

## Review

# Harnessing *Trichoderma* in Agriculture for Productivity and Sustainability

Nur Syafikah Abdullah <sup>1</sup>, Febri Doni <sup>2</sup> , Muhamad Shakirin Mispan <sup>3,4</sup>, Mohd Zuwairi Saiman <sup>3,4</sup> , Yusmin Mohd Yusuf <sup>4,5</sup>, Mushafau Adebayo Oke <sup>6</sup>  and Nurul Shamsinah Mohd Suhaimi <sup>3,\*</sup> 

<sup>1</sup> Institute for Advanced Studies, University of Malaya, Kuala Lumpur 50603, Malaysia; 17190571@siswa.um.edu.my

<sup>2</sup> Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, Jatinangor 45363, Indonesia; febri@unpad.ac.id

<sup>3</sup> Institute of Biological Sciences, Faculty of Science, University of Malaya, Kuala Lumpur 50603, Malaysia; shakirin@um.edu.my (M.S.M.); zuwairi@um.edu.my (M.Z.S.)

<sup>4</sup> Centre for Research in Biotechnology for Agriculture (CEBAR), University of Malaya, Kuala Lumpur 50603, Malaysia; yusmin\_y@um.edu.my

<sup>5</sup> Centre for Foundation Studies in Science, University of Malaya, Kuala Lumpur 50603, Malaysia

<sup>6</sup> Department of Agricultural, Food and Nutritional Science, Faculty of Agriculture, Life & Environmental Sciences, University of Alberta, Edmonton, AB T6G 2P5, Canada; mushafau@ualberta.ca

\* Correspondence: nurull@um.edu.my



**Citation:** Abdullah, N.S.; Doni, F.; Mispan, M.S.; Saiman, M.Z.; Yusuf, Y.M.; Oke, M.A.; Suhaimi, N.S.M. Harnessing *Trichoderma* in Agriculture for Productivity and Sustainability. *Agronomy* **2021**, *11*, 2559. <https://doi.org/10.3390/agronomy11122559>

Academic Editors: Jorge M. S. Faria, Clarisse Brigido and Esther Menéndez

Received: 24 September 2021

Accepted: 27 October 2021

Published: 16 December 2021

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

**Abstract:** Increased agricultural activities driven by rising food demand have led to environmental problems mostly arising from the high levels of external inputs and resources that are required. Additionally, environmental changes, such as global warming, can lead to various biotic and abiotic stresses, which have negative impacts on crop production. Numerous solutions and agricultural strategies have been introduced to overcome these problems. One of the ways to improve plant production as well as to increase resistance towards biotic and abiotic stresses is by utilizing beneficial microbes as soil inoculants. A better understanding of the ability of *Trichoderma* to enhance crop production and the mechanisms that are involved are important for deriving maximum benefits from their exploitation. These versatile fungi hold great promise for the development of viable commercial products that can be used widely in agriculture for increasing crop productivity in a more sustainable way. Many previous reviews on *Trichoderma* have tended to focus on the mechanisms of *Trichoderma* in enhancing plant growth and yield. This current review discusses the sustainability aspect of using *Trichoderma* as plant growth regulators, the impact on plant growth and yield as well as their effects in regulating biotic and abiotic stresses.

**Keywords:** *Trichoderma*; growth promoter fungi; sustainable agriculture; stress tolerance; biocontrol

## 1. Introduction

Continuous growth in the world's population has led to a corresponding increase in food demand, which has necessitated the mass production of agricultural products [1]. By 2050, the population to be fed will be over 9 billion people. Not only do we have to increase food availability, but we also must ensure that supplies are sustainably produced by not compromising the services that nature is able to provide [2]. Intensive large-scale industrial agriculture requires high-external input and resources, and these ultimately cause environmental problems such as water shortages, destruction of biodiversity, a decline in soil fertility, and elevated levels of greenhouse gases, leading to an increase in biotic and abiotic stresses, which threaten agricultural productivity and food security [3,4].

Beneficial microbes employ various mechanisms of action that increase plant productivity through the promotion of plant growth and health, such as (a) colonizing soil and/or plant parts, thereby occupying space and limiting the proliferation of phytopathogens;

(b) producing enzymes, antibiotic substances, and volatile organic compounds that suppress the phytopathogens; (c) facilitating nutrient and water uptake; (d) producing phytohormone; (e) inducing local or systemic resistance responses in plants; and (f) improving various physiological and molecular processes [5–7]. *Trichoderma* is among the most widespread fungi in the world and is a plant symbiont that resides in varying habitats, including the rhizosphere and plant tissue (as an endophyte). *Trichoderma* is also widely used as biocontrol agent against phytopathogenic microorganisms. For example, *Trichoderma* was found to endophytically colonize *Brassica oleracea* (kale) and activated the systemic resistance of kale plants against the bacterial pathogen, *Xanthomonas campestris* [8]. Some of the mechanisms involved in promoting plant growth and disease protection by means of endophytic fungi include increasing access to nutrients (nitrogen, phosphorus, potassium, zinc, iron, etc.), the production of antibiotics, the production of plant hormones, a reduction in ethylene, or an increase in water acquisition rate [9].

Numerous studies have been conducted to elucidate the mechanisms by which *Trichoderma* confers resistance to plant pathogens and resilience against various kinds of biotic and abiotic stresses [10,11]. Over the years, scientists and agricultural practitioners have focused on the search for environmentally friendly options for the management of cropping systems. Finding the best method for improving crop production is crucial in order to achieve a sufficient food supply for the continuously rising population. Agroecology has been a prominent way of redesigning food systems to achieve greener agriculture approaches with higher sustainability [12,13]. One important agroecological approach for maximizing root and rhizosphere efficiency is the application of beneficial microbes, including *Trichoderma* [14,15]. This strategy can lead to improved crop productivity and better nutrient use efficiency while providing a friendlier option for human health and the environment [16,17].

This review discusses *Trichoderma*–plant interactions that result in improved plant production and resistance towards biotic and abiotic stresses as well as the potential applications for *Trichoderma* in sustainable crop production. We also highlight the ability of *Trichoderma* to resist those stresses, thereby contributing to better plant growth and development. Despite the advancements achieved through research studies, the application of *Trichoderma* as a commercialized biofertilizer is yet to attain a satisfactory level. Deeper knowledge on the roles of *Trichoderma*–plant relationships and the underlying mechanisms involved are essential for the better understanding and application of these fungi by agricultural practitioners for sustainable food production. Sustainable agriculture is important in order to practice cleaner and healthier food production without jeopardizing the environment and the ability of future generations to produce food.

## 2. Roles of *Trichoderma* in Sustainable Crop Production

The effects of root inoculation by *Trichoderma* are not restricted to the site of colonization but exist throughout the entire plant system. Colonization involves a complex system whereby the fungus is able to invade plant cells but can only live symbiotically without killing the plant. *Trichoderma* resides at the outermost layer of the roots and does not penetrate into the inner vascular tissue [18]. In *Trichoderma* studies with arabidopsis, the plants were seen to restrict the invasion of *Trichoderma* in the vascular bundle through the presence of metabolites such as salicylic acid (SA) and glucosinolates (GSLs) [19,20]. A successful *Trichoderma*–plant interaction results in improved plant growth and crop yield upon the cumulative positive effects induced by the fungus that subsequently improve nutrient uptake and transport in plants [21,22]. For instance, composted kitchen wastes comprising *T. harzianum* showed considerable promise as a biofertilizer for tomato plants with yield increases of up to 336.5% [23]. In a chickpea study, *Trichoderma* spp. caused an increase in the growth and yield parameters of the treated plants compared to the uninoculated controls. This result was found to be caused by the enhanced solubilisation and uptake of phosphate [24]. Furthermore, a maximum yield of chilies (69.55 q/ha) was recorded when the seeds were pre-treated with *T. harzianum* together with its foliar sprays.

Nutrient solubility and availability are induced by the acidification of soils by plant roots upon inoculation with the fungus. The process occurs through the secretion of some organic acids such as gluconic, citric, and fumaric acids [25]. In the case of sugarcane, both *T. harzianum* and *T. viride* were significantly effective in enhancing the uptake of phosphorus as well as other micronutrients, thereby improving germination, tiller population, millable canes output, and commercial cane sugar yield (CCS t/ha) [26]. In tomato plants, shoot and root growth attributes as well as chlorophyll content were significantly increased when sown in *Trichoderma*-fortified soil. Mineral contents in both shoot and root were higher compared to control plants [27]. Upon the application of *T. virens*, the efficiency of nitrogen uptake in lettuce and rocket plants was greater with enhanced crop yield and quality. Those acids reduce soil pH, subsequently allowing better nutrients solubility and uptake [28]. Other than acidification, the induction of root growth by the fungus and the increase in root biomass contributed to better nutrient absorption. It was observed that the single inoculation of broccoli plants with *T. viride* significantly increased the above-ground fresh weight, root length, chlorophyll *b*, head diameter, root phosphorus content, and shoot nitrogen content compared to uninoculated control plants [29].

*Trichoderma* sp. also secretes secondary metabolites that play important roles in elevating plant growth and yield. For example, *T. harzianum* and *T. atroviride*, with their main secondary metabolites harzianic acid (HA) and 6-pentyl- $\alpha$ -pyrone (6PP), respectively, were observed to improve grape plant growth, yield, and quality [30]. Vinale et al. [31] showed that the 6PP produced by *Trichoderma* has an auxin-like mechanism of action that is involved in plant growth improvement. Further study demonstrated that 6PP is responsible for promoting plant growth and regulating root architecture, inhibiting primary root growth, and inducing lateral root formation [32]. This study showed that 6PP modulated the expression of *PIN* auxin-transport proteins in a specific and dose-dependent manner in primary roots. Other than that, *T. harzianum* was found to release a metabolite called harzianolide, which is a plant growth regulator that is responsible for improving the growth of tomato seedlings [33]. This study revealed that harzianolide enhances root length and tips as well as induces the expression of genes involved in the salicylic acid (PR1 and GLU) and jasmonate/ethylene (JERF3) signaling pathways that are related to the plant defence mechanism. In arabidopsis, *T. virens* and *T. atroviride* were found to secrete indole acetic acid (IAA) and auxin-related substances; these metabolites are important for root development [34]. Studies have shown that rice plants inoculated with *T. asperellum* produced better plant architecture, higher panicle number, longer panicle length, and increased plant height [35–37]. This is in agreement with previous study on the application of *T. harzianum* on maize plants. When applied to the soil or directly to the seeds, the fungus caused an increase in all of the measured parameters, including growth parameters and levels of chlorophyll, starch, nucleic acids, total protein, and phytohormones of the plants [38].

