf life of biofertilizers. Various solid biofertilizers such as diatomaceous earth, lignite, peat, charcoal, and agricultural wastes like rice and wheat bran, clay minerals have been employed as organic matter. However, in recent times, researchers have predominantly employed clay minerals, rice bran, and agricultural wastes such as Empty Fruit Bunches (EFB), Palm Oil Mill Effluent (POME), and crop residues as substrates [100], [101]. Adhesives such as gums, arabic methyl ethyl cellulose, and vegetable oils are used during inoculation to provide a firm cover to the seed surface [47].

3 Microorganisms Employed in Biofertilizer Production

Microorganisms frequently employed as components of biofertilizers include nitrogen-fixing agents (N-fixing agents), potassium-solubilizing agents (K-solubilizing agents), phosphorus-solubilizing agents (P-solubilizing agents), or mold and fungal agents combination [102], [103]. Most bacteria, including organic fertilizers, are closely associated with plant roots. Rhizobium has a symbiotic relationship with the roots of leguminous plants, and rhizobacteria live on the root surface and in the soil of the rhizosphere. Phosphorylating microorganisms, mainly bacteria and fungi, make insoluble phosphorus available to plants. Some soil bacteria and some fungi can convert insoluble soil phosphates into soluble forms through the secretion of organic acids [104]. These acids lower the pH of the soil and facilitate the dissolution of bound forms of phosphate. In contrast to the specificity of Rhizobium, Blue-Green Algae (BGA) and Azollacrop, biovaccines such as Azotobacter, *Azospirillum*, Phosphorus Solubilizing Bacteria (PSB) and Vesicular Arbuscular Mycorrhiza (VAM) can be considered broad-spectrum biofertilizers [104]. VAMs are the most commonly used fungi in crops to promote nutrient accumulation in plants. It has been reported that VAM stimulates growth and reduces the high impact of diseases caused by this pathogen through physiological effects [104]. Such free-living nitrogen-fixing bacteria include *Clostridium pasteurianum*, obligate aerobes (*Azotobacter*), facultative anaerobes, photosynthetic bacteria (*Rhodobacter*), cyanobacteria, and some contain methanogens. An examples of K solvent is *Bacillus muscilaginus*. According to a study by Singh *et al.*, [105], K solvent, also known as potassium solubilizing bacteria (KSB), is a key component in the production of biofertilizers due to its ability to solubilize potassium from insoluble minerals, making it available for plant uptake. Khan *et al.*, ([106] found that KSB significantly increased the growth parameters of wheat plants, including shoot length, root length, and dry weight, as a result of solubilization of potassium from minerals such as mica and feldspar by the KSB. Akhtar *et al.*, [107] investigated the effect of KSB on maize growth and yield. The results showed that KSB-treated plants had higher grain yield, plant height, and chlorophyll content compared to control plants, also noted that KSB increased the availability of potassium in the soil, which could have contributed to the observed increase in plant growth and yield. Examples of P solvents are *Bacillus megaterium*, *Bacillus circulans*, *Bacillus subtilis* and *Pseudomonas straita* [23]. P solvent, also known as phosphorus solubilizing bacteria (PSB), plays a crucial role in the production of biofertilizers due to its ability to solubilize insoluble forms of phosphorus in the soil, making it more available for plant uptake. According to the research conducted by Yadav *et al.*, [108], PSB has the potential to enhance plant growth and improve soil fertility. Another study by Sahu *et al.*, [109] reported that PSB application can improve the phosphorus availability in the soil, leading to increased plant growth and yield.

3.1 *Procedure in mass production of biofertilizer*

The procedure involved in the mass production of biofertilizer is shown in Figure 3.

3.2 *Mass production of biofertilizer*

Various scientists have made efforts to isolate *Trichoderma* spp., using a wide range of substrates such as pigeon beans, farm compost, wheat bran, neem cakes, mustard cakes, sawdust, coffee husks, vermicompost, sorghum grains, etc., but their use in mass propagation and formulation is mostly not studied [110]. The fact that the efficacy of the strains produced is generally unstable under a variety of environmental conditions which had to be infiltrated before the final product of organic

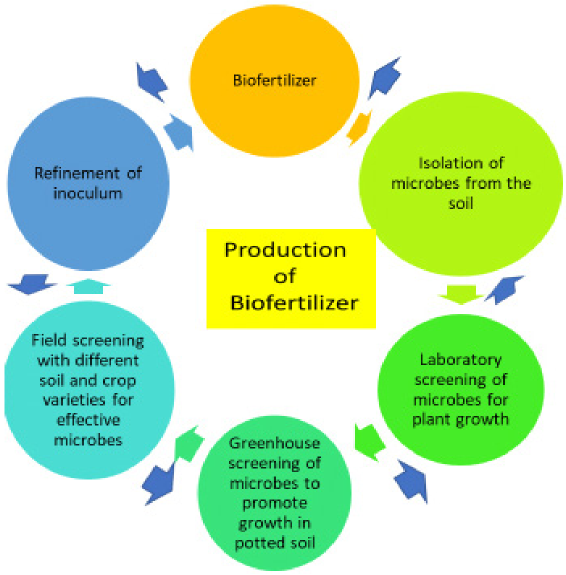

Figure 3: The procedure of mass production of biofertilizer.

origin reached the farmer's field is a factor in efficiency and a major challenge encountered in converting a commercial biocontrol agent into a commercial enterprise. The following properties are essential for developing a successful biofertilizer formulation: 1) a strong ability to function in the rhizosphere; 2) competitive saprophytic capacity; 3) improved plant growth; 4) enhanced mass growth; 5) wide range of activities; 6) preferable and reliable control; 7) environmentally safe; 8) compatible with other biological agents; 9) must be resistant to dryness, heat, oxidants and UV light [111]. There are different formulations as reported by researchers over the decades as follows.

