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A review on the biological properties of *Trichoderma* spp. as a prospective biocontrol agent and biofertilizer

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Abstract

The over-use of synthetic pesticides and fertilizers has resulted in favoring the selection of resistant plant pathogens and the reduction of soil fertility. Eco-friendly alternatives such as the use of biocontrol agents and biofertilizers should be practiced as substitutes to the synthetic chemicals in this present day. The use of fungi such as *Trichoderma* species as biocontrol agents has been widely practiced in forestry and industrial agriculture. Biocontrol agents are effective against many pathogenic fungi and benefit immensely in growth, health, and productivity of plants. They are also relatively less harmful as they are obtained from natural derivatives when compared to synthetic pesticides. Likewise, biofertilizers enable nitrogen fixation, solubilization of soil phosphates, and production of plant growth substances in the soil improving the soil health and fertility. The article reviews in detail the various beneficial aspects of *Trichoderma* species as biocontrol agent and biofertilizers as they are claimed as an effective and successful commercial agent in controlling various plant diseases and promote plant growth.

1. INTRODUCTION

Since the last few decades, the agricultural systems have continuously improved in efforts to maximize the production of a sufficient supply of safe, nutritious, and high-quality food globally. The wide use of agrochemicals such as synthetic fertilizers and pesticides undeniably plays a significant part in increasing crop yield in the shortest possible time and in maintaining sufficient food supplies [1,2]. However, a significant number of issues have arisen, which associate the usage of these agrochemicals to environmental issues. The excessive inputs of synthetic pesticides and fertilizers have led to many adverse effects such as the rise of resistant plant pathogens, atmospheric pollution, groundwater pollution, soil degradation, fertility reduction, health hazard, and environmental hazards [1,3,4]. These problems have prompted the need to identify harmless alternatives that are also inexpensive and sustainable. Therefore, eco-friendly alternatives such as biocontrol agents and biofertilizers were considered as a substitute to the use of synthetic chemicals in this present day.

The use of fungi as biological control agents has been widely practiced in forestry and industrial agriculture. In recent years, more studies are highlighting the importance of fungi with implications for plant yield and food production by a mechanism of suppressing undesirable diseases caused by pests or pathogens. Nowadays, there are many fungi used as biocontrol agents, some examples are *Aspergillus* spp., *Ampelomyces* spp., *Candida* spp., *Coniothyrium* spp., *Gliocladium* spp., and *Trichoderma* spp. [5-8]. Among these fungi, *Trichoderma* is the most competent for being able to control the development of pathogenic fungi [9] and to promote plant growth. The study would aim to describe the role of *Trichoderma* species in details as a biocontrol agent and biofertilizer along with the recent advancements, mechanism involved, and would attempt to brief on the commercially available products of *Trichoderma* species for application.

1.1. Trichoderma

Trichoderma is a genus of a heterogeneous group of fungal species. They are mainly classified as anamorphic *Hypocreales* and are further described by quick development and bountiful production of conidial spores as well as the capacity to produce sclerotia [10]. *Trichoderma* species are ubiquitous saprophytic fungi and they are usually found in the soil and root ecosystems [11-14] as well as above ground such as on rotting wood and other organic materials [15-19]. Some of them are capable of being mycoparasites [20] and may be antagonistic to other fungi using their cell walls and cytoplasmic parts as nourishing assets. Further, *Trichoderma* strains produce few pigments, ranging from a greenish-yellow up to a reddish tinge and sometimes colorless strains might likewise be available. The conidia can have different hues, going from drab to various tints of green or dim or earthy colored hints [10]. The characteristics of *Trichoderma* are as follows: Septate and translucent hyphae; conidiophores are short, translucent, branched often giving the pyramidal appearance, not verticillate, bearing

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phialides which may appear singly or in groups; spores produced are conidia which are translucent, ovoid in shape, borne in small terminal clusters at the tips of phialides [21,22].

In general, *Trichoderma* is not viewed as pathogenic or destructive to plant development. Their presence in the rhizosphere as biofertilizers can promote plant development and improvement [10]. Moreover, there have been numerous reports on the capacity of *Trichoderma* species to colonize roots as symbionts, and to initiate systemic and localized resistance in plants, which protects the plants against various pathogens such as fungi, bacteria, viruses, and even insects [10,11,18,23] as well as to stimulate plant development and growth [24]. In addition, *Trichoderma* can thrive effectively under very competitive conditions due to their natural resistance to antibiotics produced by other competing microorganisms [25]. In economic essence, they have a wide scope of valuable features for numerous biotechnological applications, mainly in agriculture, industry, and environmental biotechnology [10].

2. TRICHODERMA AS BIOCONTROL AGENTS

Plant diseases caused by pathogens have resulted in a decreased crop yield, growth, and development. Pathogens including certain fungal strains are mainly accountable for causing diseases in plants leading to high loss of yield [14,26-28]. Out of various ways to prevent yield losses due to pathogenic fungi, the use of synthetic fungicides is a widely practiced [14,27,29]. However, they may have destructive implications on the environment and human health [30-32], and it may also result in the resistance development of the pathogenic fungi infecting the plants [33]. Over time, once the pathogen develops resistance, the existing synthetic fungicides may become ineffective and the use of new fungicides will have to be implemented for future effective disease control [14]. A potentially effective and powerful method to control plant disease is using microorganisms as biocontrol agents as an alternative agro-practice [14,34]. This approach depends on the antagonistic relationship between such organisms and the target pathogens [35]. For example, soil-borne plant pathogens can possibly be controlled by the addition of antagonistic microorganisms to the soil, which is a non-chemical means for plant disease control [36].

Fungi in recent years are considered as good candidates for biocontrol agents and as good alternatives for substituting chemical usages. Köhl *et al*. [37] defined biological control as the process that lessens the number of microbial pathogens by other microorganisms that act as antagonists. Different mechanisms of biocontrol can operate under different conditions. Unlike other biocontrol agents such as viruses and bacteria, fungi do not need to be ingested to infect their hosts but rather they attack directly through the organisms. *Trichoderma* is commonly used in the development of biocontrol agents. Biocontrol agents are microorganisms that are capable to antagonize and suppress plant disease causing pathogens [10]. They are safer to be used compared to using chemical pesticides and at the same time are not any less effective. Biocontrol agents also have no harmful implications to other organisms that are beneficial for plant growth, health, and productivity. An effective biocontrol agent should be genetically stable, and able to be mass-produced efficiently using cheap media, as well as effective at low concentrations against various pathogens [38,39]. Moreover, the biocontrol agent must not be toxic to humans, be impervious to pesticides, not harmful to the environment, and not pathogenic to the host plant [14,39,40].

The unique property of *Trichoderma* spp. to secrete mycolytic enzymes and its non-phytopathogenic nature makes it a most attractive biocontrol agent [41] compared to the other fungal species known for their biocontrol activity. Biocontrol by *Trichoderma* involves a number of mechanisms including mycoparasitism or hyperparasitism, antibiosis, induction of resistance, and competition for nutrients and space with plant pathogens [12,15,20,33,42]. In addition, alteration of the root architecture which improves the plant's resistance to pathogens, and destruction of the root-knot nematode at the different stages of its growth phases, and of certain segments of adult nematodes have also been reported [43]. Table 1 describes the various bio-active compounds secreted by the *Trichoderma* species and their roles in biological control. The mechanism of biocontrol activity of the species could be further categorized into two modes, that is, the direct and the indirect mode.

2.1. Direct Mode of Biocontrol Activity by *Trichoderma* spp.

2.1.1. Mycoparasitism

Many studies have reported that *Trichoderma* can prevent some plant diseases via inhibition of the plant pathogens mostly found in the rhizosphere, through mycoparasitism or hyperparasitism [119,120]. It refers to the process in which *Trichoderma* lives in the expense of another plant parasite by either colonizing on the parasite or living inside the parasite [121-123]. For example, hyper-parasitic *Trichoderma harzianum* is used in controlling the choke disease caused by the fungal *Epichloe typhina* in a grass species *Puccinellia distans* [121]. This method has been widely used in controlling various plant pathogens such as *Sclerotium rolfsii, Botrytis cinerea*, and *Rhizoctonia solani* [124]. Trichodex is the commercially available *Trichoderma* formulation that is widely applied to reduce plant diseases [121,125].

Mycoparasitism is a common mechanism by which there is an antagonistic direct contact action towards a pathogen. There are several stages of mycoparasitism by *Trichoderma* including pathogen recognition, binding to the target, enzymatic disruption of the fungal cell wall, and assimilation of the cytoplasmic content [10,12,14,126]. *Trichoderma* can attach to a target pathogen by binding the carbohydrates of their cell wall to the lectin of the pathogen. Upon contact, *Trichoderma* will coil around the target fungus and develop appressoria. *Trichoderma* can produce cell wall degrading enzymes for example amylase, cellulase, chitinase, glucanase, lipase, pectinase, protease, and xylanase [127], and also numerous volatile compounds for example 6-pentyl-α-pyrone (6-PAP), toluene, D-limonene and α-bergamotene [128]. Other metabolites can also be produced [Table 1]. The cell wall degrading enzymes play a significant role in facilitating the hydrolytic degradation of the cell wall of the fungal pathogen, which can be made up of chitin and glucan polysaccharides [10]. *Trichoderma* can produce a high level of extracellular enzymes that degrade cellulose and chitin [10]. According to Howell [15], the preliminary degradation of the cell wall of *Botrytis cinerea* and *Fusarium oxysporum* by lytic enzymes enabled the easier penetration of antibiotics into the pathogen cells.