Numerous studies have been conducted to elaborate the mechanisms by which *Trichoderma* promotes plant growth and development [30,31,39–41]. Some of these mechanisms can be explained by the upregulation of photosynthesis-related proteins resulting in a better photosynthetic rate, plant nitrogen use efficiency [39], and enhancement of plant nutrient uptake [42]. While molecular studies on *Trichoderma* effects are still in a nascent stage, some are showing promising results. For example, a large portion of the genes related to carbohydrate metabolism, stress modulation, and photosynthesis were up-regulated in maize plants upon inoculation with *Trichoderma* [43]. Similarly, in rice, the presence of *T. asperellum* was found to be correlated with the up-regulation of different genes, some of which have been identified to be involved in photosynthesis and chlorophyll biosynthesis. The up-regulation of genes related to CO<sub>2</sub> fixation, response to light, and stomatal complex development indicated an enhancement of the plant's efficiency in photosynthesis [44]. Table 1 summarizes the genes reported to be up-regulated in various plants upon *Trichoderma* inoculation.

**Table 1.** Up-regulated genes in some plants upon *Trichoderma* inoculation.

Plants	<i>Trichoderma</i> Species	Genes	Observed Effects	References
Arabidopsis, cucumber	<i>T. asperelloides</i>	MDAR	Increased osmo-protection/oxidative stress.	[45]
Arabidopsis	<i>T. atroviride</i> , <i>T. virens</i>	AtERD14	Mitigated cold stress effects.	[46]
Rapeseed	<i>T. parareesei</i>	NCED3, ACCO1, ERF1 and PYL4	Improved tolerance to drought and salinity.	[47]
Wheat	<i>T. longibrachiatum</i>	SOD, POD, and CAT	Seedlings were protected from salinity.	[48]
Tomato	<i>T. harzianum</i>	TAS14 and P5CS	Improved tolerance to cold.	[49]
Potato	<i>T. harzianum</i>	Lox and GST1	Induction of plant disease resistance.	[50]
Poplar	<i>T. asperellum</i>	PdPapARF1	Promoted growth and defence responses.	[51]

### 3. Roles of *Trichoderma* in Sustainable Plant Disease Management

Since the 1920s, the very common, soil-inhabiting fungi, *Trichoderma* spp. have been recognized for their capability to act as biocontrol agents against many phytopathogens based on their abilities to parasitize other fungi and to produce antibiotics [42,52]. Later, their principal mechanism of action for plant protection was known to be based on the induction of disease resistance. *Trichoderma* has been documented to control many pathogenic microorganisms that affect plants, including bacteria (*Pseudomonas* and *Xanthomonas*), other fungi (e.g., *Fusarium*, *Curvularia*, *Colletotrichum*, *Alternaria*, *Rhizoctonia*, and *Magnaporthe*), the oomycetes (*Pythium* and *Phytophthora*), and at least one virulent virus (green mottle mosaic virus on cucumber) [42].

#### 3.1. *Trichoderma* as Biocontrol Agents against Plant Pathogenic Bacteria

Plant diseases caused by bacteria are relatively difficult to control. However, the most common methods used to effectively control these diseases include plant breeding and cultural, chemical, biological, and physical control measures. Biocontrol agents are effective in controlling bacterial pathogens and are safer for the environment than chemical bactericides are. The excessive application of chemicals and consumer acceptance towards resistant cultivars can be very complex, which makes the use of biocontrol agents an attractive alternative [22].

*Trichoderma* showed an inhibitory effect on the growth and survival of the pathogenic Gram-negative bacterium, *Ralstonia* spp., in tomato plants, which was attributed to the secretion of various compounds such as lysosime, viridifungin, and trichokonin [53]. Moreover, bacterial wilt caused by the soilborne bacterium *R. solanacearum* was inhibited by the application of *T. asperellum*, and the disease incidence was subsequently decreased with concomitant improvement in plant growth and yield under field conditions. This was achieved through the induction of a maximum level of defence enzyme activities, such as POX, PPO, and PAL,  $\beta$ -1,3-glucanase, and the total phenolic contents in plants [54]. Other examples of biocontrol of bacterial phytopathogens include the induction of resistance by *Trichoderma* conferred protection in tomato plants against *Xanthomonas euvesicatoria* (the causative agent of bacterial spot) and [55] cucumber plants grown in the presence of *Trichoderma* exhibiting greater protection against *Pseudomonas syringae* pv. *lachrymans* infection. *T. harzianum* activated separate metabolic pathways in cucumber that are involved in plant signaling and biosynthesis. Plant protection may be conferred by a combination of several modes of action provided by *Trichoderma*, such as phytoalexins biosynthesis, lignification, and the accumulation of pathogenesis related proteins and antimicrobial secondary metabolites [56].

### 3.2. *Trichoderma* as Biocontrol Agents against Phytopathogenic Fungi

Other than bacterial infections, fungal diseases are often associated with damage to crops, causing major losses in agricultural activities and food production. Thus, finding the best option to eradicate this problem is crucial. *Trichoderma* was found to have the ability to eliminate phytopathogenic fungi through a mechanism known as mycoparasitism. This involves the suppression of other microorganisms at the same site, thereby making it the dominant organism at the location [15,57].

Mycoparasitism by *Trichoderma* species involves an attack on the pathogen's cell or structures [58]. It was reported that *T. koningii* did not invade healthy tissues but colonized infected or damaged onion root tissues as a secondary colonizer, where it reduced *Sclerotium cepivorum* infection by destroying the hyphae [59]. On the other hand, *T. virens* not only parasitized the hyphae of many pathogenic fungal species, but also penetrated and destroyed some of the resting structures of these fungi, thereby reducing their inoculum potential in soil [60]. The pre-emergence of damping-off diseases in cotton seedlings caused by *Rhizopus oryzae* was observed to be controlled upon *T. virens* treatment. This fungus metabolized the pathogen propagule germination stimulants that emanated from the germinating cotton seed [61].

Several species of *Trichoderma* also produce volatile and non-volatile antibiotics and enzymes, which have shown antagonistic effects towards phytopathogenic fungi [62]. Protease, endochitinases,  $\beta$ -glucosidases, mannosidases, and phosphatases released by *T. harzianum* were found to be involved in the biocontrol of various pathogens, including *Guignardia citricarpa* (the causative agent of citrus black spot). These enzymes are involved in the degradation of pathogen cell wall membranes and proteins [63]. *Trichoderma* also releases metabolites that are capable of diminishing or antagonizing pathogenic microbes [64]. Fungal terpenoids (desoxyhemigossypol, hemigossypol, and gossypol) synthesized in cotton roots by *T. virens* were found to be involved in combating *R. solani*-incited cotton seedling [65]. The application of *Trichoderma* on *R. solani*-infected chilies improved plant growth and yield. This was attributed to the reduction of the damping-off disease of seedlings as well as to reducing root and stem rot in chilies [66].

In another report, inoculation of *T. harzianum* inhibits *R. solani* growth by the induction and expression of lipoxygenase (Lox) and glutathione S-transferase (GST1) genes in the roots of potato plantlets that have been simultaneously inoculated with both organisms [50]. The Lox gene product is crucial for lipid peroxidation processes during plant defence responses to pathogen infection [67]. On the other hand, GST1 is a defence gene that is involved in the detoxification of toxic substances by their conjugation with glutathione, the attenuation of oxidative stress, and participation in hormone transport [68]. Biotic stresses can induce plants to produce higher levels of damaging reactive oxygen species (ROS). The excessive production of ROS causes oxidative stress resulting in the damage of cellular components, consequently leading to the death of plant cells [69]. A study conducted by Herrera-Téllez et al. [70] found that tomato plants pre-treated with *T. asperellum* and that were subsequently challenged with two fungal pathogens, *Fusarium oxysporum* and *B. cinerea*, experienced less severe wilting and stunting symptoms compared to non-treated plants due to the ROS modulation by *Trichoderma*.

Besides their direct antagonistic effects against fungal and bacterial plant pathogens, *Trichoderma* species have also been found to induce resistance against various plant diseases. This resistance induction can be either localized or systemic. The effects of systemic resistance induced by *Trichoderma* were recorded using a model rhizobacterium. For example, *T. virens* successfully induced plant-systemic resistance in maize against *Colletotrichum graminicola* [71]. Other than that, *T. virens* was capable of inducing localized resistance against *R. solani* infection of cotton roots through the stimulation of terpenoid synthesis by the plant [65]. The mechanisms involved in these inductions are associated with different kinds of changes at the biochemical and molecular levels in the plants [72].

The capability of *Trichoderma* to protect plants against different bacterial and fungal pathogens is summarized with examples in Table 2.