Talc-based formulations for seed biopriming of *Trichoderma viride*, *T. harzianum*, *T. virens*, *P. fluorescens*, *B. subtilis*, and *Pseudomonas spp*. 10^8 CFU/g was used. By improving plumage length, root length and seedling freshness, seeds biopriming *T. harzianum*, *T. viride*, or *P. fluorecens* with 10 g talc-based formulations per kg of seed showed a high seed germination and vigorous seedling. It is an effective strategy for achieving seed germination and tall seedlings [112]. Harman *et al.*, [113] found that the use of talc-based formulations of *Trichoderma* as a seed treatment resulted in significant improvements in plant growth and disease control in several crops. Contreras-Cornejo *et al.*, [114] showed that the use of talc-based formulations of *Trichoderma* for seed biopriming resulted in significant improvements in plant growth and disease control in tomato plants.

Coffee husk was used in Karnataka in 1996 to prepare a *Trichoderma* formulation. Numerous studies have shown this product to be highly effective in treating black pepper foot rot. It is widely distributed in the states of Kerala and Karnataka according to Sawant and Sawant [115]. Microbial production of Bio Control Agent from coffee grounds eliminates contamination and improves biomass production under SSF. Due to its abundance of organic compounds and nutrients, *Trichoderma* species can develop on the coffee husks [116]. Santin *et al.*, [117] showed that *Trichoderma harzianum* produced in a coffee husk-based substrate had higher survival rates when applied to soybean seeds than when produced in a commercial substrate. Ferreira *et al.*, [118] investigated the use of coffee husk as a substrate for the production of *Trichoderma viride* and its application as a biopriming agent for maize seeds. The researchers also found that the application of the coffee husk-based formulation improved the seed germination and growth of soybean plants and also resulted in better plant growth and higher disease resistance in maize plants.

Vermiculite wheat bran formulation: Molasses and yeast were used as media for 10 days. After baking 100 grams of vermiculite and 33 grams of wheat bran at 70 °C for 3 days, fermenter biomass, 0.05 N medium, and concentrate or whole biomass contaminated with HCl are added. Vermiculite and wheat bran are used as a substrate to support the growth of beneficial microorganisms such as bacteria and fungi. Molasses and yeast are added to the substrate as a medium to promote the growth of microorganisms. After the substrate is baked to remove any potential contaminants, the microorganisms are introduced and allowed to grow for a period of time. The resulting mixture is a biofertilizer that can be applied to plants to enhance their growth and health [119]. Singh *et al.*, [105] reported that a vermiculite wheat bran-based formulation of *Trichoderma* harzianum effectively controlled the growth of *Fusarium oxysporum* in tomato plants, resulting in a significant increase in plant growth and yield. Anitha *et al.*, [120] investigated the efficacy of a vermiculite wheat bran-based formulation of *Trichoderma viride* against Phytophthora infestans, the causal agent of potato late blight. The results showed that the formulation significantly reduced disease severity and increased plant growth parameters.

Banana waste formulation: *Bacillus* polymixa and *P. sajor caju* cultures were used together with *Trichoderma viride* urea, phosphate rocks and urea-phosphate rock mixtures. The waste materials, like banana peels, pseudostoms and cores are sliced into pieces that are 5–8 cm long. Each ingredient is layered in five different layers within the pit. Each layer contains 1 tonne of banana waste, 5 kg of urea, 125 kg of phosphate rock, and 1 liter of a culture of *B. polymixa*, *P. sajor caju* and *T. viride*. Degradation of banana wastes is within 45 days and concentrated cultures are available in large quantities for field applications [121]. Studies have shown that banana waste-based formulations can be an effective carrier for *Trichoderma* and can improve its shelf life and viability [122]. The use of banana waste not only provides a cost-effective alternative for *Trichoderma* formulation, but also helps in managing waste from the banana industry. Banana waste-based formulation was developed for *Trichoderma viride* and its efficacy was tested on tomato plants. Results showed that the formulation not only enhanced plant growth and yield but also provided protection against *Fusarium* wilt disease [123]. Another study demonstrated the efficacy of a banana waste-based formulation of *Trichoderma* as a biocontrol agent against root-knot nematodes in tomato plants [124]. Research has demonstrated that *Trichoderma* asperellum can be produced locally using maize kernels as an inexpensive and effective carrier for the fungus [125]. Table 4 below shows the formulation and ingredients used in different *Trichoderma* species in liquid formulation.