2.2. Indirect Mode of Biocontrol Activity by *Trichoderma* spp.

2.2.1. Antibiosis

Most fungal species are capable of secreting one or more compounds with antibiotic properties. Many *Trichoderma* species can produce low molecular weight secondary metabolites with antibiotic properties which can interfere with the development of various microorganisms through inhibition [10]. This inhibition action is called antibiosis. It is another mechanism found in *Trichoderma* for controlling plant pathogens, which depends on the secretion of antimicrobial compounds

Table 1: Secondary metabolites secreted by *Trichoderma* spp. and their bio-active role

Chemical nature	Secondary metabolites	*Trichoderma* species involved	Bio-activity observed	References
Alcohol	1-Octen-3-ol	*Trichoderma atroviride*	Induces conidiation and defense responses through JA	[44-46]
	2-Phenylethanol	*Trichoderma harzianum*	Reduces the growth of *Aspergillus flavus* and aflatoxin production	[47,48]
	Tyrosol	*Trichoderma harzianum*	A quorum-sensing molecule	[47]
Anthraquinone	Chrysophanol	*Trichoderma aureoviride*, *Trichoderma viride*	Related to pigmentation	[49]
	Pachybasin	*Trichoderma harzianum*	Increases the number of coils of the biocontrol agent against *R. solani*	[50]
	Emodin	*Trichoderma viride*	Antimicrobial and antineoplasic agent	[51-53]
Azaphilone	T22azaphilone	*Trichoderma harzianum*	Inhibits the growth of *Rhizoctonia solani*, *Pythium ultimum* and *Gaeumannomyces graminis*	[54]
	Fleephilone	*Trichoderma harzianum*	Inhibitory activity against the binding of regulation of virion expression (REV) proteins to REV responsive element RNA	[55]
	Harziphilone	*Trichoderma harzianum*	Cytotoxicity against the murine tumor cell line M-109	[55]
Bisorbicillinoid	Bisvertinolone	*Trichoderma longibrachiatum*	Antifungal properties via inhibition of β-(1,6)-glucan biosynthesis	[56]
	Trichodimerol	*Trichoderma longibrachiatum*	Inhibitory activity against lipopolysaccharide-induced production of tumor necrosis factor α in human monocytes	[57]
	Bisorbicillinol	*Trichoderma* spp. strain USF-2690	Antioxidant properties	[58]
Butenolide	5-Hydroxyvertinolide	*Trichoderma longibrachiatum*	Potential antagonistic activity against the fungus *Mycena citricolor*	[59]
	dehydro-derivative of harzianolide	*Trichoderma harzianum*	Antifungal activity against *Gaeumannomyces graminis* var. *tritici*	[60-62]
	T39butenolide	*Trichoderma harzianum*		[54]
Carotanes	Trichocaranes A, B, C and D	*Trichoderma virens*	Inhibits the growth of etiolated wheat coleoptiles	[63]
Diketopiperazine	Gliotoxin	*Trichoderma hamatum* *Trichoderma viride* *Trichoderma virens*	Antiviral, antibacterial, fungistatic activity and immuno-suppressive properties	[64,65]
	Gliovirin	*Trichoderma virens*	Antimicrobial compound against oomycetes and *Staphylococcus aureus*	[66]
Dipeptide	Trichodermamide A	*Trichoderma virens*	Has a weak cytotoxic effect on three cell lines, P388, A-549 and HL-60	[67,68]
	Trichodermamide B	*Trichoderma virens*	Displays cytotoxicity against HCT-116 human colon carcinoma	[64]
Ergosterol-derivated compound	Ergokonin A	*Trichoderma longibrachiatum*, *Trichoderma koningii*, *Trichoderma viride*	Antifungal activity against *Candida* spp.	[64]
Hydrocarbonated compound	Ethylene (ET)	*Trichoderma atroviride*	Regulates cell diferentiation and defense responses	[69]
Hydrolytic enzymes	Cellulases	*Trichoderma reesei*	Degrades cellulase during root colonization to penetrate the plant tissue	[70,71]
	β-1,6-Glucanases	*Trichoderma* spp.	Hydrolyses fungal pathogen cell walls of *B. cinerea*, *R. solani*, *Phytophthora citrophthora*	[16]
	Chitinases	*Trichoderma* spp.	Hydrolytic enzymes of the fungal cell wall	[72,73]
Indolic compound	Indole-3-acetic acid (IAA)	*Trichoderma atroviride*, *Trichoderma virens*	Controls a number of growth and development processes in plants	[74]

(*Contd...*)

Table 1: (*Continued*)

Chemical nature	Secondary metabolites	*Trichoderma* species involved	Bio-activity observed	References
	Indole-3-acetaldehyde	*Trichoderma atroviride*, *Trichoderma virens*	Controls root growth in *A. thaliana*	[74]
	Indole-3-carboxaldehyde	*Trichoderma atroviride*, *Trichoderma virens*	Induces adventitious root formation in *A. thaliana*	[23]
Isocyano metabolite	MR566A, a chlorine-substituted cyclopentyl isonitrile	*Trichoderma harzianum*	Inhibits melanin biosynthesis in B16 melanoma cells	[75,76]
Isoprenoid	Abscisic acid (ABA)	*Trichoderma atroviride*, *Trichoderma virens*	Regulates stomatal aperture in *A. thaliana*	[77]
Ketone	3-Octanone	*Trichoderma atroviride*	Induces condiation	[45,46]
Koninginins	koninginins A–E	*Trichoderma koningii* *Trichoderma harzianum*	Antifungal activity against *F. oxysporum*, *Fusarium solani*, and *Alternaria panax*	[78-80]
Monoterpene	β-Myrcene	*Trichoderma virens*	Regulates the expression of genes related to abiotic and biotic stresses	[81,82]
	cis- and *trans*-β-Ocimene	*Trichoderma virens*	Induces expression of JA defense response-related genes in *A. thaliana*	[81,82]
Nitrogen heterocyclic compound	Harzianic acid	*Trichoderma arundinaceum*; *Trichoderma harzianum*	Antimicrobial metabolite, siderophore and plant growth regulator	[83-86]
	Harzianopyridone	*Trichoderma harzianum*	Antifungal activity against *Botrytis cinerea*, *R. solani* and inhibitor of the protein phosphatase type 2A (PP2A)	[87,88]
	Melanoxadin	spp. strain ATF-451	Inhibits melanin formation in the larval hemolymph of the silkworm, *Bombyx mori*	[89]
Peptaibol	Alamethicin	*Trichoderma viride*	Induces plant defense in lima bean and pathogen resistance	[65,90,91]
	Trichovirin II	*Trichoderma virens*	Induces resistance in cucumber plants	[65]
	sm1	*Trichoderma virens*	Activates defense responses in cotton, rice and maize	[92,93]
	Epl1	*Trichoderma atroviride*	Triggers defense responses through JA and SA in maize	[94]
	trichokonins VI, VII, and VIII	*Trichoderma koningii*	Broad-spectrum antimicrobial activity against a range of important plant pathogens, such as *R. solani*, *Fusarium oxysporum*, *Verticillium dahliae*, and *Botrytis cinerea*	[91,95]
	Peptide based antibiotic	*Trichoderma citrinoviride* VKPM F-1228	Broad spectrum antibiotic activity against pathogenic bacteria, clinical *Aspergillus* spp., and micromycetes	[96]
Peptide	Trichokonin VI (Tk VI)	*Trichoderma longibrachiatum*	Inhibits primary root growth in *A. thaliana*	[97]
Pyrane	Koninginin A	*Trichoderma koningii*	Plant growth regulator	[78]
	Koninginin D	*Trichoderma koningii*	Alters pathogen fungal growth of *R. solani*, *Phytophthora cinnamomi*, *Pythium middletonii*, *Fusarium oxysporum* and *Bipolaris sorokiniana*	[98]
Pyridones	Hharzianopyridone	*Trichoderma harzianum*	antifungal activity against plant pathogenic fungi, such as *P. ultimum, G. graminis* var. *tritici*, *R. solani*, and *B. cinerea*	[54,87]
Pyrones	6-pentyl-2H-pyran-2-one	*Trichoderma viride* *Trichoderma atroviride* *Trichoderma harzianum* *Trichoderma koningii*	Antifungal activity against *R. solani, F. oxysporum, Botrytis* spp., *Penicillium* spp., *Aspergillus fumigatus*, *Candida albicans* and *Cryptococcus neoformans* Antinematode and plant growth-promoting activities in tomato and *A. thaliana*	[46,61,64,99, 100,101]
	Viridepyronone	*Trichoderma viride*	Antagonistic activity against *Sclerotium rolfsii*	[102]

(*Contd...*)

Table 1: (*Continued*)

Chemical nature	Secondary metabolites	*Trichoderma* species involved	Bio-activity observed	References
Sesquiterpene	Cyclonerodiol	*Trichoderma harzianum* *Trichoderma koningii*	Inhibits growth of etiolated wheat coleoptiles	[79,103]
	Heptelidic acid (koningic acid)	*Trichoderma virens*, *Trichoderma viride*	Potential activity against the human malaria parasite, *Plasmodium falciparum*	[64,104,105]
	β-Farnesene	*Trichoderma atroviride*	Acts as an alarm pheromone in aphids	[46,106]
	β-Caryophyllene	*Trichoderma virens*	Attracts nematodes that prey on insect larvae	[82,107,108]
Setin-like metabolite	Trichosetin	*Trichoderma harzianum*	Inhibits the growth of rice, tomato and medicago	[64]
Siderophore	Fusarinine C	*Trichoderma* spp.	Fe-chelated, can be available to plants	[109]
	Ferricrocin	*Trichoderma atroviride*[a], *Trichoderma virens*[a], *Trichoderma reesei*[a]	Key metabolite in the competition for iron in the rhizophere	[110]
	Coprogen B	*Trichoderma* spp.	Solubilizes iron unavailable to the plant	[103]
Statin	Compactin (mevastatin)	*Trichoderma longibrachiatum*, *Trichoderma pseudokoningii*	Activity as a cholesterol-lowering agent	[111-113]
Steroidal compound	Viridin	*Trichoderma koningii*, *Trichoderma virens*, *Trichoderma viride*	Antifungal metabolite that alter the spore germination of *Botrytis allii*, *Colletotrichum lini* and *Fusarium caeruleum*	[64]
	Viridiol	*Trichoderma virens*	Herbicidal properties	[114]
	Wortmannolone	*Trichoderma virens*	Inhibits phosphatidylinositol 3-kinase with potential to attack human neoplasms	[64,115]
	Virone	*Trichoderma virens*	Inhibits phosphatidylinositol 3-kinase	[64,115]
Trichothecene	Trichodermin	*Trichoderma brevicompactum*	Fungitoxic metabolite against *Candida* spp.	[116,117]
	Trichodermin	*Trichoderma brevicompactum*	Phytotoxic effect	[86]
	Trichodermin	*Trichoderma viride*, *Trichoderma polysporum*, *Trichoderma sporulosum*, *Trichoderma reesei*	Inhibits the elongation and termination steps in protein synthesis	[64]
	Trichodermol	*Trichoderma* spp.	Antimalarial agent	[64]
	Trichodermin and harzianum	*Trichoderma arundinaceum*	Plant defence	[118]

or specific secondary metabolites that exhibit inhibitory properties. There are more than 180 secondary metabolites of *Trichoderma* that has been characterized into various classes of compounds [64,129]. These compounds have different roles in the biological control of different pathogens. Some secondary metabolites have the capability of modifying plant metabolism and growth. *Trichoderma* strains, for example, *Trichoderma viride*, *T. harzianum,* and *Trichoderma koningii*, are capable of production and secretion of a volatile metabolite, 6-PAP which is responsible for the biocontrol of several pathogenic species such as *Botrytis cinerea, Rhizoctonia solani,* and *Fusarium oxysporum* [10]. According to Harman [11], different groups of metabolites might play an important role as plant resistance inducers.