**Table 2.** *Trichoderma* species and their biotic stress regulation mechanisms.

Plants	<i>Trichoderma</i> Species	Phytopathogens	Observed Effects	References
Tomato	<i>T. harzianum</i>	<i>Clavibacter michiganensis</i>	Prevented the incidence of bacterial canker.	[73]
Tomato	<i>T. harzianum</i> and <i>T. longibrachiatum</i>	<i>X. euvesicatoria</i> , <i>Alternaria solani</i>	Reduced bacterial spots, triggering systemic acquired resistance (SAR) or induced systemic resistance (ISR).	[55]
Tomato	<i>T. harzianum</i>	<i>Ralstonia</i> spp.	<i>Trichoderma</i> spp. AA2 inhibited the growth and survival of <i>Ralstonia</i> spp.	[53]
Tomato	<i>T. asperellum</i>	<i>R. solanacearum</i>	Delayed wilt development, effectively decreased disease incidence, increased fruit yield, and improved plant growth promotion.	[54]
Tomato	<i>T. asperellum</i>	<i>F. oxysporum</i> , <i>B. cinerea</i>	Inhibited ROS production.	[70]
<i>Arabidopsis thaliana</i>	<i>T. asperelloides</i>	<i>P. syringae</i>	Lesser necrotic lesions surrounded by extensively spreading chlorosis.	[74]
Radish, lettuce, tomato	<i>T. hamatum</i>	<i>X. campestris</i>	Lowered bacterial population and disease severity (bacterial leaf spot).	[75]
Rice	<i>T. harzianum</i>	<i>X. oryzae</i>	Bacterial leaf blight severity was reduced while plant growth was improved.	[76]
Cucumber	<i>T. asperellum</i>	<i>P. syringae</i> pv. <i>lachrymans</i>	Transcript accumulation of biosynthetic defence related genes and accumulation of phenolic compounds (antimicrobial activity).	[56]
Citrus	<i>T. harzianum</i>	<i>G. citricarpa</i>	The involvement of protease affecting the germination of <i>G. citricarpa</i> conidia, able to deactivate the pathogen's hydrolytic enzymes that are responsible for plant tissues necrosis.	[63]
Onion	<i>T. koningii</i>	<i>S. cepivorum</i>	Destroyed the hyphae, making it detached at septa, cell walls dissolved, and many hyphal apices burst.	[59]
Cotton	<i>T. virens</i>	<i>R. solani</i>	Induced terpenoid synthesis, toxic to the pathogen.	[65]
Cotton	<i>T. virens</i> and <i>T. longibrachiatum</i>	<i>R. oryzae</i>	Metabolized pathogen propagule germination stimulants that emanate from the germinating cotton seed.	[61]
Cotton	<i>T. virens</i>	<i>R. solani</i>	Penetrated and destroyed some of the resting structures of the pathogen.	[60]
Sunflower	<i>T. koningii</i> , <i>T. aureoviride</i> , <i>T. longibrachiatum</i>	<i>S. sclerotiorum</i>	Head rot incidence was significantly reduced, delayed epidemic onset.	[77]
Wheat	<i>T. harzianum</i> , <i>T. aureoviride</i> , <i>T. koningii</i>	<i>Pyrenophora tritici-repentis</i>	Pathogen mycelium on the leaf surface collapsed or disintegrated.	[78]
Rambutan	<i>T. harzianum</i>	<i>Botryodiplodia theobromae</i> , <i>Colletotrichum gloeosporioides</i> , <i>Gliocephalotrichum microclamydosporum</i>	Reduced the occurrence of the three postharvest diseases, also retained the overall quality and colour of the fruits.	[79]
Chickpea	<i>T. atroviride</i> , <i>T. koningii</i> , <i>T. harzianum</i> , <i>T. hamatum</i>	<i>F. oxysporum</i> , <i>Ascochyta rabiei</i>	Suppressed fungal infections by mycoparasitism, antibiosis, and competition for space and/or nutrients.	[80]
<i>Arabidopsis</i> , Rapeseed	<i>T. harzianum</i>	<i>B. cinerea</i>	Induction of systemic defence, mediated by jasmonic acid.	[81]

### 3.3. *Trichoderma* as Biocontrol Agents against Pests and Plant-Parasitic Nematodes

Plant diseases caused by insect pests and plant-parasitic nematodes (PPNs) are also considered to be a significant threat to global agricultural productivity and sustainability. Insect pests can cause agricultural losses of up to 70% [82], while 12% of worldwide food production is lost due to plant-parasitic nematodes (PPNs) [83].

Among the common nematode antagonistic fungi, also known as nematophagous fungi, *T. harzianum*, *T. viride*, and *T. lignorum* have been commercially produced as fungal biocontrol agents for the management of phytonematodes [84]. An experiment employing *Trichoderma* for the control of the root-feeding nematode *Meloidogyne hapla* in tomatoes revealed that tomato plants that were prior inoculated with *Trichoderma* exhibited a lower number of nematode eggs laid on or near the roots of about 1000 (2%) eggs compared to 50,000 eggs laid on the roots of untreated plant controls [85]. Earlier, an experiment in India showed that the bio-integration of *T. harzianum* in combination with oil cakes could significantly reduce the population of citrus nematode *Tylenchulus semipenetrans* in both soil and root [86].

Fungi belonging to the *Trichoderma* genus are also well-known for their beneficial effects in conferring plant protection against insect pests and parasitic nematodes. Based on previous studies on the mode of action of *Trichoderma* as the mycoparasite fungus, *Trichoderma* species can act directly as an entomopathogen through parasitism, and the production of insecticidal secondary metabolites, antifeedant compounds and repellent metabolites. On top of that, this versatile fungus can act indirectly as a mycoparasite through the activation of systemic plant defensive responses, the attraction of natural enemies, or the parasitism of insect-symbiotic microorganisms [82]. For example, *T. longibrachiatum* that was formulated into a biopesticide was reported to be able to control the insect pest *Leucinodes orbonalis* in brinjal plants as well as increasing crop yield by 56.02% [87]. Moreover, under laboratory conditions *T. harzianum* exhibited an inhibitory activity of around 70–80% towards *Xylotrechus arvicola* (an important pest in vineyards) and *Acanthoscelides obtectus* (a causal agent of severe post-harvest losses in the common bean) [88].

The application of *T. gamsii* to the roots of *Arabidopsis thaliana* decreased the feeding behaviour of herbivore *Trichoplusia ni* through the modulation of the metabolome as well as affecting the content of phytohormones in plant leaves. *T. gamsii*-inoculated plant leaves recorded higher levels of amino acids and abscisic acid and lower concentrations of sugars compared to untreated plants [89]. Maize plant roots associated with *T. atroviride* recorded higher resistance against the insect herbivore *Spodoptera frugiperda* compared to untreated plants. Further examination indicated that there was a significant increase with regards to the emission of volatile terpenes and the accumulation of jasmonic in roots of inoculated rice plants. Chemical analyses revealed that *T. atroviride* produced the volatiles 1-octen-3-ol and 6-pentyl-2H-pyran-2-one, which were believed to have an important role in reducing the consumption of the foliar tissue of maize plants by *S. frugiperda* [90].

The inoculation of *T. atroviride* in tomato plants induced plant resistance to the insects *Spodoptera littoralis* and *Macrosiphum euphorbiae*. These protection capacities were attributed to a plant response induced by *T. atroviride* that was linked with molecular and biochemical changes in tomato plants. *T. atroviride* also produced alterations in plant metabolic pathways leading to the production and release of volatile organic compounds (VOCs) that are involved in the attraction of the aphid *Aphidius ervi* (a parasitoid with activity against many pests), thus reinforcing indirect plant defence barriers [91]. The insecticidal efficacy of *T. harzianum* with natural protectants was also found to be an acceptable approach for the management of stored product damage resulting from the insects *Callosobruchus maculatus* and *C. chinensis* in cowpea seeds. The *T. harzianum*-based biofungicide formulation caused complete insect mortality and inhibited progeny production. Thus, this eco-friendly product can be an effective strategy for the management of both insects on stored cowpea seeds [92].

#### 4. *Trichoderma* Species as Abiotic Stress Relievers in Crops

Drought is one of the main abiotic stresses that occur due to water deficit and is escalated by increasing evapotranspiration [93]. Drought has deleterious effects that may reduce growth and cause plant death [94]. The inoculation of plants with *Trichoderma* activates a number of different kinds of responses toward drought. For example, *T. harzianum* was found to postpone or delay drought responses in rice. This was due to the enhancement of root growth regardless of the water deficit that was shown by the delayed increase of the stress-induced metabolites proline, malondialdehyde (MDA), and hydrogen peroxide content as well as increased phenolic compound concentration [95]. *T. atroviride* inoculation in maize plants could diminish the injurious effects of drought and might have a function in arranging resilience against stress by inducing the antioxidant machinery that helps to overcome the unfavourable conditions caused by the overproduction of ROS [96]. It was found that the maize plants inoculated with *T. harzianum* had a high starch content in their leaves [38]. This could be beneficial in drought conditions, where prolonged stomatal conductance leads to carbon starvation.

Other than drought, cold is an example of extreme temperature conditions that constitute a serious threat to the sustainability of crop yields and that can lead to major crop losses. This stress happens when plants are exposed to low temperatures, such as those caused by sudden frosts in fall, freezing temperatures in winter, and late cold spring events [97]. The inhibition of decline in plant growth due to cold weather can be induced by *Trichoderma*. For example, *T. harzianum* colonization was found to alleviate the detrimental effects of cold stress on most commercial varieties of tomato, a cold-sensitive plant. Upon inoculation of *T. harzianum*, both the fresh and dry weights of tomato leaves and roots were enhanced compared to those of cold-treated plants. Other than that, improved photosynthesis and growth rate, leaf water content, and proline accumulation were observed, while indicators of cold injuries such as lipid peroxidation rate and electrolyte leakage were reduced [49].