4 *Trichoderma* Benefits as a Biofertilizer

Trichoderma species as plant pathogen biological control agents are widely used to control soil-borne fungi. It may contain residues of pesticides if it is isolated from the rhizosphere of plants in the soil. Besides removing residual insecticides, these bacteria also act as antagonists. Katayama and Matsumura found that *T. harzianum* degrades DDT, dieldrin, endosulfan, pentachloronitrobenzene, and pentachlorophenol and reported that the main enzymatic in *T. harzianum* for endosulfan degradation is the oxidative system [133]. *Trichoderma* species can degrade herbicides to the pyrazolone compound topramezone [134]. Almost all soils and other habitats contain *Trichoderma species*. There are several species of *Trichoderma*, such as *T. harzianum*, *T. viride*, *T. koningii*, *T. hamatum* [135], [136]. *Trichoderma* colonizes the root surfaces or cortex and tends to flourish in healthy roots and nutrient-rich [137]. *Trichoderma* has developed numerous mechanisms to combat fungal attacks and promote root growth. This includes producing antibiotics and parasitizing other fungi to keep harmful bacteria at bay [138]. Research has shown that this is the primary way by which *Trichoderma* positively influences the growth and development of plants [75]. Using numerous mechanisms including mycoparasitism, antibiotics, toxin degradation, inactivation of pathogen enzymatic pathways, pathogen resistance, improved Solubilization, sequestration, and increased uptake of nutrients by root hair which serves as an advantage of *Trichoderma* species in enhancing plant growth [27], [139]. In addition to stimulating root growth and root hair formation, *Trichoderma* induces the production of plant hormones. *Trichoderma* enhances the utilization of micronutrients like nitrogen, phosphate, and

Table 4: Liquid based formulation

S/N	Trichoderma Species	Substrate	References
1	Based 24 *T. hamatum*, *T. harzianum*, *T. viride*	Molasses and Brewer's yeast	[126]
2	*T. harzianum*	RM8	[127]
3	*T. harzianum* strain 1295-22	Modified RM8	[127]
4	*T. harzianum*	Czapeck's Dox Broth and V8 Broth	[128]
5	*T. harzianum* strain P1	Defined basal culture medium with mineral solution	[129]
6	*T. harzianum*, *Rifai*	Potato Dextrose Broth, V8 juice and molasses yeast medium	[130]
7	*T. harzianum*, *Rifai*	Potato Dextrose Broth, Czapeck's Dox Broth and Modified Richards' Broth	[131]
8	*T. harzianum*	Local cow urine, Jersey cow urine, Butter milk, Vermiwash	[132]

potassium, while also boosting seedling vigor and promoting germination [140]. *Trichoderma* is used on virtually all types of plants with or without additives, but when combined with compost it can produce superior results to other fertilizers. It contributes to the soluble transfer of micronutrients, such as Cu, Zn, Fe, and Na, from the soil to plants, and makes phosphate available to them [141]. Wang *et al.*, [142] reported the inhibitory effect of *T. viride* on volatilization, and (a) *T. viride* biofertilizers reduced soil pH during peak ammonia volatilization, and the two treatments (one with *T. viride* biofertilizer and one without) exhibited significantly different soil pH results. (b) *T. viride* biofertilizer improved nitrogen uptake in sweet sorghum and fertilizer utilization. (c) *T. viride* enhances nitrification rather than altering the functional bacterial community composition by increasing the abundance of functional genes. *Trichoderma* species produce a wide range of secondary metabolites and chemicals, which have been identified [143], [144]. Antibiotics, enzymes, hormones, and pathogens are classified according to Khan *et al.*, [144]. As enzymes, fungal phytochemicals contribute significantly to the breakdown of pesticide residues. Preparing *Trichoderma* seeds increases root shoot growth, vigor index and the amount of germinated seeds. In addition, *Trichoderma* species. Spraying significantly increased the yield of strawberries, peppers and cucumbers [145]. As an alternative to pesticides, *T. harzianum* can help increase tomato yields and decrease the occurrence of tomato wilt [146]. Application of *T. harzianum* T969 to seeds increased chlorophyll levels [147]. There are several mechanisms involved in this process, such as the solubilization of essential nutrients like phosphates, micronutrients, and minerals like Fe, Mn, and Mg that are important for plant growth. Root infections caused by various pathogens, both big and small, can invade the rhizosphere and lead to plant infection indirectly. Certain *Trichoderma* species can also aid in plant growth [148], and improve biotic and abiotic stress tolerance in plants [140]. *Trichoderma* helps improve productivity when treated vegetables are harvested 3–7 days earlier than control conditions [149]. Figure 4 shows the general mechanisms used by *Trichoderma* in agricultural productivity. *Trichoderma* species have multiple functions that can promote optimal crop growth and yield, including their ability to act as biocontrol agents and boost productivity. As a result,