2.2.2. Competition

Some studies suggest the existence of a competition between fungi and pathogens as another mechanism of biocontrol. *Trichoderma* may compete for essential nutrients and limit the growth of pathogens [130]. Apart from nutrients, *Trichoderma* can also compete with other pathogens for space including infection sites on plant roots [10]. *Trichoderma* can easily colonize the rhizosphere of diverse environments and cause significant changes in plant metabolism [11,42]. The mechanisms which aid in the colonization of the diverse ecological niches are exceptionally evolved and vary in *Trichoderma* [12,131,132]. Moreover, *Trichoderma* is resistant to toxic metabolites that are produced by plants such as flavonoids, terpenoids, phenols, and phytoalexins in response to infection. *Trichoderma* can defend plants against pathogens through a physical interaction between *Trichoderma* and the plants up to the outer layer of the epidermis and the root bark [42]. *Trichoderma* can acidify their surrounding environment to produce adverse conditions for the growth of pathogens [10,33]. Furthermore, the wide metabolic versatility of many *Trichoderma* species has enabled them to use different and complex carbon and nitrogen sources, which allow *Trichoderma* to limit competing pathogens from growing and spreading in the environment [25].

2.2.3. Induction of systemic resistance

Trichoderma spp. are capable of inducing systemic and local resistance in the plants against the plant pathogens as a result of the physiological and biochemical changes initiated by complex interactions between the microbial biomolecules and plant receptors [11,133,134]. This triggers the formation of the defense enhancing chemical, that is, salicylic acid in the entire plant as a systematically induced defense mechanism and also by inducing the synthesis of regulatory plant proteins that could help in the defense mechanism by recognizing the microbial biomolecules [135]. It is also documented that the induction of systematic and local resistance in a plant is further dependent on the plant species, pathogenic microbial species, environmental factors, and rhizosphere and symbiont relationship [136].

3. TRICHODERMA AS BIOFERTILIZERS

Biofertilizers are defined as substances containing beneficial living microorganisms that colonize the soil ecosystems and enhance plant growth by increasing the supply of primary nutrients to the host plants [1,137,138], improve soil chemical and biological properties, phosphates solubilization, and agricultural production [139]. Biofertilizers have many benefits compared to synthetic fertilizers such as they increase absorption of nutrients in plants, minimize leeching, and are involved in composting of solid wastes [14,137,138,140]. One of the main sources of biofertilizers is fungi that are used for the inoculation of seed and soil to increase nutrient availability for plants [141]. They can restore the nutrient cycle in the soil, form soil organic matter by releasing growth-promoting hormones and improve root proliferation [1]. These biofertilizers are capable of fixing atmospheric nitrogen, decomposing organic materials, and solubilizing soil phosphates, which are beneficial in improving soil fertility as well as enhancing plant growth through the supply of nutrients [14,142]. Furthermore, they are environmentally friendly and are safe for crops or other plants [143].

Trichoderma species are known biofertilizers for promoting plant growth and development, and are regularly utilized by most crop types with or without amendments [19]. They are well known to improve plant nutrient uptake, produce growth hormones and provide plant protection from pathogens [144,145]. According to Chang and Baker [146], when *Trichoderma* are applied regularly to plant soil, they promote plant growth and seed germination, development of roots, and improvement in height and weight of the plant. *Trichoderma* are known to improve overall plant health and produce different types of secondary metabolites including growth hormones and certain enzymes, and to benefit plants through *Trichoderma*-plant interactions [19,33]. From these interactions, it is evident that plant growth is stimulated from the production of vitamins, increased availability of biogenic elements such as nitrogen and phosphorus, mobilization of nutrients in soil and plants, and improved mineral uptake and transport [10] [Table 2].

Mastouri *et al*. [165] stated that these fungi mobilize nutrients in plants to increase crop yield. Some *Trichoderma* strains can produce organic acids such as gluconic acid, citric acid, and coumaric acid and acidify the surrounding environment to solubilize phosphorus ions, micronutrients, and mineral cations, for example, Fe^{3+}, Mn^{4+}, and Mg^{2+}, which then become available in the soil for plants utilization [11,19,133]. *Trichoderma* strains are also known to produce phytohormones to promote root and shoot growth in plants [11,167]. As an example, *Trichoderma* can produce zeaxanthin and gibberellin compounds that help in rapid seed germination [10]. The fungal biofertilizer can be used as a soil conditioning agent which helps in improving the diversity and concentration of plant beneficial microorganisms thus helping in the mitigation of greenhouse gases (carbon dioxide and methane) that cause climate change [19]. *Trichoderma* strains can also eliminate minor pathogens in the rhizosphere to maximize the potential of plant growth [10,168]. Further, their ecofriendly and human friendly nature has attracted various researchers and farmers worldwide, increasing their usage and application [160]. The phytohormones and enzymes produced by *Trichoderma* eventually help in promoting plant growth, yield, nutrient absorption, phosphate solubilization, mineral absorption, antioxidant activity, and soil conditioning [169-176]. They are also reported to improve the nutrient absorption quality and yield of many vegetables that include brinjal, tomato, sugar beet, chilies, potato, cauliflower, onion, peas, and also other plants such as groundnut, cotton, wheat, tobacco, Bengal gram, sugarcane, red gram, banana, soybean, citrus, and sunflower [19,150,177].

Phytohormones play a key role in the plant growth, especially during the shoot and root elongation. Appropriate levels of phytohormones in the requisite time of support would enable the increased and healthy plant growth which generally leads to the increased crop yield [175]. The presence of *Trichoderma* in the germination stage of a seed helps in the improved production (balanced quantities) of growth hormones such as gibberellic acid and indole-3-acetic acid which improves the germination rate and seedling vigor [147] [Table 2].

Similarly, phosphate being an important nutrient that plays an imperative role in the plant growth and development is always inadequately absorbed by the plants or inadequately available for plant's absorption especially in the acidic soil [164]. Many *Trichoderma* species, specifically *T. harzianum* and *Trichoderma reesei,* are well known for their ability to solubilize phosphorous with the production of a specific enzyme phytase which on reaction with insoluble tricalcium phosphate solubilizes it and makes it available for plants absorption [150,173,178] [Table 2]. On the other hand, *Trichoderma koningiopsis* produces alkaline phosphatase enzyme for the effective solubilization of the insoluble phosphate available in the soil [174].

As nutrients are the essential compound promoting the plant growth and development, an altered uptake of nutrients can result in the malnourished crops with stunted growth and reduced crop yield. *Trichoderma* application as biofertilizer improves the uptake of nutrients in crops and also the availability of nutrients in soil for crop's absorption. Yadav *et al*. [153] have suggested that the presence of *T. viride* in soil improved the uptake of nitrogen, phosphorus, potassium, and organic carbon in the sugarcane crops. Another report stated that the presence of *Trichoderma* in rhizosphere can lead to the colonization of crop roots as endophytes, which in turn enabling the solubilization, better availability, and improved absorption of nutrients by the crop [179].

4. COMMERCIALLY AVAILABLE TRICHODERMA BASED BIOACTIVE COMPOUNDS AND BIOFERTILIZERS

Several commercial formulations of *Trichoderma* as bioactive compounds and biofertilizers are known and are used worldwide. Moreover, many initiatives and studies were carried out by various researchers and commercial agencies for the development and usage of *Trichoderma* as an agent controlling plant diseases and enhancing plant growth [180]. As these compounds are prepared to support the plants during adverse environmental conditions, it is highly essential to stipulate standard norms for the production and the maintenance of the compound as altered environmental conditions such as pH, temperature, and so on could influence the formulation's activity. Hence, it has been stipulated that the standard formulation should have a shelf-life period of 2 years, easy handling procedures, and should have an endurance to the temperature ranging from 5°C to 35°C [181]. It should also not be phytotoxic, cost effective, easily get dissolved in

Table 2: *Trichoderma* sp. as bio-fertilizers and their role in promoting plant growth and yield.