Soil salinity stress is accompanied by high osmotic potential and specific ion toxicity and is another growth limiting factor for plants. However, treatment with *T. harzianum* on wheat plants was able to reduce the severity of saline conditions [98]. The application of *T. asperelloides* prior to salt stress imposition in both arabidopsis and cucumber plants showed significantly improved seed germination [45]. Increased salinity can lower the photosynthetic rate, thereby reducing the supply of carbohydrates needed for plant growth [99]. The inoculation of the Indian mustard plant with *T. harzianum* was able to restore the photosynthetic pigment to an appreciable level [100]. In saline or degenerated soils, *T. asperellum* was found to be involved in the solubilization of the large amounts of insoluble organic and inorganic phosphate compounds needed for cucumber growth. Cucumber plants inoculated with *Trichoderma* exhibited growth in both normal and saline conditions, indicating the role of the fungus in helping plants to overcome the inhibition of plant root development caused by high salt levels [101,102]. In addition, in response to biotic and abiotic stresses, several genes related to the rice plant response to these stresses were upregulated upon *Trichoderma* inoculation. For example, genes that are involved in plant defence response and ROS metabolism were up-regulated with *T. asperellum* inoculation [44]. Table 3 summarizes the effects of *Trichoderma* inoculation towards abiotic stresses in plants.



**Table 3.** *Trichoderma* and their abiotic stress regulation mechanisms.

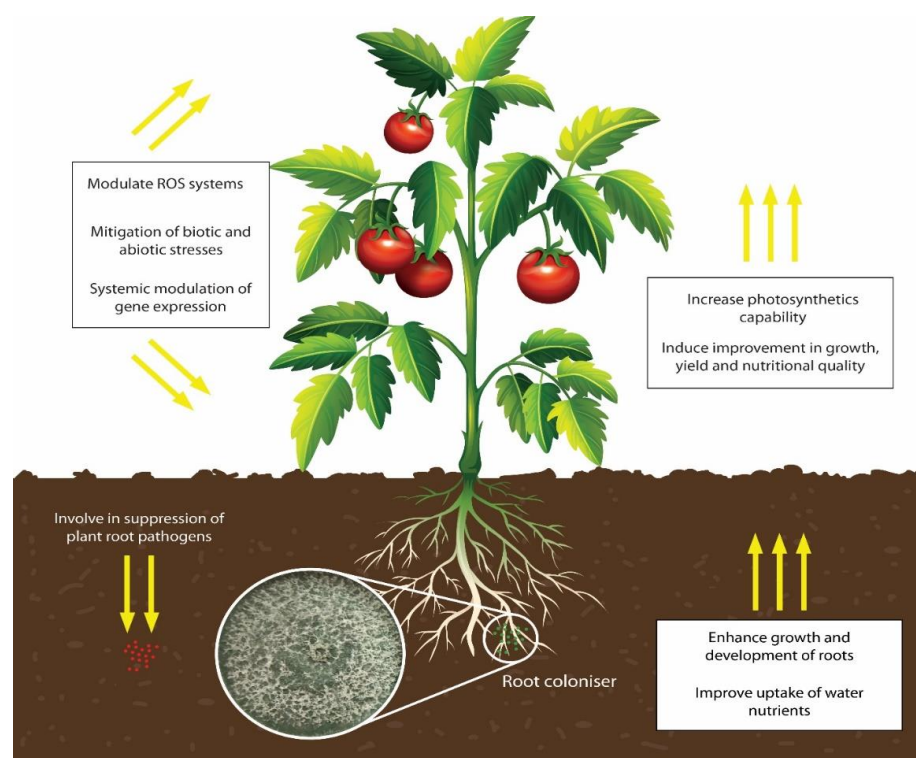
Plants	<i>Trichoderma</i> Species	Mechanisms	References
Rice	<i>T. harzianum</i>	Promotion of root growth in water deficit conditions.	[95]
Maize	<i>T. atroviride</i>	Improved drought-induced damages such as fresh and dry weights of maize roots, lipid peroxidation, photosynthetic machinery and inducing antioxidant enzyme activity and hydrogen peroxide.	[96]
Maize	<i>T. harzianum</i>	High starch content.	[43]
Tomato	<i>T. harzianum</i>	Maintained a high level of growth regulators, modulated plant secondary metabolites.	[103]
Tomato	<i>T. harzianum</i>	Improved growth attributes together with reduced cold injuries.	[49]
Arabidopsis, Cucumber	<i>T. asperelloides</i>	Improved seed germination.	[45]
Indian mustard	<i>T. harzianum</i>	Restored photosynthetic pigment level.	[100]

### 5. Challenges and Future Prospects for Up-Scaling the Use of *Trichoderma* for Sustainable Crop Production

In summary, numerous studies have provided strong evidence that *Trichoderma* species integrated into crop production can achieve improved overall plant health, growth, yield, and disease resistance (Figure 1). Based on a study completed by Zhang et al. [104], the application of *Trichoderma* biofertilizer (composted cattle manure + inoculum) effectively regulated soil chemistry and microbial communities, which substantially improved aboveground plant biomass compared to the organic fertilizer alone. Furthermore, the presence of *Trichoderma* can increase the relative abundance of beneficial fungi while significantly decreasing the number of phytopathogenic microorganisms. This was shown by the increase of *Archaeorhizomyces* and *Trichoderma* while decreasing *Ophiostoma* abundance. In one in vitro study, *Trichoderma* was seen to inhibit the growth of *Fusarium solani*, but no inhibition area was observed when it was cultured together with *Pseudomonas* strains [105]. *Trichoderma* tends to be compatible and live mutually with beneficial microbes that contribute to plant growth rather than harmful ones.

Realization of the beneficial capabilities of *Trichoderma* is important to meet current societal needs [106]. There are increasing concerns about the possible adverse effects of biological control agents (BCAs) and the risks associated with the use of these biological compounds on mammalian health. A study conducted by Santos et al. [107] analyzed and discussed the interaction between *Trichoderma* spp. and mammalian immune system cells. The study indicated that *T. asperelloides* spores in mice reduced the quantity of neutrophils (a type of white blood cell that involves in healing damaged tissues and resolving infections) and monocytes. However, these preliminary results indicated that the impact of *Trichoderma* on the immune system could be more significant than previously supposed. However, further studies are required to elucidate the effects of BCAs on mammalian immune responses that are possibly associated with infectious, inflammatory diseases and defective defences [108]. That said, the majority of BCAs products are safe for consumers and the environment [109]. Nevertheless, consumers need to handle BCAs properly and must comply with safety and health standards [37]. A number of *Trichoderma*-based products have been developed and marketed globally as BCAs and biofertilizers, a majority of the work on the BCAs has focused on isolation, identification, and the development of the selected isolates and only a few of such products are registered and commercialized. This is due to the fact that the commercialization of the end products is tedious, laborious, time-consuming, and quite costly [84]. On top of that, the investigation on the long-term effect of BCAs and biofertilizers on consumers should always be included in order to prevent any potential harm from such compounds and to allow consumers to make informed decisions

based on scientific data [110]. To translate early-stage BCA research, a suitable company that is capable of manufacturing and marketing products must be approached. As this is not easily achieved, researchers might have to resort to their personal means to develop and produce the intended product up until the commercialization process. Without proper instructions and knowledge passed to the consumers, such a product will not reach or stay relevant on the market.



**Figure 1.** The effects of *Trichoderma* on plant growth, development and health.

Despite the constraints, the Asian continent, particularly India, has seen the greatest commercialization of *Trichoderma*-based products, followed by South and Central America [111]. Several challenges have limited the full-scale commercialization of *Trichoderma* bioproducts, and these have also been major reasons for the relatively small number of registered products. In many countries, guidelines for microbial control agents are lacking; hence, regulatory requirements for the approval of these products are modelled after those of chemical agents. This approach makes it difficult due to the incompatibility of biocontrol agents with some of the criteria used for chemical agents [112]. Furthermore, the requirements for testing, validation, patenting, and other processes make the registration an expensive venture, thus discouraging aspiring entrepreneurs [112,113]. In developing countries, the required resources and expertise for the large-scale commercial production of *Trichoderma* products are also lacking [113,114].

Conceivably, the most serious hindrance against the commercialization of *Trichoderma*-based products is their poor shelf life [111]. Several strategies have been attempted and have shown great promise for extending the shelf life of such products without severely impacting their beneficial properties. Among the measures that have been used to extend the shelf life of *Trichoderma* preparations are the use of carrier materials [115] such as starch and pH and copper amendments [116] and encapsulation in granules [117]. Recently, a novel biodegradable lignin shell was used to encapsulate *T. reesei* spores in a layer-by-layer assembly [118]. This strategy prevented the unwanted germination of the spores and permitted their selective germination upon contact with a lignin-degrading fungal pathogen.

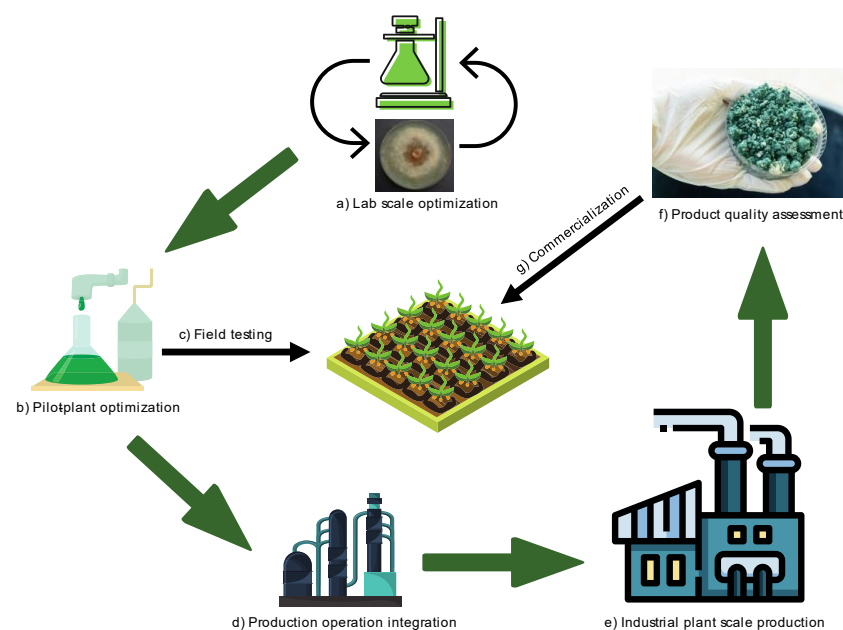
Hence, efforts targeted at addressing these problems will facilitate commercialization and will increase the accessibility of bioproducts derived from this versatile fungal genus. Other than that, since biofertilizers normally depend on soil conditions, continuous study and refinement on the product design and workability are needed to allow different environmental areas to gain the same benefits [119]. Ultimately, both subsistent and large-scale agriculture would benefit from such measures.