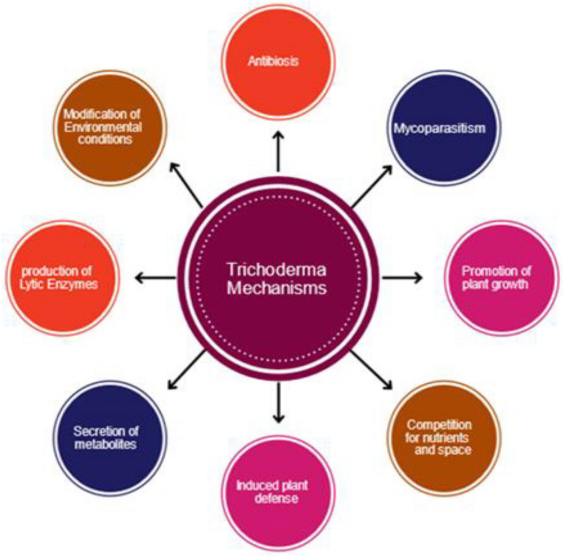

Figure 4: Mechanism used by *Trichoderma* to perform as a good biofertilizer.

incorporating *Trichoderma* into agricultural practices may help to increase food production while preserving natural resources. There are several commercially available products containing *Trichoderma* strains, such as *Trichoderma harzianum*, *Trichoderma viride*, and *Trichoderma* koningii that are used for crop protection and growth promotion. Figure 5 depicts the roles played by *Trichoderma* species in facilitating optimal crop growth and yield. The market cost of *Trichoderma*-based biopesticides varies depending on the product and the region, but generally, they are more expensive than chemical pesticides. However, the long-term benefits of using biopesticides, such as improved soil health and reduced environmental impact, can outweigh the initial cost. According to a study by Singh *et al.*, [150], the market cost of *Trichoderma*-based biopesticides in India ranges from INR 400–1500 per kilogram. Kumar *et al.*, [151] reported that the cost of *Trichoderma*-based biopesticides in India ranges from INR 150–200 per liter for liquid formulations and INR 300–350 per kilogram for solid formulations. In the United States, the cost of *Trichoderma*-based biopesticides varies between $10–30 per pound (USD) [152]. In addition, the global green revolution will always be driven by biofertilizers, which would play a crucial role in sustainable agricultural output. Economic cost, proper handling and storage practices,

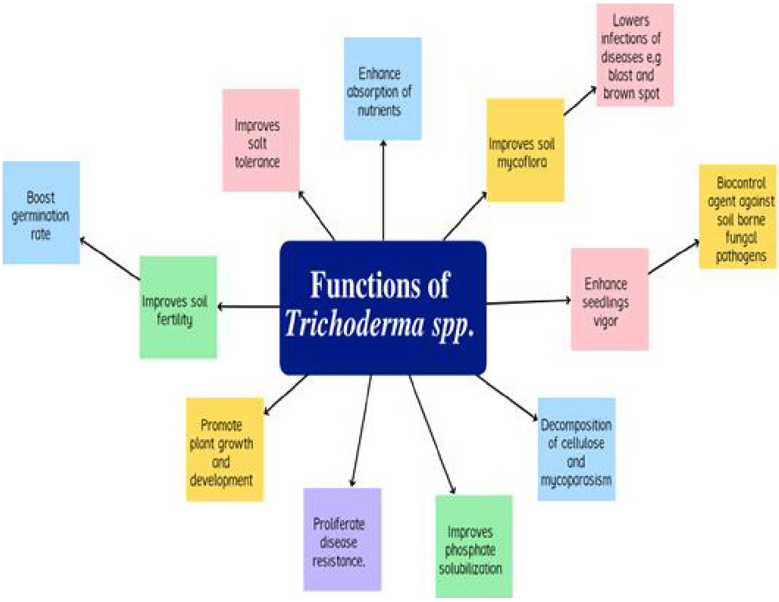

Figure 5: Functions of *Trichoderma* species for optimal crop growth and yield.

improvements, and market mechanisms for easy accessibility are important variables that will increase farmers' acceptance and sustainability. The necessity of biofertilizers to ecosystems and public health cannot be overemphasized. Therefore, it is necessary to emphasize this a lot to increase agricultural production. Long-term use of chemical additives causes ecosystems to deteriorate and become less productive, which finally results in the extinction of the natural resources and inhabitants of the area. To solve the existing issues brought on by the use of chemicals as inputs in agriculture, it should be encouraged to promote and embrace better future plans. This technique should be sustainable, sophisticated, better, more cost-effective, and have a longer shelf life.