Compound	Strain	Crops	Application mode	Beneficial outcome	References
Biofertilizer	*Trichoderma azevedoi*	Lettuce	Simple exposure	Increases carotenoids and chlorophyll with reduction in the white mould attack to about 78.83%	[147]
	Trichoderma afroharzianum	Tomato	Seed inoculation or treatment	Helps in the secretion of phytohormones like homeostasis, antioxidant activity, phenylpropanoid biosynthesis and glutathione metabolism	[148]
	Trichoderma harzianum, Trichoderma asperellum, Trichoderma hamatum, Trichoderma atroviride	Chinese cabbage	Irrigation	Increases soil enzyme activity, yield by 37%, and increases the concentration of inorganic nitrogen and phosphorus content of the soil	[149]
	Trichoderma brevicompactum, Trichoderma gamsii, Trichoderma harzianum	Tomato	Seedling drenching	Improved growth and yield due to the production of indole-3 acetic acid	[19,150]
	Trichoderma harzianum Rifai, Trichoderma asperellum	Tomato	Seed treatment	Improves phosphorus uptake	[151]
	Trichoderma brevicompactum, Trichoderma gamsii, Trichoderma harzianum	Tomato	Seed drenching	Improves phosphorus solubilization	[150]
	Trichoderma erinaceum	Rice	Seed treatment	Improves germination, vigor, and yield	[147]
	Trichoderma harzianum T22	Tomato	Seed treatment	Improves soil fertility, level of minerals and antioxidants, nutrient uptake, and yield	[152]
	Trichoderma harzianum T22	Tomatp	Soil amendment as compost	Increase in yield to about 12.9%	[153]
	Trichoderma viride	Sugar cane	Powder as fertilizers	Improves nutrient uptake	[154]
	Trichoderma asperellum T34	Cucumber	Seedling drenching	Enhanced nutrient uptake	[155]
	Trichoderma harzianum	All crops	Compost	Enhances residue decomposition resulting in availability of soil nutrients	[20]
	Trichoderma simmonsii	Bell pepper	Seedling drenching	Improves yield to about 67%	[156]
	Trichoderma reesei	Chickpea	Seed treatment	Enhanced mineral uptake	[157]
	Trichoderma harzianum	Mustard	Soil inoculation	Improved nitrogen absorption and increased yield to about 108 and 203%	[43,158]
	Trichoderma harzianum	Chilli	Soil inoculation	Increased yield	[159]
	Trichoderma harzianum	Barley	Seed inoculation	17% increase in yield	[160]
	Trichoderma viridae	Wheat	Soil and seed inoculation	75.8% increase in yield with improved nutrient absorption	[161]
	Trichoderma viridae	Potato	Soil inoculation	Increased yield with an average of 16.25 tubers/ plant	[162]
	Trichoderma viridae	Red beet cabbage	Seed inoculation	29% increase in yield	[163]
	Trichoderma harzianum	Onion seedlings	Seedling inoculation	Enhanced growth and yield	[164]
Soil conditioner	*Trichoderma asperellum*	Maize	Soil granules	Improves yield	[161,165]

water, easy, and cheap availability of carrier materials, and should be compatible with agrochemicals [182]. Table 3 describes the various formulations available worldwide with its applications. Further, these formulations are available in two different forms namely solid and liquid forms.

Kumar [182] have suggested that the solid formulations are available as dry dust, wet dust, capsules, and granules at the concentration of 10^8 to 10^9 propagules available in a gram of the carriers such as clay, compost, and adhesives such as Arabic gums and carboxymethylcellulose. Further, they are formulated by pulverizing and grinding the dried *Trichoderma* mats which are further mixed with the appropriate carriers for different applications. Similarly, liquid formulation is limited in production due to difficulty in handling and maintenance. They are generally applied through irrigation of the crops [181].

5. SUMMARY ON FEW REVIEWS AVAILABLE

Few other reviews are available explaining the beneficial role of *Trichoderma* spp. either as a biocontrol agent or as an effective biofertilizer. The antagonistic biocontrol activity exerted by *Trichoderma* spp. following the direct and indirect mechanisms and the influence of extrinsic factors such as available fungal pathogen, crop species, pH, available nutrient conditions in soil, iron concentration, and temperature has been elaborated by Benítez *et al*. [33]. Similarly, Zin and Badaluddin [20] have presented in detail the role of *Trichoderma* spp. as plant growth promoter, as a plant disease

Table 3: Description of commercially available bioactive compounds and biofertilizers produced from *Trichoderma* species.

***Trichoderma* species**	**Commercial products barnd/name**	**Activity**	**Manufacturer details**
Trichoderma harzianum	Root shield	Fungicide/fertilizer	BioWorks, New York (https://bioworksinc.com/?s=Trichoderma)
Trichoderma sp.	Mikrobs	Fertilizer	Arizona (https://www.arbico-organics.com/product/mikrobs-soil-amendment-bioinoculant/trichoderma-soil-borne-disease-resistance)
Trichoderma viride	Trichoderma viride powder	Fungicide/fertilizer	OrganigDews, Bio Organic, India
Trichoderma harzianum, Trichoderma polysporum	Binab T	Bioactive compound	BINAB Bio-Innovation AB, Sweden (http://www.algonet.se)
Trichoderma harzianum	Plant shield	Bioactive compound	BioWorks, Inc., USA (http:// www.bioworksbiocontrol.com)
Trichoderma spp.	Antagon	Bioactive compound	DeCeusterMeststoffenN.V. (DCM), Belgium (http://www.agreoBiologicals.com)
Trichoderma spp., *Trichoderma harzianum, Trichoderma koningii*	Promot Plus WP Promot PlusDD	Bioactive compound	Tan Quy, Vietnam
Trichoderma viride	Antagon TV	Bioactive compound	Green Tech Agroproducts, Tamil Nadu, India [181]
Trichoderma harzianum	Trichostar	Bioactive compound	Green Tech Agroproducts, Tamil Nadu, India [181]
Trichoderma virens	Gliostar	Bioactive compound	GBPUAT, Pantnagar, India [181]
Trichoderma sp.	Monitor	Bioactive compound	Agricultural and Biotech Pvt. Ltd. Gujarat, India [181]
Trichoderma viride, Trichoderma harzianum	Bioderma	Bioactive compound	Biotech International Ltd. India [181]
Trichoderma viride	Bio Fit	Bioactive compound	Ajay Biotech (India) Ltd. India [181]
Trichoderma viride	Ecofit	Bioactive compound	Hoechst Schering Afgro Evo Ltd, India [181]
Trichoderma viride	Trichoguard	Bioactive compound	Anu Biotech Int. Ltd. Faridabad, India [181]
Trichoderma viride	Biocon	Bioactive compound	Tocklai Experimental Station Tea Research Association, Jorhat (Assam), India [181]

controlling agent, secondary metabolites produced, and their role in decomposition and bioremediation processes. Further, Nusaibah and Musa [134] have specifically explained the current updates on the mechanism of *Trichoderma* spp. in controlling stem rot of oil palm disease caused by the devastating fungi *Ganoderma* spp. Tyśkiewicz *et al*. [183] have reported in detail the various beneficial role of *Trichoderma* spp. along with their mechanism especially on the phytohormones and the 1-aminocyclopropane-1-carboxylate deaminase enzyme produced by the fungi. In 2018, Kamal *et al*. [19] have outlined the factual data and information on the commercialization of *Trichoderma* spp. biofertilizers and the widespread use of the biofertilizer among the farmers. They have also suggested that biofertilizers improves the uptake of micronutrients from the soil and enhances the production of plant growth stimulating hormones with their secondary metabolites. Likewise, Kubheka and Ziena [184] have detailed the sustainable role of *Trichoderma* spp. as biofertilizer and bio-fungicide.

6. CONCLUSION

This report reviews the importance of the application of *Trichoderma* as a biocontrol agent to control diseases in plants by suppressing the growth of the fungal pathogens and as a biofertilizer to improve plant growth and development in industrial agriculture. These eco-friendly alternatives can substitute the excessive use of synthetic products that can cause problems in the long term. There are many commercial mycofungicides and biofertilizers available that are produced from fungi such as *Trichoderma* globally. The biotechnological advances from these microorganisms such as fungi are immense and yet to be explored. Thus, more studies need to be explored on the development of sustainable biotechnological applications of the products developed on the biocontrol agents and biofertilizers.

7. FUTURE NEEDS AND LIMITATION

Although several studies have been carried out on the beneficial role of *Trichoderma* spp. as a biocontrol agent and biofertilizer, it is essential to well define the mode and mechanism of the species specific and pathogen specific antagonistic behavior expressed by the fungi. Also, it is imperative to ascertain the dose concentration of the plant growth stimulating metabolites and their activity specific to each plant species.

8. AUTHOR'S CONTRIBUTION

All authors of the paper have made substantial contributions in conceptualization and designing of the manuscript, data acquisition and interpretation of the results, and drafting and revising the manuscript with all the possible intellectual content. Further all the authors mutually agree to submit to the manuscript; approved the version to be published; and agreed to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

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The authors have mutually agreed to submit the manuscript to the journal and declare no financial or other conflict of interest in the work discussed.

11. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

12. DATA AVAILABILITY

Study does not involve any huge data acquisition and the corresponding author may be contacted for further assistance of the subject discussed.