#### Industrial Production of *Trichoderma*

The main characteristic for a selected endophytic fungal to be commercialized as a biocontrol or biofertilizer product is the ability to be mass produced through the economical generation of the utmost amount of effective propagules (chlamydospores, conidia, microsclerotia) in the shortest period of time. A higher cost of production due to expensive substrate, low biomass output, or restricted economies of scale can be a limiting factor in the commercialization of the end products [120].

Prior to the biomass production, practical research has been initiated with the isolation and identification of the specific *Trichoderma* species. After the isolation and characterization of pure culture of the selected *Trichoderma*, the propagules can be in the form of hyphae, chlamydospores, and conidia [37,84]. The mass production of *Trichoderma* propagules can be completed through solid state as well as by submersed fermentation [121]. Substrates for mass production can be obtained from crop residues, livestock wastes, industrial wastes, and any organic material [122].

The industrial production of *Trichoderma* can be conducted in the following steps: (1) optimization of the culture condition at a laboratory scale in order to obtain high yield and active biomass, (2) optimization of biomass production at pilot-plant level to determine and solve various engineering variables; the resulting products can be tested for field application, (3) integration of selected unit operations from fermentation, bioseparation, and formulation into a single process, and (4) industrial plant-scale production of propagules of *Trichoderma* [120,123]. The production process of *Trichoderma*-based biofertilizer from laboratory to industrial scale is summarized in Figure 2.



**Figure 2.** Strategy and organization flow for industrial production of *Trichoderma*. (a) Optimization of culture condition at laboratory scale; (b) pilot-plant production to optimize biomass production; (c) field testing from optimized product; (d) operation integration of fermentation, bioseparation, and formulation into a single process; (e) industrial plan-scale production of *Trichoderma* propagules; (f) assessment of product quality and standard; (g) commercialization and distribution for public use.

## 6. Conclusions

*Trichoderma* is able to enhance the growth and development of various plant species safely and sustainably. This includes combating both biotic and abiotic stresses that often deteriorate plant normal development and cause crop losses. The positive effects of *Trichoderma* towards plant growth and development have proven that these fungi can be used extensively for the advancement of sustainable agriculture. Currently, there are intensive efforts to hasten their integration into agricultural production systems to achieve the development of successful inoculation systems and workable modes of delivery. An improved understanding of the mechanisms involved in various processes by *Trichoderma* is important to develop practicable products for a sustainable agriculture sector. Furthermore, the application of different omics approaches in phytobiome studies has become invaluable for unveiling a comprehensive interaction among *Trichoderma*, plants, and their environment. The acceptance of workable *Trichoderma*-based products will help to reduce the use of chemical fertilizers and pesticides and will subsequently lead to healthier, cleaner food production, and sustainable agricultural practice.

**Author Contributions:** Writing—original draft preparation, N.S.A.; conceptualization, F.D.; writing—review and editing, F.D., M.S.M., M.Z.S., Y.M.Y., M.A.O. and N.S.M.S.; supervision and project administration, F.D., Y.M.Y. and N.S.M.S.; visualization, F.D. and N.S.M.S.; funding acquisition, N.S.M.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This review was funded by the Ministry of Higher Education (MOHE), Malaysia, through Fundamental Research Grant Scheme (FRGS) awarded to N.S.M.S., grant number FRGS/1/2019/STG03/UM/02/16.

**Acknowledgments:** We thank Jennifer Ann Harikrishna for providing helpful suggestions and comments for the improvement of the manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Raza, A.; Razzaq, A.; Mehmood, S.; Zou, X.; Zhang, X.; Lv, Y.; Xu, J. Impact of climate change on crops adaptation and strategies to tackle its outcome: A review. *Plants* **2019**, *8*, 34. [CrossRef] [PubMed]
2. Grafton, R.Q.; Daugbjerg, C.; Qureshi, M.E. Towards food security by 2050. *Food Sec.* **2015**, *7*, 179–183. [CrossRef]
3. Pandey, P.; Irulappan, V.; Bagavathiannan, M.V.; Senthil-Kumar, M. Impact of combined abiotic and biotic stresses on plant growth and avenues for crop improvement by exploiting physio-morphological traits. *Front. Plant Sci.* **2017**, *8*, 537. [CrossRef] [PubMed]
4. FAO. The 10 Elements of Agroecology. 2020. Available online: <http://www.fao.org/3/i9037en/i9037en.pdf> (accessed on 18 May 2020).
5. Saba, H.D.; Vibhash, M.; Manisha, K.S.; Prashant Farham, H.; Tauseff, A. *Trichoderma*—A promising plant growth stimulator and biocontrol agent. *Mycosphere* **2012**, *3*, 524–531. [CrossRef]
6. Poveda, J. Beneficial effects of microbial volatile organic compounds (MVOCs) in plants. *Appl. Soil Ecol.* **2021**, *168*, 104118. [CrossRef]
7. Harman, G.E.; Doni, F.; Khadka, R.B.; Uphoff, N. Endophytic strains of *Trichoderma* increase plants' photosynthetic capability. *J. Appl. Microbiol.* **2021**, *130*, 529–546. [CrossRef]
8. Poveda, J.; Zabalgogazcoa, I.; Soengas, P.; Rodríguez, V.M.; Cartea, M.E.; Abilleira, R.; Velasco, P. *Brassica oleracea* var. *acephala* (kale) improvement by biological activity of root endophytic fungi. *Sci. Rep.* **2020**, *10*, 20224. [CrossRef]
9. Poveda, J.; Eugui, D.; Abril-Urias, P.; Velasco, P. Endophytic fungi as direct plant growth promoters for sustainable agricultural production. *Symbiosis* **2021**, *85*, 1–19. [CrossRef]
10. Singh, A.; Shukla, N.; Kabadwal, B.C.; Tewari, A.K.; Kumar, J. Review on plant-*Trichoderma*-pathogen interaction. *Int. J. Curr. Microbiol. Appl. Sci.* **2018**, *7*, 2382–2397. [CrossRef]
11. Hidangmayum, A.; Dwivedi, P. Plant responses to *Trichoderma* spp. and their tolerance to abiotic stresses: A review. *J. Pharmacog. Phytochem.* **2018**, *7*, 758–766.
12. Altieri, M.; Nicholls, C.; Montalba, R. Technological approaches to sustainable agriculture at a crossroads: An agroecological perspective. *Sustainability* **2017**, *9*, 349. [CrossRef]
13. Altieri, M.; Nicholls, C. Agroecology and the reconstruction of a post-COVID-19 agriculture. *J. Peasant Stud.* **2020**, *4*, 881–898. [CrossRef]
14. Baez-Rogelio, A.; Morales-García, Y.E.; Quintero-Hernández, V.; Muñoz-Rojas, J. Next generation of microbial inoculants for agriculture and bioremediation. *Microb. Biotechnol.* **2016**, *10*, 19–21. [CrossRef]