5 Effect of *Trichoderma* spp. Secondary Metabolites on remediated insecticide contaminated soil

Several studies have investigated the effects of insecticide-contaminated soil on crop growth and production. For example, Yuan *et al.*, [153] reported that exposure to soil contaminated with the insecticide chlorpyrifos reduced the growth and yield of rice. Li *et al.*, [154] found that soil contaminated with the insecticide imidacloprid reduced the abundance and diversity of soil microorganisms, which are essential for healthy soil ecosystems and crop growth Qian *et al.*, [155] found that repeated exposure to rice crops to the insecticide chlorantraniliprole led to the development of insecticide-resistant pests and reduced crop yields. The use of *Trichoderma* will reduce the over-dependent on chemical insecticides and mitigate the negative impacts on soil and crops. A 150% crude secondary metabolite suspension of *T. harzianum* T213 produced an increase of 30.19% in the height of maize plant. There were no significant changes in leaves, showing that the healthy soil still supports the growth of leaves. A 150% crude secondary metabolite application of *T. harzianum* T213 yielded a 45% increase in terms of the fresh weight of maize plants. A crude secondary metabolite concentration of 150% was recorded for *T. harzianum* T213. The largest maize root length measured was 45%, the highest in the species [156]. In a study by Peerzada *et al.*, [157], the impact of various organic additives on *Trichoderma* bioagents in soil was analyzed. The results showed that these chemicals had a significant effect on the growth and reproduction of *Trichoderma* species. The fungus *Trichoderma* contributes to the reduction of late blight in potatoes by creating a symbiotic relationship between it and the plant. As a result of this relationship, various secondary metabolites are generated, such as growth hormones, enzymes called endochitinase, and proteolytic. In total, *Trichoderma* aids plant health [158]. Applying secondary metabolites from *Trichoderma* species can enhance the physiological characteristics of plants, such as strengthening the roots, shoots, biomass, leaves, branches, and fruits. Additionally, the use of these crude secondary metabolites in soil can improve plant nutrient uptake and promote plant height [159]. The secondary metabolites produced by *T. harzianum* play a significant role in increasing plant growth by promoting root length development. However, they also act as organic substances that can reduce the quality of natural products. On the positive side, these substances aid in accelerating decomposition processes and help maintain soil fertility over time [156]. By adsorbing organic acids and saturating soil nutrients, *Trichoderma* species' crude secondary metabolites promote nutrient uptake and increase soil nutrient mobility and absorption [160]. *Trichoderma* is attracted to chemical substances released by plant roots. The phytochemicals produced by *Trichoderma* are absorbed by the roots and supplied to all parts of the plant. There are several key secondary metabolites that aid in nutrient cycling and enzymatic activity. These include ureases, sucrases, phosphatases, and organic acids [161], [162]. In remediated soil, secondary metabolites of *T. harzianum* T213 improve nutrient distribution and provide supports that enable healthy soil for optimal plant growth [163]. It has been shown that *T. harzianum* T213 produces growth regulators, which improve plant growth and root development [159]. The application of *T. harzianum* also aids in mineral absorption from soil [160], [164]. Gibberellic acid (GA3), indoleacetic acid (IAA) and benzylaminopurine (BAP) are hormones produced by *T. harzianum* that promote plant growth [165], [166]. *Trichoderma* can be used alongside biofertilizers and organic fertilizers such phosphobacteria, *Azospirillum*, Rhizobium, and *Bacillus* subtilis [141].

6 Analysis of the impact of Trichoderma species on specific crops

Trichoderma biofertilizer can be used on a variety of crops including peanuts, cotton, wheat, tobacco, red gram, bengal gram, sugarcane, eggplant, chili pepper, potato, soybean, citrus, cauliflower, banana, sugar beet onions and peas, sunflowers, coffee, tea, ginger, turmeric, pepper, betel, and cardamom [141]. The annual

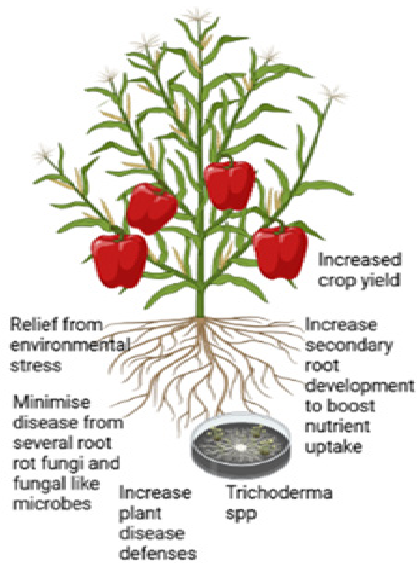

Figure 6: Show a complete function of *Trichoderma* on crop plants.

seedlings of P. sylvestris var. mongolica demonstrated higher soil enzyme activity and nutrient levels following *Trichoderma* inoculation as reported by [159]. Figure 6 shows a typical crop grown through *Trichoderma*. All propagation by *Trichoderma* inoculum improves the absorption area and growth parameters of seedlings, such as seedling height, root length, root diameter, and total biomass. Benefits of *Trichoderma* on crop plants are shown in Table 5.

7 Shelf life of *Trichoderma* formulations

Shelf life is an important aspect when commercializing biocontrol agents. In general, antagonists have longer shelf lives when replicated on organic diets than when grown on inert or inorganic diets. The two most common formulation technologies are liquid and solid technologies. In some regions of India, wettable powder formulations based on liquid fermentation are prominent. These formulations are characterized by a short shelf life [192]. Liquid fermentation is commonly used for mass production of *Trichoderma* spores from fungal strains [193]. Compared to conventional fermentation, liquid fermentation has many advantages such as better control of contamination levels, reduced labor and space requirements, and process control. Liquid fermentation can increase