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REFERENCES

1. Hanapi SZ, Awad HM, Sarmidi MR, Aziz R. Biofertilizer: Ingredients for sustainable agriculture. In: Biotechnology Development in Agriculture, Industry and Health. Current Industrial Application & Future Trends. Vol. 13. Malaysia: Penerbit Universiti Universiti Teknologi Malaysia; 2012. p. 358-392.
2. Choudhary DK, Varma A, Tuteja N. Plant-Microbe Interaction: An Approach to Sustainable Agriculture. Singapore: Springer Nature Singapore Pte Ltd.; 2017.
3. Tomer S, Suyal DC, Goel R. In: Choudhary DK, Varma A, Tuteja N, editors. Plant-Microbe Interaction: An Approach to Sustainable Agriculture. Singapore: Springer Nature Singapore Pte Ltd.; 2016.
4. Kourgialas NN, Karatzas GP, Koubouris GC. A GIS policy approach for assessing the effect of fertilizers on the quality of drinking and irrigation water and wellhead protection zones (Crete, Greece). J Environ Manage 2017;189:150-9.
5. Mavrodi DV, Mavrodi OV, McSpaddenss-Gardener BB, Landa BB, Weller DM, Thomashow LS. Identification of differences in genome content among ph ID-positive *Pseudomonas fluorescens* strains by using PCR based substractive hybridization. Appl Environ Microbiol 2002;68:5170-6.
6. Koumoutsi A, Chen XH, Henne A, Liesegang H, Hitzeroth G, Franhe P, *et al*. Structural and functional characterization of gene clusters directing nonribosomal synthesis of bioactive cyclic lipopeptides in *Bacillus amyloliquefaciens* strain FZB42. J Bactriol 2004;186:1084-96.
7. Atehnkeng J, Ojiambo PS, Ikotum T, Sikora RA, Cotty PJ, Bandyopadhyay R. Evaluation of atoxigenic isolates of *Aspergillus flavus* as potential biocontrol agents for aflatoxin in maize. Food Addit Contam Part A Chem Anal Control Expo Risk Assess 2008;25:1266-73.
8. Gilardi G, Manker DC, Garibaddi A, Gullino ML. Efficacy of the biocontrol agents *Bacillus subtilis* and *Ampelomyces quisqualis* applied in combination with fungicides against powdery mildew of Zucchini. J Plant Dis Protect 2008;115:208-13.
9. Gawai DU. Role of fungi as biocontrol agents for the control of plant diseases in sustainable agriculture. In: Fungi and their Role in Sustainable Development: Current Perspectives. Berlin: Springer; 2018. p. 283-91.
10. Rincón AM, Benítez T, Codón AC, Moreno-Mateos MA. Biotechnological aspects of *Trichoderma* spp. In: Rai M, Bridge PD, editors. Applied Mycology. London, UK: CAB International; 2009. p. 216-23.
11. Harman GE, Howell CR, Viterbo A, Chet I, Lorito M. *Trichoderma* plant symbionts species-opportunistic, avirulent plant symbionts. Nat Rev Microbiol 2004;2:43-56.
12. Vinale FK, Sivasithamparam LE, Ghisalberti R, Marra LS, Lorito M. *Trichoderma*-plant-pathogen interactions. Soil Biol Biochem 2008;40:1-10.
13. Kodsueb R, McKenzie EH, Lumyong S, Hyde KD. Diversity of saprobic fungi on *Magnoliaceae.* Fungal Divers 2008;30:37-53.
14. Kaewchai S, Soytong K, Hyde KD. Mycofungicides and fungal biofertilizers. Fungal Divers 2009;38:25-50.
15. Howell CR. Mechanisms employed by *Trichoderma* species in the biological control of plant diseases; The history and evolution of current concepts. Plant Dis 2003;87:4-10.
16. Druzhinina IS, Seidl-Seiboth V, Herrera-Estrella A, Horwitz BA, Kenerley CM, Monte E, *et al*. *Trichoderma*: The genomics of opportunistic success. Nat Rev Microbiol 2011;9:749-59.
17. Mukherjee AK, Kumar AS, Kranthi S, Mukherjee PK. Biocontrol potential of three novel *Trichoderma* strains: Isolation, evaluation and formulation. 3Biotech 2014;4:275-81.
18. Swain H, Adak T, Mukherjee AK, Mukherjee PK, Bhattacharyya P, Behera S, *et al*. Novel *Trichoderma* strains isolated from tree barks as potential biocontrol agents and biofertilizers for direct seeded rice. Microbiol Res 2018;214:83-90.
19. Kamal RK, Athisayam V, Gusain YS, Kumar V. *Trichoderma*: A most common biofertilizer with multiple roles in agriculture. Biomed J Sci Tech Res 2018;4:001107.
20. Zin NA, Badaluddin NA. Biological functions of *Trichoderma* spp. for agriculture applications. Ann Agric Sci 2020;65:168-78.
21. Barnett HL, Hunter BB. Illustrated Genera of Imperfect Fungi. 4th ed. St. Paul: APS Press; 1998. p. 92.
22. Gomez-Mendez E, BritoVega H, Lopez-Ferrer U, Salaya Dominguez J, Salinas-Hernandez R, Gomez-Vazquez A, *et al*. The Morphological and Molecular Characterization of *Trichoderma* spp. in Cocoa Agroforestry System. Open Sci J 2020,5:1-14.
23. Contreras-Cornejo HA, Macias-Rodriguez L, Beltran-Pe´na E, Herrera-Estrella A, Lopez-Bucio J. *Trichoderma*-induced plant immunity likely involves both hormonal and camalexin dependent mechanisms in *Arabidopsis thaliana* and confers resistance against necrotrophic fungi *Botrytis cinerea*. Plant Signal Behav 2011;6:1554-63.
24. Abdul-Halim AM, Shivanand P, Taha H. Performance of a selected *Trichoderma* strain as plant pathogen inhibitor and biofertilizer. Malaysian J Microbiol 2022;18:446-54.
25. Hjeljord L, Tronsmo A. *Trichoderma* and *Gliocladium* in biological control, an overview. In: Harman GE, Kubicek CB, editors. *Trichoderma* and *Gliocladium*. Vol. 2. London: Taylor & Francis Ltd.; 1998. p. 131-52.
26. Shenoy BD, Jeewon R, Hyde KD. Impact of DNA sequence-data on the taxonomy of anamorphic fungi. Fungal Divers 2007;26:1-54.
27. Than PP, Prihastuti H, Phoulivong S, Taylor PW, Hyde KD. Chilli anthracnose disease caused by *Colletotrichum* species. J Zhejiang Univ Sci B9 2008a;9:764-78.
28. Than PP, Shivas RG, Jeewon R, Pongsupasamit S, Marney TS, Taylor PW, *et al*. Epitypification and phylogeny of *Colletotrichum acutatum* J.H. Simmonds. Fungal Divers 2008b;28:97-108.
29. Rosslenbroich HJ, Stuebler D. *Botrytis cinerea*- history of chemical control and novel fungicides for its management. Crop Protect 2000;19:557-61.
30. Voorrips RE, Finkers R, Sanjaya L, Groenwold R. QTL mapping of anthracnose (*Colletotrichum* spp.) resistance in a cross between *Capsicum annuum* and *C. chinense*. Theor Appl Genet 2004;109:1275-82.
31. Soytong K, Srinon W, Rattanacherdchai K, Kanokmedhakul S, Kanokmedhakul K. Application of antagonistic fungi to control antracnose disease of grape. Int J Agric Technol 2005;1:33-41.
32. Haggag WM, Mohamed HA. Biotechnological aspects of

microorganisms used in plant biological control. Am Eurasian J Sustain Agric 2007;1:7-12.
33. Benítez T, Rincón AM, Limón MC, Codón AC. Biocontrol mechanisms of *Trichoderma* strains. Int Microbiol 2004;7:249-60.
34. Kulkarni M, Chaudhari R, Chaudhari A. Novel tensio-active microbial compounds for biocontrol applicatins. In: Ciancio A, Mukerji KG, editors. General Concepts in Integrated Pest and Disease Management. Berlin: Springer; 2007. p. 295-304.
35. Lahlani R, Hijri M. Screening, identification and evaluation of potential biocontrol fungal endophytes against *Rhizoctonia solani* AG3 on potato plants. FEMS Microbiol Lett 2010;311:152-9.
36. Abbas A, Mubeen M, Zheng H, Sohail MA, Shakeel Q, Solanki MK, *et al*. *Trichoderma* spp. Genes Involved in the biocontrol activity against *Rhizoctonia solani*. Front Microbiol 2022;13:884469.
37. Köhl J, Kolnaar R, Ravensberg WJ. Mode of action of microbial biological control agents against plant diseases: Relevance beyond efficacy. Front Plant Sci 2019;10:845.
38. Wraight SP, Jackson MA, de Kock SL. Production, stabilization and formulation of fungi biocontrol agents. In: Butt TM, Jackson CW, Magan N, editors. Fungi as Biocontrol Agents Progress, Problem and Potential. Wallingford: CABI Publishing; 2001. p. 253-88.
39. Irtwange VS. Application of biological control agents in pre-and postharvest operations. Agric Eng Int 2006;3:1-12.
40. Fravel RD. Commercialization and implementation of biocontrol. Ann Rev Phytopathol 2005;43:337-59.
41. Hyder S, Inam-ul-Haq M, Bibi S, Malik AH, Ghuffar S, Iqbal S. Novel potential of *Trichoderma* Spp. As biocontrol agent. J Entomol Zool Stud 2017;5:214-22.
42. Mayo S, Gutiérrez S, Malmierca MG, Lorenzana A, Campelo MP, Hermosa R, *et al*. Influence of *Rhizoctonia solani* and *Trichoderma* spp. in Growth of Bean (*Phaseolus vulgaris* L.) and in the induction of plant defense-related genes. Front Plant Sci 2015;6:685.
43. Kumar A, Patel A, Singh S, Tiwari R. Effect of *Trichoderma* sp. in plant growth promotion in Chilli. Int J Curr Microbiol Appl Sci 2019;8:1574-81.
44. Kishimoto K, Matsui K, Ozawa R, Takabayashi J. Volatile 1-octen-3-ol induces a defensive response in *Arabidopsis thaliana*. J Gen Plant Pathol 2007;73:35-7.
45. Nemcovic M, Jakubikova L, Viden I, Farkas V. Induction of conidiation by endogenous volatile compounds in *Trichoderma* spp. FEMS Microbiol Lett 2008;284:231236.
46. Stoppacher N, Kluger B, Zeilinger S, Krska R, Schuhmacher R. Identification and profiling of volatile metabolites of the biocontrol fungus *Trichoderma atroviride* by HS-SPME-GC-MS. J Microbiol Methods 2010;81:187-93.
47. Tarus PK, Langat-Thoruwa CC, Wanyonyi AW, Chhabra SC. Bioactive metabolites from *Trichoderma harzianum* and *Trichoderma longibrachiatum.* B Chem Soc Ethiopia 2003;17:185-90.
48. Chang PK, Hua SS, Sarreal SB, Li RW. Suppression of aflatoxin biosynthesis in *Aspergillus flavus* by 2-phenylethanol is associated with stimulated growth and decreased degradation of branched-chain amino acids. Toxins (Basel) 2015;7:3887-902.
49. De Stefano S, Nicoletti R. Pachybasin and chrysophanol, two anthraquinones produced by the fungus *Trichoderma aureoviride*. Il Tabacco 1999;7:21-4.
50. Lin YR, Lo CT, Liu SY, Peng KC. Involvement of pachybasin and emodin in self-regulation of *Trichoderma harzianum* mycoparasitic coiling. J Agric Food Chem 2012;60:2123-8.
51. Ali S, Watson MS, Osborne RH. The stimulant cathartic, emodin, contracts the rat isolated ileum by triggering release of endogenous acetylcholine. Auton. Autacoid Pharmacol 2004;24:103-5.
52. Huang Q, Shen HM, Shui G, Wenk MR, Ong CN. Emodin inhibits tumor cell adhesion through disruption of the membrane lipid raft-associated integrin signaling pathway. Cancer Res 2006;66:5807-15.
53. Wu YW, Ouyang J, Xiao XH, Gao WY, Liu Y. Antimicrobial properties and toxicity of anthraquinones by microcalorimetric bioassay. Chin J Chem 2006;24:45-50.
54. Vinale F, Marra R, Scala F, Ghisalberti EL, Lorito M, Sivasithamparam K. Major secondary metabolites produced by two commercial *Trichoderma* strains active against different phytopathogens. Lett Appl Microbiol 2006;43:143-8.
55. Qian-Cutrone J, Huang S, Chang LP, Pirnik DM, Klohr SE, Dalterio RA, *et al*. Harziphilone and fleephilone, two new HIV REV/RRE binding inhibitors produced by *Trichoderma harzianum*. J Antibiot (Tokyo) 1996;49:990-7.
56. Kontani M, Sakagami Y, Marumo S. First β-1,6-glucan biosynthesis inhibitor, bisvertinolone isolated from fungus, *Acremonium strictum* and its absolute stereochemistry. Tetrahedron Lett 1994;35:2577-80.
57. Mazzucco CE, Warr G. Trichodimerol (BMS-182123) inhibits lipopolysaccharide-induced eicosanoid secretion in THP-1 human monocytic cells. J Leukoc Biol 1996;60:271-7.
58. Abe N, Murata T, Hirota A. Novel DPPH radical scavengers, Bisorbicillinol and Demethyltrichodimerol, from a fungus. Biosci Biotechnol Biochem 1998;62:661-6.
59. Andrade R, Ayer WA, Mebe PP. The metabolites of *Trichoderma longibrachiatum*. Part 1. Isolation of the metabolites and the structure of trichodimerol. Can J Chem 1992;70:2526-35.
60. Almassi F, Ghisalberti EL, Narbey MJ, Sivasithamparam K. New antibiotics from strains of *Trichoderma harzianum*. J Nat Prod 1991;54:396-402.
61. Cai F, Yu G, Wang P, Wei Z, Fu L, Shen Q, *et al*. Harzianolide, a novel plant growth regulator and systemic resistance elicitor from *Trichoderma harzianum*. Plant Physiol Biochem 2013;73:106-13.
62. Ordentlich A, Wiesman Z, Gottlieb HE, Cojocaru M, Chet I. Inhibitory furanone produced by the biocontrol agent *Trichoderma harzianum*. Phytochemistry 1992;31:485-86.
63. Macias FA, Varela RM, Simonet AM, Cutler HG, Cutler SJ, Eden MA, *et al*. Bioactive carotanes from *Trichoderma* virens. J Nat Prod 2000;63:1197-200.
64. Reino JL, Guerrero RF, Hernandez-Gal R, Collado IG. Secondary metabolites from species of the biocontrol agent *Trichoderma*. Phytochem Rev 2008;7:89-123.
65. Mukherjee PK, Horwitz BA, Kenerley CM. Secondary metabolism in *Trichoderma*-a genomic perspective. Microbiology 2012;158:35-45.
66. Howell CR, Stipanovic R, Lumsden R. Antibiotic production by strains of *Gliocladium* virens and its relation to biocontrol of cotton seedling diseases. Biocontrol Sci Technol 1993;3:435-41.
67. Garo E, Starks CM, Jensen PR, Fenical W, Lobkovsky E, Clardy J. Trichodermamides A and B, cytotoxic modified dipeptides from the marine-derived fungus *Trichoderma* virens. J Nat Prod 2003;66:423-6.
68. Liu R, Gu QQ, Zhu WM, Cui CB, Fan GT. Trichodermamide A and aspergillazine A, two cytotoxic modified dipeptides from a marine-derived fungus *Spicaria elegans*. Arch Pharmacol Res 2005;28:1042-6.
69. Contreras-Cornejo HA, Lopez-Bucio JS, Mendez-Bravo A, Maciaz-Rodriguez L, Ramos-Vega M, Guevara-Garcia AA, *et al*. Mitogen-activated protein kinase 6 and ethylene and auxin signaling pathways are involved in Arabidopsis root-system architecture alterations by *Trichoderma atroviride*. Mol Plant Microbe Interact 2015a;28:701-10.
70. Henrissat B, Driguez H, Viet C, Schulein M. Synergism of cellulases from *Trichoderma reesei* in the degradation of cellulose. Nat Biotechnol 1985;3:722-6.
71. Payne CM, Knott BC, Mayes HB, Hansson H, Himmel ME, Sandgren M, *et al*. Fungal cellulases. Chem Rev 2015;115:1308-448.
72. Gruber S, Seidl-Seiboth V. Self versus non-self: fungal cell wall degradation in *Trichoderma*. Microbiology (Reading) 2012;158:26-34.
73. Tzelepis G, Dubey M, Jensen DF, Karlsson M. Identifying glycoside hydrolase family 18 genes in the mycoparasitic fungal species *Clonostachys rosea*. Microbiology (Reading) 2015;161:1407-19.