15. Harman, G.; Khadka, R.; Doni, F.; Uphoff, N. Benefits to plant health and productivity from enhancing plant microbial symbionts. *Front. Plant Sci.* **2021**, *11*, 610065. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Finkel, O.M.; Castrillo, G.; Herrera Paredes, S.; Salas González, I.; Dangel, J.L. Understanding and exploiting plant beneficial microbes. *Curr. Opin. Plant Biol.* **2017**, *38*, 155–163. [\[CrossRef\]](#)
17. Mahato, D. *Trichoderma's* contribution in environmentally friendly plant disease management. *Biotica Res. Today* **2021**, *3*, 591–594.
18. Poveda, J.; Eugui, D.; Abril-Urias, P. Could *Trichoderma* Be a Plant Pathogen? Successful Root Colonization. In *Trichoderma. Rhizosphere Biology*; Sharma, A., Sharma, P., Eds.; Springer: Singapore, 2020; pp. 35–59. [\[CrossRef\]](#)
19. Alonso-Ramírez, A.; Poveda, J.; Martín, I.; Hermosa, R.; Monte, E.; Nicolás, C. Salicylic acid Prevents *Trichoderma harzianum* from entering the vascular system of roots. *Mol. Plant Pathol.* **2014**, *15*, 823–831. [\[CrossRef\]](#)
20. Poveda, J. Glucosinolates profile of *Arabidopsis thaliana* modified root colonization of *Trichoderma* species. *Biol. Control* **2021**, *155*, 104522. [\[CrossRef\]](#)
21. Imadi, S.R.; Shazadi, K.; Gul, A.; Hakeem K., R. Sustainable Crop Production System. In *Plant, Soil and Microbes*; Hakeem, K., Akhtar, M., Abdullah, S., Eds.; Springer: Cham, Switzerland, 2016; pp. 103–116. [\[CrossRef\]](#)
22. Al-Ani, L.K.T. *Trichoderma*: Beneficial Role in Sustainable Agriculture by Plant Disease Management. In *Plant Microbiome: Stress Response. Microorganisms for Sustainability*; Egamberdieva, D., Ahmad, P., Eds.; Springer: Singapore, 2018; pp. 105–126. [\[CrossRef\]](#)
23. Molla, A.H.; Haque, M.M.; Haque, M.A.; Ilias, G.N.M. *Trichoderma*-enriched biofertilizer enhances production and nutritional quality of tomato (*Lycopersicon esculentum* Mill.) and minimizes NPK fertilizer Use. *Agric. Res.* **2012**, *1*, 265–272. [\[CrossRef\]](#)
24. Rudresh, D.L.; Shivaprakash, M.K.; Prasad, R.D. Tricalcium phosphate solubilizing abilities of *Trichoderma* spp. in relation to P uptake and growth and yield parameters of chickpea (*Cicer arietinum* L.). *Can. J. Microbiol.* **2005**, *51*, 217–222. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Kumar, A. Effect of *Trichoderma* spp. in plant growth promotion in chilli. *Int. J. Curr. Microbiol. Appl. Sci.* **2019**, *8*, 1574–1581. [\[CrossRef\]](#)
26. Srivastava, S.N.; Singh, V.; Awasthi, S.K. *Trichoderma* induced improvement in growth, yield and quality of sugarcane. *Sugar Tech* **2006**, *8*, 166–169. [\[CrossRef\]](#)
27. Azarmi, R.; Hajieghrari, B.; Giglou, A. Effect of *Trichoderma* isolates on tomato seedling growth response and nutrient uptake. *Afr. J. Biotechnol.* **2011**, *10*, 5850–5855. [\[CrossRef\]](#)
28. Fiorentino, N.; Ventorino, V.; Woo, S.L.; Pepe, O.; De Rosa, A.; Gioia, L.; Romano, I.; Lombardi, N.; Napolitano, M.; Colla, G.; et al. *Trichoderma*-based biostimulants modulate rhizosphere microbial populations and improve N uptake efficiency, yield, and nutritional quality of leafy vegetables. *Front. Plant Sci.* **2018**, *9*, 743. [\[CrossRef\]](#)
29. Tanwar, A.; Aggarwal, A.; Kaushish, S.; Chauhan, S. Interactive effect of AM fungi with *Trichoderma viride* and *Pseudomonas fluorescens* on growth and yield of broccoli. *Plant Prot. Sci.* **2013**, *49*, 137–145. [\[CrossRef\]](#)
30. Pascale, A.; Vinale, F.; Manganiello, G.; Nigro, M.; Lanzuise, S.; Ruocco, M.; Marra, R.; Lombardi, N.; Woo, S.L.; Lorito, M. *Trichoderma* and its secondary metabolites improve yield and quality of grapes. *Crop Prot.* **2017**, *92*, 176–181. [\[CrossRef\]](#)
31. Vinale, F.; Sivasithamparam, K.; Ghisalberti, E.L.; Marra, R.; Barbetti, M.J.; Li, H.; Woo, S.L.; Lorito, M. A novel role for *Trichoderma* secondary metabolites in the interactions with plants. *Physiol. Mol. Plant Pathol.* **2008**, *72*, 80–86. [\[CrossRef\]](#)
32. Garnica-Vergara, A.; Barrera-Ortiz, S.; Muñoz-Parra, E.; Raya-González, J.; Méndez-Bravo, A.; Macías-Rodríguez, L.; Ruiz-Herrera, L.F.; López-Bucio, J. The volatile 6-pentyl-2H-pyran-2-one from *Trichoderma atroviride* regulates *Arabidopsis thaliana* root morphogenesis via auxin signaling and ETHYLENE INSENSITIVE 2 functioning. *New Phytol.* **2016**, *209*, 1496–1512. [\[CrossRef\]](#)
33. Cai, F.; Yu, G.; Wang, P.; Wei, Z.; Fu, L.; Shen, Q.; Chen, W. Harzianolide, a novel plant growth regulator and systemic resistance elicitor from *Trichoderma harzianum*. *Plant Physiol. Biochem.* **2013**, *73*, 106–113. [\[CrossRef\]](#)
34. Contreras-Cornejo, H.A.; Macías-Rodríguez, L.; Alfaro-Cuevas, R.; López-Bucio, J. *Trichoderma* spp. improve growth of *Arabidopsis* seedlings under salt stress through enhanced root development, osmolyte production, and Na<sup>+</sup> elimination through root exudates. *Mol. Plant-Microbe Interact.* **2014**, *27*, 503–514. [\[CrossRef\]](#)
35. Doni, F.; Isahak, A.; Zain, C.R.C.M.; Yusoff, W.M.W. Physiological and growth response of rice plants (*Oryza sativa* L.) to *Trichoderma* spp. inoculants. *AMB Express* **2014**, *4*, 45. [\[CrossRef\]](#)
36. Doni, F.; Zain, C.R.; Isahak, A.; Fathurrahman, F.; Sulaiman, N.; Uphoff, N.; Yusoff, W.M. Relationships observed between *Trichoderma* inoculation and characteristics of rice grown under System of Rice Intensification (SRI) vs. conventional methods of cultivation. *Symbiosis* **2016**, *72*, 45–59. [\[CrossRef\]](#)
37. Doni, F.; Zain, C.R.; Isahak, A.; Fathurrahman, F.; Anhar, A.; Mohamad, W.N.; Wan Yusoff, W.M.; Uphoff, N. A simple, efficient, and farmer-friendly *Trichoderma*-based biofertilizer evaluated with the SRI Rice Management System. *Org. Agric.* **2018**, *8*, 207–223. [\[CrossRef\]](#)
38. Akladios, S.A.; Abbas, S.M. Application of *Trichoderma harzianum* T22 as a biofertilizer supporting maize growth. *Afr. J. Biotechnol.* **2012**, *11*, 8672–8683. [\[CrossRef\]](#)
39. Shores, M.; Harman, G.E.; Mastouri, F. Induced systemic resistance and plant responses to fungal biocontrol agents. *Annu. Rev. Phytopathol.* **2010**, *48*, 21–43. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Vinale, F.; Sivasithamparam, K.; Ghisalberti, E.L.; Ruocco, M.; Woo, S.; Lorito, M. *Trichoderma* secondary metabolites that affect plant metabolism. *Nat. Prod. Commun.* **2012**, *7*, 1545–1550. [\[CrossRef\]](#)
41. Vinale, F.; Nigro, M.; Sivasithamparam, K.; Flematti, G.; Ghisalberti, E.L.; Ruocco, M.; Varlese, R.; Marra, R.; Lanzuise, S.; Eid, A.; et al. Harzianic acid: A novel siderophore from *Trichoderma harzianum*. *FEMS Microbiol. Lett.* **2013**, *347*, 123–129. [\[CrossRef\]](#) [\[PubMed\]](#)