Table 5: Analysis of the impact of *Trichoderma* species on specific crops

S/N	Trichodrema spp.	Crops	Outcomes	References
1	*T. harzianum*	Rambutan	The three prevalence postharvest diseases were reduced while maintaining the outstanding quality and coloration of fruits	[167]
2	*T. harzianum*	Potato	Stimulation of plant disease resistance.	[168]
3	*T. asperellum* SL2	Rice	When tested in controlled gnotobiotic greenhouse conditions, the growth, physiological characteristics, nutrient uptake, and yield of rice plants were all found to be improved.	[169], [170]
4	*T. harzianum*	Tomato	Increase yield of up to 336.5%	[171]
5.	*T. harzianum*	Chillies	Highest yield of chilies was recorded at (69.55 q/ha)	[172]
6	*T. asperelloides*	Arabidopsis, cucumber	Increased osmo-protection/oxidative stress thereby enhancing seed germination	[173]
7	*T. atroviride*, *T. virens*	Arabidopsis	Reduction in cold stress effects.	[174]
8	*T. parareesei*	Rapeseed	Systemic defense is induced due to jasmonic acid. Enhance adaptation to drought and salinity.	[175], [176]
9	*T.longibrachiatum*	Wheat	Seedlings were defended against salinity	[177]
10	*T. harzianum*	Tomato	Hindering the occurrence of bacterial canker, improving cold tolerance, promoting growth attributes, and reducing cold injuries in plants. Additionally, they support a high proportion of controlled plant secondary metabolites and growth regulators	[178]–[180]
11	*T. asperellum*	Poplar	Increase growth and defense responses.	[181]
12	*T. atroviride*, *T. koningii*, *T. harzianum*, *T. hamatum*	Chickpea	Restrained fungal infections	[182]
13	*T. harzianum*	Rice	Improve root growth, reduction of undesirable bacterial leaf blight and plant growth improvement.	[183], [184]
14	*T. atroviride*	Maize	Improved drought-induced damage to the photosynthetic system, lipid peroxidation, fresh and dry weights of maize roots, and activation of antioxidant enzymes and hydrogen peroxide.	[185]
15	*T. harzianum*	Indian mustard Rice	*Restored photosynthetic pigment level.* Increased yield of 30%	[184]
16	*Trichoderma asperellum*			[185]
17	*T. harzianum*	Mustard and tomato	50% N and Trichoderma enhanced yield by 108 and 203% over the control	[171], [186]
18	*T. viride*	Red beet Cabbage	Yield increased by 29%	[187]
19	*T. viride*	Wheat	75.8% increase with NPK, 41.8% with Farm Yard Manure	[188]
20	*T. viride*	Potato	16.25 more tubers per plant than the control 2.25 tubers per plant.	[189]
21	*T. harzianum*	Barley	Increase in yield by 17%	[190]
22	*T. harzianum*	Cucumber	Enhanced crop growth and fruit quality	[191]
23	*T. harzianum*	Chilli	improve yield by 11 q/ha compare that of control (58 q/ha)	[172]