74. Contreras-Cornejo HA, Macias-Rodriguez L, Cortes-Penagos C, Lopez-Bucio J. *Trichoderma* virens, a plant beneficial fungus enhances biomass production and promotes lateral root growth through an auxin dependent mechanism in *Arabidopsis*. Plant Physiol 2009;149:1579-92.
75. Lee CH, Chung MC, Lee HJ, Bae KS, Kho YH. MR566A and MR566B, new melanin synthesis inhibitors produced by *Trichoderma harzianum*. I. Taxonomy, fermentation, isolation and biological activities. J Antibiot 1997a;50:469-73.
76. Lee CH, Koshino H, Chung MC, Lee HJ, Hong JK, Yoo JS, *et al*. MR566A and MR566B, new melanin synthesis inhibitors produced by *Trichoderma harzianum*. II. Physico-chemical properties and structural elucidation. J Antibiot 1997b;50:474-8.
77. Contreras-Cornejo HA, Macias-Rodriguez L, Garnica-Vergara A, Lopez-Bucio J. *Trichoderma* modulates stomatal aperture and leaf transpiration through an abscisic acid-dependent mechanism. J Plant Growth Regul 2015b;34:425-32.
78. Cutler HG, Himmelsbach DS, Arrendale RF, Cole PD, Cox RH. Koninginin A: A novel plant growth regulator from *Trichoderma koningii*. Agric Biol Chem 1989;53:2605-11.
79. Cutler HG, Himmelsbach DS, Yagen B, Arrendale RF, Jacyno JM, Cole PD, *et al*. Koninginin B: A biologically active congener of Koninginin A from *Trichoderma koningii*. J Agric Food Chem 1991;39:977-80.
80. Chen JL, Liu K, Miao CP, Guan HL, Zhao LX, Sun SZ. Chemical constituents with siderophores activities from *Trichoderma koningiopsis* YIM PH30002. Nat Prod Res Dev 2015;27:1878-83.
81. Godard K, White R, Bohlmann J. Monoterpene-induced molecular responses in *Arabidopsis thaliana*. Phytochemistry 2008;69:1838-49.
82. Crutcher FK, Parich A, Schuhmacher R, Mukherjee PK, Zeilinger S, Kenerley CM. A putative terpene cyclase, vir4, is responsible for the biosynthesis of volatile terpene compounds in the biocontrol fungus *Trichoderma* virens. Fungal Genet Biol 2013;56:67-77.
83. Sawa R, Mori Y, Iinuma H, Naganawa H, Hamada M, Yoshida S, *et al*. Harzianic acid, a new antimicrobial antibiotic from a fungus. J Antibiot (Tokyo) 1994;47:731-2.
84. Vinale F, Flematti G, Sivasithamparam K, Lorito M, Marra R, Skelton BW, *et al*. Harzianic acid, an antifungal and plant growth promoting metabolite from *Trichoderma harzianum*. J Nat Prod 2009;72:2032-5.
85. Vinale F, Nigro M, Sivasithamparam K, Flematti G, Ghisalberti EL, Ruocco M, *et al*. Harzianic acid: A novel siderophore from *Trichoderma harzianum*. FEMS Microbiol Lett 2013;347:123-9.
86. Malmierca MG, Cardoza RE, Alexander NJ, McCormick SP, Collado IG, Hermosa R, *et al*. Relevance of trichothecenes in fungal physiology: Disruption of tri5 in *Trichoderma arundinaceum*. Fungal Genet Biol 2013;53:22-33.
87. Dickinson JM, Hanson JR, Hitchcock PB, Claydon N. Structure and biosynthesis of harzianopyridone, an antifungal metabolite of *Trichoderma harzianum*. J Chem Soc Perkin Trans 1989;1:1885-7.
88. Kawada M, Yoshimoto Y, Kumagai H, Someno T, Momose I, Kawamura N, *et al*. PP2A inhibitors, harzianic acid and related compounds produced by fungal strain F-1531. J Antibiot 2004;57:235-7.
89. Hashimoto R, Takahashi S, Hamano K, Nakagawa A. A new melanin biosynthesis inhibitor, melanoxadin from fungal metabolite by using the larval haemolymph of the silkworm, *Bombyx mori*. J Antibiot 1995;48:1052-4.
90. Engelberth J, Koch T, Schuler G, Bachmann N, Rechtenbach J, Boland W. Ion channel-forming alamethicin is a potent elicitor of volatile biosynthesis and tendril coiling. Cross talk between jasmonate and salicylate signaling in lima bean. Plant Physiol 2001;125:369-77.
91. Khan RA, Najeeb S, Hussain S, Xie B, Li Y. Bioactive secondary metabolites from *Trichoderma* spp. against phytopathogenic fungi. Microorganisms 2020;8:817.
92. Djonovic S, Pozo MJ, Dangott LJ, Howell CR, Kenerley CM. Sm1, a proteinaceous elicitor by the biocontrol fungus *Trichoderma* virens induces plant defense responses and systemic resistance. Mol Plant Microbe Interact 2006;19:838-53.
93. Djonovic S, Vargas WA, Kolomiets MV, Horndeski M, Wiest A, Kenerley CM. A proteinaceous elicitor Sm1 from the beneficial fungus *Trichoderma* virens is required for induced systemic resistance in maize. Plant Physiol 2007;145:875-89.
94. Vargas WA, Djonovic S, Sukno SA, Kenerley CM. Dimerization controls the activity of fungal elicitors that trigger systemic resistance in plants. J Biol Chem 2008;283:19804-15.
95. Yan SX, Shen QT, Xie ST, Chen XL, Sun CY, Zhang YZ. Broad-spectrum antimicrobial activityand high stability of Trichokonins from *Trichoderma koningii* SMF2 against plant pathogens. FEMS Microbiol Lett 2006;260:119-25.
96. Sadykova VS, Kurakov AV, Korshun VA, Rogozhin EA, Gromovykh TI, Kuvarina AE, *et al*. Antimicrobial activity of substances produced by *Trichoderma citrinoviride* Strain VKPM F-1228: Optimization of cultivation and assessment of spectrum of individual peptaibols. Antibiot Khimioter 2015;60:3-8.
97. Shi WL, Chen XL, Wang LX, Gong ZT, Li S, Li CL, *et al*. Cellular and molecular insight into the inhibition of primary root growth of *Arabidopsis* induced by peptaibols, a class of linear peptide antibiotics mainly produced by *Trichoderma* spp. J Exp Bot 2016;67:2191-205.
98. Dunlop RW, Simon A, Sivasithamparam K, Ghisalberti EL. An antibiotic from *Trichoderma koningii* active against soilborne plant pathogens. J Nat Prod 1989;52:67-74.
99. Parker RS, Cutler HG, Jacyno JM, Hill RA. Biological activity of 6-pentyl-2H-pyran-2-one and its analogs. J Agric Food Chem 1997;45:2774-6.
100. Yang Z, Yu Z, Lei L, Xia Z, Shao L, Zhang K, *et al*. Nematicidal effect of volatiles produced by *Trichoderma* sp. J Asia Pac Entomol 2012;15:647-50.
101. Garnica-Vergara A, Barrera-Ortiz S, Munoz-Parra E, Raya-Gonzalez J, Mendez-Bravo A, Macias-Rodriguez L, *et al*. The volatile 6-pentyl-2H-pyran-2-one from *Trichoderma atroviride* regulates Arabidopsis thaliana root morphogenesis via auxin signalling and ETHYLENE INSENSITIVE 2 functioning. New Phytol 2015;209:1496-512.
102. Evidente A, Cabras A, Maddau L, Serra S, Andolfi A, Motta A. Viridepyronone, a new antifungal 6-substituted 2H-pyran-2-one produced by *Trichoderma viride*. J Agric Food Chem 2003;51:6957-60.
103. Vinale F, Sivasithamparam K, Ghisalberti EL, Ruocco M, Wood S, Lorito M. *Trichoderma* secondary metabolites that affect plant metabolism. Nat Prod Commun 2012;7:1545-50.
104. Itoh Y, Kodama K, Furuya K, Takahashi S, Haneishi T, Takiguchi Y, *et al*. A new sesquiterpene antibiotic, heptelidic acid producing organisms, fermentation, isolation and characterization. J Antibiot 1980;33:468-73.
105. Tanaka Y, Shiomi K, Kamei K, Sugoh-Hagino M, Enomoto Y, Fang F, *et al*. Antimalarial activity of radicicol, heptelidic acid and other fungal metabolites. J Antibiot (Tokyo) 1998;51:153-60.
106. Kunert G, Otto S, Rose US, Gershenzon J, Boland W, Weisser WW. Alarm pheromone mediates production of winged dispersal morphs in aphids. Ecol Lett 2005;8:596-603.
107. Rasmann S, Köllner TG, Degenhardt J, Hiltpold I, Toepfer S, Kuhlmann U, *et al*. Recruitment of entomopathogenic nematodes by insect-damaged maize roots. Nature 2005;434:732-7.
108. Contreras-Cornejo HA, Macias-Rodriguez L, Lopez-Bucio J. Enhanced plant immunity using *Trichoderma*. In: Gupta VK, editor. Biotechnology and Biology of *Trichoderma*. Oxford: Elsevier; 2014. p. 495-504.
109. Anke H, Kinn J, Bergquist KE, Sterner O. Production of siderophores