42. Harman, G.E.; Howell, C.R.; Viterbo, A.; Chet, I.; Lorito, M. *Trichoderma* species, opportunistic avirulent plant symbionts. *Nature* **2004**, *2*, 43–56. [[CrossRef](#)]
43. Shores, M.; Harman, G.E. The molecular basis of shoot responses of maize seedlings to *Trichoderma harzianum* T22 inoculation of the root: A proteomic approach. *Plant Physiol.* **2008**, *147*, 2147–2163. [[CrossRef](#)] [[PubMed](#)]
44. Doni, F.; Fathurrahman, F.; Mispan, M.S.; Suhaimi, N.S.; Yusoff, W.M.; Uphoff, N. Transcriptomic profiling of rice seedlings inoculated with the symbiotic fungus *Trichoderma asperellum* SL2. *J. Plant Growth Regul.* **2019**, *38*, 1507–1515. [[CrossRef](#)]
45. Brotman, Y.; Landau, U.; Cuadros-Inostroza, Á.; Takayuki, T.; Fernie, A.R.; Chet, I.; Viterbo, A.; Willmitzer, L. *Trichoderma*-plant root colonization: Escaping early plant defense responses and activation of the antioxidant machinery for saline stress tolerance. *PLoS Pathog.* **2013**, *9*, e1003221. [[CrossRef](#)]
46. González-Pérez, E.; Ortega-Amaro, M.A.; Salazar-Badillo, F.B.; Bautista, E.; Douterlungne, D.; Jiménez-Bremont, J.F. The arabidopsis-*Trichoderma* interaction reveals that the fungal growth medium is an important factor in plant growth induction. *Sci. Rep.* **2018**, *8*, 16427. [[CrossRef](#)]
47. Poveda, J. *Trichoderma parareesei* favors the tolerance of rapeseed (*Brassica napus* L.) to salinity and drought due to a chorismate mutase. *Agron.* **2020**, *10*, 118. [[CrossRef](#)]
48. Zhang, S.; Gan, Y.; Xu, B. Application of plant-growth-promoting fungi *Trichoderma longibrachiatum* T6 enhances tolerance of wheat to salt stress through improvement of antioxidative defense system and gene expression. *Front. Plant Sci.* **2016**, *7*, 1405. [[CrossRef](#)]
49. Ghorbanpour, A.; Salimi, A.; Ghanbary, M.A.T.; Pirdashti, H.; Dehestani, A. The effect of *Trichoderma harzianum* in mitigating low temperature stress in tomato (*Solanum lycopersicum* L.) plants. *Sci. Hortic.* **2018**, *230*, 134–141. [[CrossRef](#)]
50. Gallou, A.; Cranenbrouck, S.; Declerck, S. *Trichoderma harzianum* elicits defence response genes in roots of potato plantlets challenged by *Rhizoctonia solani*. *Eur. J. Plant Pathol.* **2008**, *124*, 219–230. [[CrossRef](#)]
51. Wang, Y.; Hou, X.; Deng, J.; Yao, Z.; Lyu, M.; Zhang, R. Auxin response factor 1 acts as a positive regulator in the response of poplar to *Trichoderma asperellum* inoculation in overexpressing plants. *Plants* **2020**, *9*, 272. [[CrossRef](#)]
52. Verma, P.; Yadav, A.N.; Kumar, V.; Khan, A.; Saxena, A.K. Microbes in Termite Management: Potential Role and Strategies. In *Termites and Sustainable Management: Volume 2—Economic Losses and Management*; Khan, M.A., Ahmad, W., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 197–217. [[CrossRef](#)]
53. Yan, L.; Khan, R.A. Biological control of bacterial wilt in tomato through the metabolites produced by the biocontrol fungus, *Trichoderma harzianum*. *Egypt. J. Biol. Pest Control* **2021**, *31*, 5. [[CrossRef](#)]
54. Konappa, N.; Krishnamurthy, S.; Siddaiah, C.N.; Ramachandrapa, N.S.; Chowdappa, S. Evaluation of biological efficacy of *Trichoderma asperellum* against tomato bacterial wilt caused by *Ralstonia solanacearum*. *Egypt. J. Biol. Pest* **2018**, *28*, 63. [[CrossRef](#)]
55. Fontenelle, A.; Guzzo, S.; Lucon, C.; Harakava, R. Growth promotion and induction of resistance in tomato plant against *Xanthomonas euvesicatoria* and *Alternaria solani* by *Trichoderma* spp. *Crop Prot.* **2011**, *30*, 1492–1500. [[CrossRef](#)]
56. Yedidia, I.; Shores, M.; Kerem, Z.; Benhamou, N.; Kapulnik, Y.; Chet, I. Concomitant induction of systemic resistance to *Pseudomonas syringae* pv. *lachrymans* in cucumber by *Trichoderma asperellum* (T-203) and accumulation of phytoalexins. *Appl. Environ. Microbiol.* **2003**, *69*, 7343–7353. [[CrossRef](#)] [[PubMed](#)]
57. Howell, C.R. 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. [[CrossRef](#)]
58. Brand, A. Hyphal growth in human fungal pathogens and its role in virulence. *Int. J. Microbiol.* **2012**, *2012*, 517529. [[CrossRef](#)] [[PubMed](#)]
59. Metcalf, D.A.; Wilson, C.R. The process of antagonism of *Sclerotium cepivorum* in white rot affected onion roots by *Trichoderma koningii*. *Plant Pathol.* **2001**, *50*, 249–257. [[CrossRef](#)]
60. Howell, C.R. Understanding the mechanisms employed by *Trichoderma virens* to effect biological control of cotton diseases. *Phytopathol.* **2006**, *96*, 178–180. [[CrossRef](#)] [[PubMed](#)]
61. Howell, C.R. Cotton seedling preemergence damping-off incited by *Rhizopus oryzae* and *Pythium* spp. and its biological control with *Trichoderma* spp. *Phytopathol.* **2002**, *92*, 177–180. [[CrossRef](#)] [[PubMed](#)]
62. Kumar, M.; Ashraf, S. Role of *Trichoderma* spp. as a Biocontrol Agent of Fungal Plant Pathogens. In *Probiotics and Plant Health*; Kumar, V., Kumar, M., Sharma, S., Prasad, R., Eds.; Springer: Singapore, 2017; pp. 497–506. [[CrossRef](#)]
63. de Lima, F.B.; Félix, C.; Osório, N.; Alves, A.; Vitorino, R.; Domingues, P.; da Silva Ribeiro, R.T.; Esteves, A.C. *Trichoderma harzianum* T1A constitutively secretes proteins involved in the biological control of *Guignardia citricarpa*. *Biol. Control* **2017**, *106*, 99–109. [[CrossRef](#)]
64. Mukherjee, P.K.; Horwitz, B.A.; Kenerley, C.M. Secondary metabolism in *Trichoderma*—A genomic perspective. *Microbiol.* **2012**, *158*, 35–45. [[CrossRef](#)]
65. Howell, C.R.; Hanson, L.E.; Stipanovic, R.D.; Puckhaber, L.S. Induction of terpenoid synthesis in cotton roots and control of *Rhizoctonia solani* by seed treatment with *Trichoderma virens*. *Phytopathology* **2000**, *90*, 248–252. [[CrossRef](#)]
66. Rini, C.R.; Sulochana, K.K. Management of seedling rot of chilli (*Capsicum annuum* L.) using *Trichoderma* spp. and fluorescent pseudomonads (*Pseudomonas fluorescens*). *J. Trop. Agric.* **2006**, *44*, 79–82.
67. Hwang, I.S.; Hwang, B.K. The pepper 9-lipoxygenase gene CaLOX1 functions in defense and cell death responses to microbial pathogens. *Plant Physiol.* **2010**, *152*, 948–967. [[CrossRef](#)] [[PubMed](#)]

68. Gullner, G.; Komives, T.; Király, L.; Schröder, P. Glutathione S-transferase enzymes in plant-pathogen interactions. *Front. Plant Sci.* **2018**, *9*, 1836. [\[CrossRef\]](#) [\[PubMed\]](#)
69. Xie, X.; He, Z.; Chen, N.; Tang, Z.; Wang, Q.; Cai, Y. The roles of environmental factors in regulation of oxidative stress in plant. *BioMed Res. Int.* **2019**, *2019*, 9732325. [\[CrossRef\]](#) [\[PubMed\]](#)
70. Herrera-Téllez, V.I.; Cruz-Olmedo, A.K.; Plasencia, J.; Gavilanes-Ruiz, M.; Arce-Cervantes, O.; Hernández-León, S.; Saucedo-García, M. The protective effect of *Trichoderma asperellum* on tomato plants against *Fusarium oxysporum* and *Botrytis cinerea* diseases involves inhibition of reactive oxygen species production. *Int. J. Mol. Sci.* **2019**, *20*, 2007. [\[CrossRef\]](#)
71. Djonović, S.; Vargas, W.A.; Kolomiets, M.V.; Horndeski, M.; Wiest, A.; Kenerley, C.M. A Proteinaceous elicitor Sm1 from the beneficial fungus *Trichoderma virens* is required for induced systemic resistance in maize. *Plant Physiol.* **2007**, *145*, 875–889. [\[CrossRef\]](#)
72. Nawrocka, J.; Małolepsza, U. Diversity in plant systemic resistance induced by *Trichoderma*. *Biol. Control* **2013**, *67*, 149–156. [\[CrossRef\]](#)
73. Utkhede, R.; Koch, C. Biological treatments to control bacterial canker of greenhouse tomatoes. *BioControl* **2004**, *49*, 305–313. [\[CrossRef\]](#)
74. Brotman, Y.; Lisec, J.; Méret, M.; Chet, I.; Willmitzer, L.; Viterbo, A. Transcript and metabolite analysis of the *Trichoderma*-induced systemic resistance response to *Pseudomonas syringae* in *Arabidopsis thaliana*. *Microbiology* **2012**, *158*, 139–146. [\[CrossRef\]](#) [\[PubMed\]](#)
75. Aldahmani, J.H.; Abbasi, P.A.; Sahin, F.; Hoitink, H.A.J.; Miller, S.A. Reduction of bacterial leaf spot severity on radish, lettuce, and tomato plants grown in compost-amended potting mixes. *Can. J. Plant Pathol.* **2005**, *27*, 186–193. [\[CrossRef\]](#)
76. Jambhulkar, P.P.; Sharma, P.; Manokaran, R.; Lakshman, D.K.; Rokadia, P.; Jambhulkar, N. Assessing synergism of combined applications of *Trichoderma harzianum* and *Pseudomonas fluorescens* to control blast and bacterial leaf blight of rice. *Eur. J. Plant Pathol.* **2018**, *152*, 747–757. [\[CrossRef\]](#)
77. Escande, A.R.; Laich, F.S.; Pedraza, M.V. Field testing of honeybee-dispersed *Trichoderma* spp. to manage sunflower head rot (*Sclerotinia sclerotiorum*). *Plant Pathol.* **2002**, *51*, 346–351. [\[CrossRef\]](#)
78. Perelló, A.; Mónaco, C.; Simón, M.R.; Sisterna, M.; Bello, G.D. Biocontrol efficacy of *Trichoderma* isolates for tan spot of wheat in Argentina. *Crop Prot.* **2003**, *22*, 1099–1106. [\[CrossRef\]](#)
79. Sivakumar, D.; Wijeratnam, R.S.; Wijesundera, R.L.; Marikar, F.M.; Abeyesekere, M. Antagonistic effect of *Trichoderma harzianum* on postharvest pathogens of rambutan (*Nephelium lappaceum*). *Phytoparasitica* **2000**, *28*, 240–247. [\[CrossRef\]](#)
80. Poveda, J. Biological control of *Fusarium oxysporum* f. sp. ciceri and *Ascochyta rabiei* infecting protected geographical indication Fuentesauco-Chickpea by *Trichoderma* species. *Eur. J. Plant Pathol.* **2021**, *160*, 825–840. [\[CrossRef\]](#)
81. Poveda, J.; Hermosa, R.; Monte, E.; Nicolás, C. The *Trichoderma harzianum* Kelch protein ThKEL1 plays a key role in root colonization and the induction of systemic defense in Brassicaceae plants. *Front. Plant Sci.* **2019**, *10*, 1478. [\[CrossRef\]](#) [\[PubMed\]](#)
82. Poveda, J. *Trichoderma* as biocontrol agent against pests: New uses for a mycoparasite. *Biol. Control* **2021**, *159*, 104634. [\[CrossRef\]](#)
83. Nicol, J.M.; Turner, S.J.; Coyne, D.L.; den Nijs, L.; Hockland, S.; Tahna Maafi, Z. Current nematode threats to world agriculture. In *Genomics and Molecular Genetics of Plant-Nematode Interactions*; Jones, J., Gheysen, G., Fenoll, C., Eds.; Springer Science + Business Media: Dordrecht, The Netherlands, 2011; pp. 21–43. [\[CrossRef\]](#)
84. Moosavi, M.R.; Askary, T.H. Nematophagous fungi-commercialization. In *Biocontrol Agents of Phytonematodes*; CABI Publishing: Wallingford, UK, 2015; pp. 187–202.
85. Harman, G.E.; Uphoff, N. Symbiotic root-endophytic soil microbes improve crop productivity and provide environmental benefits. *Scientifica* **2019**, *2019*, 1–25. [\[CrossRef\]](#) [\[PubMed\]](#)
86. Reddy, P.P.; Rao, M.S.; Nagesh, M. Management of citrus nematode, *Tylenchulus semipenetrans*, by integration of *Trichoderma harzianum* with oil cakes. *Nematol. Mediterr.* **1996**, *24*, 265–267.
87. Ghosh, S.K.; Pal, S. Entomopathogenic potential of *Trichoderma longibrachiatum* and its comparative evaluation with malathion against the insect pest *Leucinodes orbonalis*. *Environ. Monit. Assess.* **2016**, *188*, 37. [\[CrossRef\]](#) [\[PubMed\]](#)
88. Rodríguez-González, Á.; Mayo, S.; González-López, Ó.; Reinoso, B.; Gutierrez, S.; Casquero, P.A. Inhibitory activity of *Beauveria bassiana* and *Trichoderma* spp. on the insect pests *Xylotrechus arvicola* (Coleoptera: Cerambycidae) and *Acanthoscelides obtectus* (Coleoptera: Curculionidae: Bruchinae). *Environ. Monit. Assess.* **2017**, *189*, 12. [\[CrossRef\]](#) [\[PubMed\]](#)
89. Zhou, D.; Huang, X.F.; Guo, J.; dos-Santos, M.L.; Vivanco, J.M. *Trichoderma gamsii* affected herbivore feeding behaviour on *Arabidopsis thaliana* by modifying the leaf metabolome and phytohormones. *Microb. Biotechnol.* **2018**, *11*, 1195–1206. [\[CrossRef\]](#) [\[PubMed\]](#)
90. Contreras-Cornejo, H.A.; Macías-Rodríguez, L.; del-Val, E.; Larsen, J. The root endophytic fungus *Trichoderma atroviride* induces foliar herbivory resistance in maize plants. *Appl. Soil Ecol.* **2018**, *124*, 45–53. [\[CrossRef\]](#)
91. Coppola, M.; Cascone, P.; Lelio, I.D.; Woo, S.L.; Lorito, M.; Rao, R.; Pennacchio, F.; Guerrieri, E.; Digilio, M.C. *Trichoderma atroviride* P1 colonization of tomato plants enhances both direct and indirect defense barriers against insects. *Front. Physiol.* **2019**, *10*, 813. [\[CrossRef\]](#)
92. Gad, H.A.; Al-Anany, M.S.; Atta, A.A.; Abdelgaleil, S.A. Efficacy of low-dose combinations of diatomaceous earth, spinosad and *Trichoderma harzianum* for the control of *Callosobruchus maculatus* and *Callosobruchus chinensis* on stored cowpea seeds. *J. Stored Prod. Res.* **2021**, *91*, 101778. [\[CrossRef\]](#)
93. Xu, Z.; Zhou, G.; Shimizu, H. Plant responses to drought and rewatering. *Plant Signal. Behav.* **2010**, *5*, 649–654. [\[CrossRef\]](#)
94. Fathi, A.; Tari, D.B. Effect of drought stress and its mechanism in plants. *Int. J. Life Sci.* **2016**, *10*, 1–6. [\[CrossRef\]](#)