the amount and rate of conidial biomass production [128]. When materials, which are soluble in water are employed to promote microbial growth, large-scale liquid fermentation methods are used [173]. For mass doubling of *T. harzianum* rifai, molasses yeast medium, V8 juice and dextrose broth made from potatoes were employed as liquid substrates [194]. The shelf life of liquid-fermented *Trichoderma* preparations needs to be increased. The viability of formulations obtained by liquid fermentation depends on many factors, including medium type, inoculum, drying method, preservatives, and environmental conditions during storage [195], [196], [197]. Glycerol is included in the formula to maintain higher levels of moisture and protect the viable reproductive organs from losing water activity during storage. When glycerol is added, formulations obtained from both shaker and fermentor cultures exhibit longer shelf lives compared to those without this addition. Inclusion of 3 or 6% glycerol in formulations retained more than 2 × 10^6 viable spores per gram. [198]. Adding glycerol alters the water activity, making the reproductive organs more resistant to dehydration. Water activity plays a critical role in the propagation of mushrooms produced by liquid fermentation, as low water activity makes propagation difficult, as reported by [76], [199]. In the current work, a drought-tolerant preparation of *T. harzianum* was obtained by reducing the water activity of the production medium by adding glycerol. The addition of glycerol, which decreased the water activity of the production medium to 9.33, had no effect on the development of viable propagules. The addition of 9% glycerol resulted in greater than 14% water retention for up to 11 months. Late in the shelf life, fungal contamination resulted in decreased viability and no seedling recovery at 106 dilutions. This was probably due to relatively elevated water levels [198]. Substrates such as grains, decaying organic matter and agricultural wastes are used in solid-state fermentation for large-scale propagation of *Trichoderma*. Sorghum and wheat have been used as solid substrates for the mass production of *T. viride*, with sorghum being preferred [200]. Solid-state fermentation batches were used to produce large amounts of *T. harzianum* using maize as substrate [201]. Palana *et al.* [202] discovered that poultry manure, goat manure, degraded coco, and coco pith were found to be suitable solid substrates for *T. viride* propagation. Wheat bran and rice straw have been identified as the most successful substrates for mass production of *T. harzianum*, along with corncob, paper waste, sawdust, sugar cane bagasse, waste straw, wheat bran and rice bran [203]. The shelf life of *Trichoderma* is about 18 months in a coffee cup. These *Trichoderma* formulations, which are based on talc, peat, lignite, and kaolin, have a shelf life of three to four months. According to Sankar and Jeyarajan [204] reported that viable *Trichoderma* propagules in talc formulations decreased by 50% after 120 days of storage. Bhat *et al.* [205] reported a shelf life of 180 days at ambient temperature for a talc-based formulation. Dryness was less pronounced between 75 and 180 days of storage than during the first 75 days. After 150 days of storage, the formulation had good reproductive viability (greater than 106 CFU/g). *T. viride* populations were higher in 100-micron-thick opalescent bags, according to his in-depth study of storage of *T. viride* formulations using polypropylene bags of various colors. In an attempt to prolong the shelf life of *Trichoderma* talc formulations, chitin and glycerol were added to the production medium in Bangalore. Furthermore, a heat shock was employed towards the end of the fermentation's exponential growth phase. As a result, the formulations can now be stored for up to a year. This was reported in a study by [198]. The study evaluated the longevity of *T. viride* in biomass sorghum grain-based formulations using charcoal. At the start of the experiment, the mean CFUs of *T. viride* in 10, 15, and 20 g of sorghum grain biomass powder/100 g of charcoal were 136.67 × 10^9, 186.00 × 10^9, and 248.00 × 10^9, respectively. After storage for 120 days, the recorded CFUs were 53.67 × 10^9 and 68.33 × 10^9 CFU/g, indicating a 71.14–72.44% decrease in survival. Nevertheless, a sufficient number of viable spores persisted in the formulation even after 120 days, suggesting that it can be stored for an extended period of time [110]. T *viride* shelf life in sorghum seed talc was assessed using three formulations at various concentrations, i.e. 10, 15, and 20 g/100 g talc, initially, the mean CFUs of *T. viride* in 10, 15, and 20 g biomass/100 g talc of sorghum grain on day 0 were 165.33 × 10^9, 202.6 × 10^9, and 252.6 × 10^9 CFU/g, respectively. Over time, the CFUs decreased to 49.0 × 10^9, 61.67 × 10^9, and 76.33 × 10^9 CFU/g after 120 days, indicating a decrease of 70.36%, 69.52%, and 69.79%, respectively. However, even after 120 days of storage, the formulation still contained a significant number of viable growth factors, suggesting that it can be preserved for an extended period of time [110]. Talc-based formulations showed the highest CFUs [206], [207]. Sarode *et al.*, [208] evaluated five different substrates and found that talc, charcoal, and fertilizer were the best carriers for storing *Trichoderma* for a long time. In order to investigate the longevity of *Trichoderma viride*, Saju *et al.*, [209] employed decomposed coffee grounds, coconut pulp, and agricultural manure, and found out that *Trichoderma* is best stored for a long time in farm manure. According to Singh *et al.* [192], the growth of *T. harzianum* is enhanced effectively using tea leaves as a substrate, with the maximum population (8 × 10^8 CFU/g) achieved after 30 days and a maximum shelf life of (2.9 × 10^5 CFU/g) observed after 210 days. Similarly, sawdust and various cereal grains have been found to provide higher CFU counts and longer shelf lives when used as substrates [210]. Furthermore, it was reported that mycelial growth promotion rate increased with increasing concentrations of deoiled cake and organic fertilizer [211].

8 Environmental Factors Influencing Trichoderma

8.1 *Temperature*

The ideal temperature range for mycelial growth is between 25 °C and 30 °C for most *Trichoderma* species, although there may be some variations in temperature requirements for certain species. However, it is worth noting that a temperature of 30 °C may not be the most suitable for achieving maximum antagonistic activity [212]. According to Karaoğlu *et al.* [213] and Contreras-Cornejo *et al.* [214], the capacity for growth differs among strains, with the highest level of growth taking place between 37 °C and 42 °C, while there is no growth at temperatures ranging from 2 °C to 4 °C. *T. polysporum* and *T. viride* are capable of growing at temperatures below 2 °C, but *T. harzianum* cannot grow below 5 °C when cultured on agar [215]. *T. pseudokoningii rifai* is the most temperature-tolerant species and can grow at high temperatures, whereas *T. viride* cannot grow above 28 °C [216]. According to a study conducted in the early 1970s on soils of forest ecosystems, *Trichoderma polysporum* and *T. viride* are generally found in cold climates, and *T. harzianum* in warm climates [217]. Widden and Scattolin reported that *T. koningii* and *T. hamatum* are capable of growing at 25 °C, but *T. polysporum* and *T. viride* grow more readily at a lower temperature [218].