by strains of the genus *Trichoderma* isolation and characterization of the new lipophilic coprogen derivative, palmitoylcoprogen. Biometals 1991;4:176-80.
110. Kubicek CP, Herrera-Estrella A, Seidl-Seiboth V, Martinez DA, Druzhinina IS, Thon M, *et al*. Comparative genome sequence analysis underscores mycoparasitism as the ancestral life style of *Trichoderma*. Genome Biol 2011;12:R40.
111. Goldstein JL, Helgeson JA, Brown MS. Inhibition of colesterol synthesis with compactin renders growth of cultured cells dependent on the low density lipoprotein receptor. J Biol Chem 1979;254:5403-9.
112. Endo A, Hasumi K, Sakai K, Kanbe T. Specific inhibition of glyceraldehyde-3-phosphate dehydrogenase by koningic acid (heptelidic acid). J Antibiot 1985;38:920-5.
113. Endo A, Hasumi K, Yamada A, Shimoda R, Takeshima H. The synthesis of compactin (ML-236B) and monacolin K in fungi. J Antibiot (Tokyo) 1986;39:1609-10.
114. Jones RW, Hancock JG. Conversion of viridin to viridiol by viridin producing fungi. Can J Microbiol 1987;33:963-6.
115. Dodge JA, Sato M, Vlahos CJ. Inhibition of Phosphatidylinositol 3-kinase with Viridin and Analogs Thereof. Germany: European Patent Office Application; 1995. p. 648492.
116. Tijerino A, Cardoza RE, Moraga J, Malmierca MG, Vicente F, Aleu J, *et al*. Overexpression of the trichodiene synthase gene tri5 increases trichodermin production and antimicrobial activity in *Trichoderma* brevicompactum. Fungal Genet Biol 2011;48:285-96.
117. Shentu XP, Liu WP, Zhan XH, Yu XP, Zhang CX. The elicitation effect of pathogenic function on Trichodermin production by *Trichoderma* brevicompactum. ScientificWorldJournal 2013;2013:607102.
118. Malmierca MG, Cardoza RE, Alexander NJ, McCormick SP, Hermosa R, Monte E, *et al*. Involvement of *Trichoderma* trichothecenes in the biocontrol activity and induction of plant defense-related genes. Appl Environ Microbiol 2012;78:4856-68.
119. Viterbo A, Landau U, Kim S, Chernin L, Chet I. Characterization of ACC deaminase from the biocontrol and plant growth-promoting agent *Trichoderma asperellum* T203. FEMS Microbiol Lett 2010;305:42-8.
120. Ng LC, Ngadin A, Azhari M, Zahari NA. Potential of *Trichoderma* spp. as biological control agents against Bakanae Pathogen (*Fusarium fujikuroi*) in Rice. Asian J Plant Pathol 2015;9:46-58.
121. Węgrzyn E, Karolina G. Influence of the fungal hyperparasite *Trichoderma harzianum* on the growth of *Epichloë typhina*, an agent of choke disease in grasses. J Plant Dis Protect 2018;126:39-45.
122. Ulloa M, Hanlin RT. Illustrated dictionary of mycology. The American Phytopathological Society. Minnesota: St. Paul Press; 2012.
123. Alderman SC, Rao S, Spinney RL, Boren PK, Cacka JF. Summary of choke control studies. In: Young WC 3rd editor. Seedproduction research at Oregon State University. Oregon: Oregon State University. Extension Service, Grants Pass; 2008. p. 19-25.
124. Omann M, Zeilinger S. How a mycoparasite employsG-protein signaling: Using the example of *Trichoderma.* J Signal Transduct 2010;2010:123126.
125. Monte E. Understanding *Trichoderma*: Between biotechnology and microbial ecology. Int Microbiol 2001;4:1-4.
126. Benhamou N, Chet I. Cellular and molecular mechanisms involved in the interaction between *Trichoderma harzianum* and *Pythium ultimum*. Appl Environ Microbiol 1997;63:2095-99.
127. Strakowska J, Błaszczyk L, Chełkowski J. The significance of cellulolytic enzymes produced by *Trichoderma* in opportunistic lifestyle of this fungus. J Basic Microbiol 2014;54:2-13.
128. Jeleń H, Błaszczyk L, Chełkowski J, Rogowicz K, Strakowska J. Formation of 6-n-pentyl-2H-pyran-2-one (6-PAP) and other volatiles by different *Trichoderma* species. Mycol Progress 2013;13:589-600.
129. Gams W, Bisset J. Morphology and identification of *Trichoderma*. In: Harman GE, Kubicek CP, editors. *Trichoderma* and Gliocladium. Vol. 393. London, UK: Taylor & Francis; 1998. p. 3-34.
130. Gosling P, Hodge A, Goodlass G, Bending GD. Arbuscular mycorrhizal fungi and organic farming. Agric Ecosyst Environ 2006;113:17-35.
131. Herrera-Estrella A, Chet I. The biological control agent *Trichoderma*-from fundamentals to applications. In: Arora DK, Dekker M, editors. Fungal Biotechnology in Agricultural, Food and Environmental Applications. Vol. 21. New York, USA: CRC Press; 2004. p. 147-56.
132. Harman GE. Overview of mechanisms and uses of *Trichoderma* spp. Phytopathology 2006;96:190-4.
133. Shoresh M, Harman GE, Mastouri F. Induced systemic resistance and plant responses to fungal biocontrol agents. Ann Rev Phytopathol 2010;48:21-43.
134. Nusaibah SA, Musa H. A Review Report on the Mechanism of *Trichoderma* spp. as biological control agent of the basal stem Rot (BSR) disease of *Elaeis guineensis*. In: Shah MM, Sharif U, Buhari TR, editors. *Trichoderma* the Most Widely Used Fungicide. London: IntechOpen; 2019.
135. Kachroo A, Robin GP. Systemic signaling during plant defense. Curr Opin Plant Biol 2013;16:527.
136. Schuster A, Schmoll M. Biology and biotechnology of *Trichoderma*. Appl Microbiol Biotechnol 2010;87:787-99.
137. Vessey JK. Plant growth promoting Rhizobacteria as Biofertilizers. Plant Soil 2003;255:571.
138. El-Ghamry AM, Mosa AA, Alshaal TA, El-Ramady HR. Nanofertilizers vs. Biofertilizers: New insights. Environ Biodivers Soil Secur 2018;2:51-72.
139. El-Habbasha SF, Hozayn M, Khalafallah MA. Integration effect between phosphorus levels and biofertilizers on quality and quantity yield of faba bean (*Vicia faba* L.) in newly cultivated sandy soils. Res J Agric Biol Sci 2007;3:966-71.
140. Das A, Prasad R, Srivastava A, Giang HP, Bhatnagar K, Varma A. Fungal siderophores: Structure, functions and regulation. In: Varma A, Chincholkar SB, editors. Soil Biology Microbial Siderophores. Vol. 12. Heidelberg: Springer-Verlag Berlin; 2007, 1-42.
141. Sadhana B. Arbuscular mycorrhizal fungi (AMF) as biofertilizer-a review. Int J Curr Microbiol Appl Sci 2014;3:384-400.
142. Alam S, Seth RK. Comparative study on effect of chemical and biofertilizer on growth, development, and yield production of paddy crop (*Oryza sativa*). Int J Sci Res 2012;2319-7064.
143. De Souza JT, Bailey BA, Pomella AW, Erbe EF, Murphy CA, Bae H. Colonization of cacao seedlings by *Trichoderma stromaticuma* mycoparasite of the witches' broom pathogen, and its influence on plant growth and resistance. Biol Control 2008;46:36-45.
144. Zhang FG, Yuan J, Yang XM, Cui YQ, Chen LH, Ran W. Putative *Trichoderma harzianum* mutant promotes cucumber growth by enhanced production of indole acetic acid and plant colonization. Plant Soil 2013;368:433-44.
145. Chang YC, Baker R. Increased growth in the presence of the biological control agent *Trichoderma harzianum.* Plant Dis 1986;76:60-5.
146. da Silva LR, Valadares-Inglis MC, Henrique G, Peixoto S, Eliza B, de Lucas G, *et al*. Volatile organic compounds emitted by *Trichoderma azevedoi* promote the growth of lettuce plants and delay the symptoms of white mold. Biol Control 2021;152:104447.
147. Juan Z, Ting LI, Wei-Cheng LI, Dian-Peng Z, Dan D, Hui-Ling WU, *et al*. Transcriptomic insights into growth promotion effect of *Trichoderma afroharzianum* TM2-4 microbial agent on tomato plants. J Integr Agric 2021;20:1266-76.
148. Ji S, Liu Z, Liu B, Wang Y, Wang J. The effect of *Trichoderma* biofertilizer on the quality of flowering Chinese cabbage and the soil environment. Sci Hortic 2020;262:109069.
149. Bader AN, Salerno GL, Covacevich F, Consolo VF. Native