8.2 *Soil moisture*

Moisture is said to regulate *Trichoderma* species. Only *T. psuedokoningii* feeds on moist soil. On the other hand, *T. polysporum* and *T. viride* grow in moist soils. *T. hamatum*, *T. harzianum*, and *T. koningii* were isolated from dry, humid, and moist forest soils, resulting in reduced sensitivity to soil moisture [219]. Additionally, research has shown that *Trichoderma* species benefit from very water-logged soils. According to some research, soil moisture has a considerably lesser impact on *Trichoderma* species' initial colonization than on their future expansion [147]. Humidity affects the physiological growth of *Trichoderma*. This is because osmoregulation consumes more energy in dry environments and less oxygen is available in wet environments. Nutrients are affected by water content in the same way that water content affects solute transport [146], [220]. Cytoplasmic translocation, or the movement of the cytoplasm to the root tip, enables them to endure adverse environments. By transitioning from a low osmotic pressure or nutrient-poor environment to a nutrient-rich one, it can also produce cell walls [158], [173], [221]. However, moisture is necessary for conidial growth. The effectiveness of *T. harzianum* in greenhouses in particular is influenced more by relative humidity than temperature on the surface of leaves [219].

8.3 *Nutrients*

Similar to chlamydospores and mycelium, conidia of *Trichoderma* species are dependent on these other media [222], [223]. Conidia need nutrients to germinate. Before conidia of various *Trichoderma* species can take up water, they must be exposed to nitrogen and carbon [92]. The germination of *T. harzianum*, *T. viride*, *T. koningii*, T. saturnisporum, and *T. polysporum* is aided by the addition of malt rather than glucose. Germination is also impacted by environmental acidity. This is because in nutrient-poor systems, more conidia grow in acidic than in alkaline conditions [224].

8.4 *pH*

Trichoderma species are affected by the acidity of the substrate because mycelium growth from conidia was greatest at a pH range of 3.7–4.7 [110], [225]. Since their pH ranges from 2.3 to 6.2, *T. hamatum* and *T. harzianum* were shown to be less sensitive. Several *Trichoderma* strains have been studied and found to be effective plant pathogen antagonists throughout a broad pH range [226], or their behavior is independent of their value. [227]. A pH range of 4.6–5 supports *Trichoderma* survival and *Fusarium* control. For growing onions in greenhouses [158]. Enzymatic activity is measured by medium pH rather than *Trichoderma* mycelial activity as a regulating mechanism [226], [228]. Most *Trichoderma* species tested exhibit a decrease in mycelial growth with increasing alkaline conditions on solid media [229]. Results from in situ research do not support in vitro experiments suggesting that *Trichoderma* growth is inhibited under alkaline conditions. The tested *Trichoderma* strain, medium, and pH level all affect the synthesis of the secondary metabolite 6-pentyl-alpha-pyrone, which has antifungal properties [230].

9 Challenges with *Trichoderma* Application Against Chemical Inputs

Despite the good performance of *Trichoderma*, there is slow progress in response to chemical control, for example, antagonistic fungi may take 2–3 weeks to complete the destruction of fungal pathogens whereas fungicides only need 2–3 h [231].

In comparison to chemical control, bio-pesticides are more expensive and have a shorter shelf life. Biopesticides need to be carefully handled, stored, and produced to maintain their effectiveness. If they are not properly stored, they tend to degrade over time and become less effective. This can increase the cost of production and the price of the final product [172].

Chemical control works effectively in any location, while bio-control can be applied successfully in places with high humidity, few pests, and fungicide-free environments [232].

Due to increased exposure to fungus or fungal compounds, this technique harms immune-depressed or immunocompromised people in terms of their health [233]. Some *Trichoderma*, particularly *T. brevicompactum*, *T. atroviride*, and *T. harzianum*, have the potential to cause opportunistic diseases in people, such as sinusitis, skin and liver infections, pneumonia, and stomatitis [234].

9.1 *Future works and recommendation*

Trichoderma species' success in a given environment depends on their capacity for colonization, reproduction, persistence, and the time taken for effective performance. The focus should be on identifying the different *Trichoderma* strains that are least affected by the environment and have high survival, reproduction and colonization rates. However, little information about its ecology and colonization has been described. The processes through which biofertilizers interact with plants and other microbial ecosystems remain concerns that need to be clarified to gain greater acceptance among farmers. Furthermore, few shelf-life studies have been conducted to determine its effectiveness as a risk factor for microbial inoculation. Atieno *et al.* [235] reported that farmers' perceptions and preferences for chemical fertilizers were more acceptable compared to organic fertilizers, and that extension workers were among farmers in hopes of improving crop yields. More awareness campaigns can be conducted to raise awareness of organic fertilizers. Therefore, further research should be done before deciding to commercialize biofertilizers in order to ascertain their long-term effects on non-target species.

10 Conclusions

The use of *Trichoderma* as a biofertilizer plays a crucial role in promoting sustainable agricultural output as an ecofriendly crop booster addressing concerns related to ecosystems and public health. Transitioning away from the long-term use of chemical additives is necessary to prevent the deterioration of ecosystems and ensure the longevity of natural resources As such, it is important to prioritize economic cost, proper handling and storage practices, improvements, and market mechanisms to increase their accessibility and acceptance among farmers. Additionally, encouraging the promotion and adoption of sustainable, sophisticated, and cost-effective techniques with longer shelf life will be key to achieving these goals.

Author Contributions

O. M. A.: conceptualization, investigation, review, writing, and editing. D. A. O.: writing, analyzing data, and editing. T. A.: writing, editing. The final version of the manuscript has been read and approved by all authors.

Conflicts of Interest

The authors declare no conflict of interest.

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