Trichoderma harzianum strains from Argentina produce indole-3 acetic acid and phosphorus solubilization, promote growth and control wilt disease on tomato (*Solanum lycopersicum* L.). J King Saud Univ Sci 2020;32:867-73.

150. Yu Z, Wang Z, Zhang Y, Wang Y, Liu Z. Biocontrol and growth-promoting effect of *Trichoderma asperellum* TaspHu1 isolate from *Juglans mandshurica* rhizosphere soil. Microbiol Res 2021;242:126596.
151. Sani MNH, Hasan M, Uddain J, Subramaniam S. Impact of application of *Trichoderma* and biochar on growth, productivity and nutritional quality of tomato under reduced N-P-K fertilization. Ann Agric Sci 2020;65:107-15.
152. Khan Y, Haque M, Molla AH, Rahman M. Antioxidant compounds and minerals in tomatoes by *Trichoderma*-enriched biofertilizer and their relationship with the soil environments. J Integr Agric 2017;16:691-703.
153. Yadav RL, Suman A, Prasad SR, Prakash O. Effect of *Gluconacetobacter diazotrophicus* and *Trichoderma* viride on soil health, yield and N-economy of sugarcane cultivation under subtropical climatic conditions of India. Euro J Agron 2009;30:296-303.
154. De SA, García-lópez AM, Manuel J, Avilés M, Delgado A. Soil biology and biochemistry effect of *Trichoderma asperellum* strain T34 and glucose addition on iron nutrition in cucumber grown on calcareous soils. Soil Biol Biochem 2013;57:598-605.
155. Rokni N, Alizadeh HS, Bazgir E, Darvishnia M, Mirzaei NH. The tripartite consortium of *Serendipita indica, Trichoderma simmonsii*, and bell pepper (*Capsicum annuum*). Biol Control 2021;158:104608.
156. Tripathi P, Singh PC, Mishra A, Tripathi RD, Nautiyal CS. Ecotoxicology and environmental safety *Trichoderma* inoculation augments grain amino acids and mineral nutrients by modulating arsenic speciation and accumulation in chickpea (*Cicer arietinum* L.). Ecotoxicol Environ Saf 2015;117:72-80.
157. Haque M, Ilias AH, Molla AH. *Trichoderma* enriched biofertilizer: A prospective substitute of inorganic fertilizer for mustard (*Brassica campestris*) production. Agriculturists 2011;8:66-73.
158. Haque MM, Ilias G, Molla A. Impact of *Trichoderma* enriched biofertilizer on the growth and yield of Mustard (*Brassica rapa* L.) and Tomato (*Solanum lycopersicon* Mill.). Agriculturists 2012;10:109-19.
159. Ghasemkheylif T, Piradasthi H, Bahmanyar M, Ghanbari T. The effect of *Trichoderma harzianum* and Cadmium on tolerance index and yield of barley (*Hordeum vulgare* L.). J Crop Ecophysiol Agric Sci 2015;8:465-81.
160. Mahato S, Bhuju S, Shrestha J. Effect of *Trichoderma* viride as biofertilizer on growth and yield of wheat. Malaysian J Sustain Agric 2018;2:1-5.
161. Susiana P, Achmadi P, Retno PS, Rina SK, Kadarwati B. The resistance of potatoes by application of *Trichoderma* viride antagonists fungus. E3S Web Conf 2018;73:06014.
162. Topolovec-Pintaric S, Zutic I, Dermic E. Enhanced growth of cabbage and red beet by *Trichoderma* viride. Acta Agric Slov 2013;101:87-92.
163. He A, Liu J, Wang XH, Zhang QG, Song W, Chen J. Soil application of *Trichoderma asperellum* GDFS1009 granules promotes growth and resistance to *Fusarium graminearum* in maize. J Integr Agric 2019;18:599-606.
164. Bayoumi Y, Taha N, Shalaby T, Alshaal T, El-Ramadyd H. Sulfur promotes biocontrol of purple blotch disease via *Trichoderma* spp. and enhances the growth, yield and quality of onion. Appl Soil Ecol 2019;134:15-24.
165. Mastouri F, Björkman T, Harman GE. *Trichoderma harzianum* enhances antioxidant defense of tomato seedlings and resistance to water deficit. Mol Plant Microbe Interact 2012;25:1264-71.
166. Grondona I, Hermosa R, Tejada M, Gomis MD, Mateos PF, Bridge PD, *et al*. Physiological and biochemical characterization of *Trichoderma harzianum*, a biological control agent against soilborne fungal plant pathogens. Appl Environ Microbiol 1997;63:3189-98.
167. Harman GE, Taylor AG, Stazs TE. Combining effective strains of *Trichoderma harzianum* and solid matrix priming to improve biological seed treatments. Plant Dis 1989;73:631-7.
168. Suebrasri T, Harada H, Jogloy S, Ekprasert J, Boonlue S. Auxin-producing fungal endophytes promote growth of sunchoke. Rhizosphere 2020;16:100271.
169. Macías-Rodríguez L, Contreras-Cornejo HA, Adame-Garnica SG, del-Val E, Larsen J. The interactions of *Trichoderma* at multiple trophic levels: Inter-kingdom communication. Microbiol Res 2020;240:126552.
170. Singh B, Boukhris I, Pragya KV, Yadav AN, Farhat-Khemakhem A, Kumar A, *et al*. Contribution of microbial phytases to the improvement of plant growth and nutrition: A review. Pedosphere 2020;30:295-313.
171. Ren K, Hayat S, Qi X, Liu T, Cheng Z. The garlic allelochemical DADS influences cucumber root growth involved in regulating hormone levels and modulating cell cycling. J Plant Physiol 2018;230:51-60.
172. Hoyos-Carvajal L, Orduz S, Bissett J. Growth stimulation in bean (*Phaseolus vulgaris* L.) by *Trichoderma*. Biol Control 2009;51:409-16.
173. Eslahi N, Kowsari M, Motallebi M, Zamani MR, Moghadasi Z. Influence of recombinant *Trichoderma* strains on growth of bean (*Phaseolus vulgaris* L) by increased root colonization and induction of root growth related genes. Sci Hortic 2020;261:108932.
174. Singh SP, Pandey S, Mishra N, Giri VP, Mahfooz S, Bhattacharya A, *et al*. Supplementation of *Trichoderma* improves the alteration of nutrient allocation and transporter genes expression in rice under nutrient deficiencies. Plant Physiol Biochem 2019;143:351-63.
175. Akladious SA, Abbas SM. Application of *Trichoderma harzianum* T22 As a biofertilizer potential in maize growth. J Plant Nutr 2014;37:30-49.
176. Sandle T. *Trichoderma*. Encycl Food Microbiol. 2nd ed., Vol. 3. Netherlands: Elsevier Ltd.; 2014. p. 644-6.
177. Gasparetti C, Nordlund E, Jänis J, Buchert J, Kruus K. Extracellular tyrosinase from the fungus *Trichoderma reesei* shows product inhibition and different inhibition mechanism from the intracellular tyrosinase from *Agaricus bisporus*. Biochim Biophys Acta 2012;1824:598-607.
178. Yin J, Yuan L, Sui Z, Huang J. Mobilization of organic nitrogen and phosphorus and reduction of synthetic fertilizer usage by *Ceriporia lacerata* HG2011 in pepper cultivation. Sci Hortic 2021;293:110721.
179. Harman GE. Myths and dogmas of biocontrol changes in perceptions on *Trichoderma harzianum* T-22. Plant Dis 2000;84:377-93.
180. Puyam A. Advent of *Trichoderma* as a bio-control agent-A review. J Appl Nat Sci 2016;8:1100-9.
181. Kumar S, Thakur M, Rani A. *Trichoderma*: Mass production, formulation, quality control, delivery and its scope in commercialization in India for the management of plant diseases. Afr J Agric Res 2014;9:3838-52.
182. Kumar S. *Trichoderma:* A biological weapon for managing plant diseases and promoting sustainability. Int J Agric Sci Vet Med 2013;1:1-16.
183. Tyśkiewicz R, Nowak A, Ozimek E, Jaroszuk-Ściseł J. *Trichoderma*: The current status of its application in agriculture for the biocontrol of fungal phytopathogens and stimulation of plant growth. Int J Mol Sci 2022;23:2329.
184. Kubheka BP, Ziena LW. *Trichoderma:* A biofertilizer and a bio-fungicide for sustainable crop production. In: *Trichoderma* Technology Uses. London: IntechOpen; 2022.

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