95. Shukla, N.; Awasthi, R.; Rawat, L.; Kumar, J. Biochemical and physiological responses of rice (*Oryza sativa* L.) as influenced by *Trichoderma harzianum* under drought stress. *Plant Physiol. Biochem.* **2012**, *54*, 78–88. [\[CrossRef\]](#)
96. Guler, N.S.; Pehlivan, N.; Karaoglu, S.A.; Guzel, S.; Bozdeveci, A. *Trichoderma atroviride* ID20G inoculation ameliorates drought stress-induced damages by improving antioxidant defence in maize seedlings. *Acta Physiol. Plant* **2016**, *38*, 132. [\[CrossRef\]](#)
97. Heidarvand, L.; Maali Amiri, R. What happens in plant molecular responses to cold stress? *Acta Physiol. Plant* **2010**, *32*, 419–431. [\[CrossRef\]](#)
98. Rawat, L.; Singh, Y.; Shukla, N.; Kumar, J. Alleviation of the adverse effects of salinity stress in wheat (*Triticum aestivum* L.) by seed biopriming with salinity tolerant isolates of *Trichoderma harzianum*. *Plant Soil* **2011**, *347*, 387–400. [\[CrossRef\]](#)
99. Betzen, B.M.; Smart, C.M.; Maricle, K.L.; Maricle, B.R. Effects of increasing salinity on photosynthesis and plant water potential in Kansas salt marsh species. *Trans. Kans. Acad. Sci.* **2019**, *122*, 49. [\[CrossRef\]](#)
100. Ahmad, P.; Hashem, A.; Abd-Allah, E.F.; Alqarawi, A.A.; John, R.; Egamberdieva, D.; Gucel, S. Role of *Trichoderma harzianum* in mitigating NaCl stress in Indian mustard (*Brassica juncea* L.) through antioxidative defense system. *Front. Plant Sci.* **2015**, *6*, 868. [\[CrossRef\]](#)
101. Zhao, L.; Zhang, Y.-Q. Effects of phosphate solubilization and phytohormone production of *Trichoderma asperellum* Q1 on promoting cucumber growth under salt stress. *J. Integr. Agric.* **2015**, *14*, 1588–1597. [\[CrossRef\]](#)
102. Bernstein, N. Effects of salinity and solidicity on root growth. *Ann. Rev. Phytopathol.* **1975**, *13*, 295–312. [\[CrossRef\]](#)
103. Mona, S.A.; Hashem, A.; Abd-Allah, E.F.; Alqarawi, A.A.; Soliman, D.W.; Wirth, S.; Egamberdieva, D. Increased resistance of drought by *Trichoderma harzianum* fungal treatment correlates with increased secondary metabolites and proline content. *J. Integr. Agric.* **2017**, *16*, 1751–1757. [\[CrossRef\]](#)
104. Zhang, F.; Huo, Y.; Cobb, A.B.; Luo, G.; Zhou, J.; Yang, G.; Wilson, G.W.; Zhang, Y. *Trichoderma* biofertilizer links to altered soil chemistry, altered microbial communities, and improved grassland biomass. *Front. Microbiol.* **2018**, *9*, 848. [\[CrossRef\]](#)
105. Dugassa, A.; Alemu, T.; Woldehawariat, Y. In-vitro compatibility assay of indigenous *Trichoderma* and *Pseudomonas* species and their antagonistic activities against black root rot disease (*Fusarium solani*) of faba bean (*Vicia faba* L.). *BMC Microbiol.* **2021**, *21*, 115. [\[CrossRef\]](#) [\[PubMed\]](#)
106. Woo, S.L.; Ruocco, M.; Vinale, F.; Nigro, M.; Marra, R.; Lombardi, N.; Pascale, A.; Lanzuise, S.; Manganiello, G.; Lorito, M. *Trichoderma*-based products and their widespread use in agriculture. *Open Mycol. J.* **2014**, *8*, 71–126. [\[CrossRef\]](#)
107. Santos, U.R.; Costa, M.C.; de Freitas, G.J.; de Oliveira, F.S.; Santos, B.R.; Silva, J.F.; Santos, D.A.; Dias, A.A.; de Carvalho, L.D.; Augusto, D.G.; et al. Exposition to biological control agent *Trichoderma stromaticum* increases the development of cancer in mice injected with murine melanoma. *Front. Cell. Infect. Microbiol.* **2020**, *10*, 252. [\[CrossRef\]](#)
108. Konstantinovas, C.; de Oliveira Mendes, T.A.; Vannier-Santos, M.A.; Lima-Santos, J. Modulation of human immune response by fungal biocontrol agents. *Front. Microbiol.* **2017**, *8*, 39. [\[CrossRef\]](#) [\[PubMed\]](#)
109. Singh, A.; Bhardwaj, R.; Singh, I.K. Biocontrol Agents: Potential of Biopesticides for Integrated Pest Management. In *Biofertilizers for Sustainable Agriculture and Environment*; Giri, B., Prasad, R., Wu, Q.S., Varma, A., Eds.; Springer: Cham, Switzerland, 2019; Volume 55. [\[CrossRef\]](#)
110. Rostaminia, M.; Habibi, D.; Shahbazi, S.; Sani, B.; Pazoki, A. Biological effects of agricultural bio-materials on some blood and tissue factors in Balb/c mice. *Iran. J. Vet. Sci. Technol.* **2020**, *12*, 63–69.
111. Kumar, S.M.; Thakur, M.A.; 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*, 3838–3852. [\[CrossRef\]](#)
112. Elad, Y. TRICHODEX: Commercialization of *Trichoderma harzianum* T39—A case study. In *Agro Report, Biopesticides: Trends and Opportunities*; Jarvis, P., Ed.; PJB: Richmond, UK, 2001; pp. 45–50.
113. Topolovec-Pintarić, S. *Trichoderma*: Invisible partner for visible impact on agriculture. In *Trichoderma: The Most Widely Used Fungicide*; Shah, M.M., Sharif, U., Buhari, T.R., Eds.; IntechOpen: London, UK, 2019; pp. 15–35. [\[CrossRef\]](#)
114. Nakkeeran, S.; Renukadevi, P.; Aiyannathan, K.E. Exploring the potential of *Trichoderma* for the management of seed and soil-borne diseases of crops. In *Integrated Pest Management of Tropical Vegetable Crops*; Muniappan, R., Heinrichs, E., Eds.; Springer: Dordrecht, The Netherlands, 2016. [\[CrossRef\]](#)
115. Prasad, R.D.; Rangeshwaran, R. Shelf life and bioefficacy of *Trichoderma harzianum* formulated in various carrier materials. *Plant Dis. Res.* **2000**, *15*, 38–42.
116. Kolombet, L.V.; Zhigletsova, S.K.; Kosareva, N.I.; Bystrova, E.V.; Derbyshev, V.V.; Krasnova, S.P.; Schisler, D. Development of an extended shelf-life, liquid formulation of the biofungicide *Trichoderma asperellum*. *World J. Microbiol. Biotechnol.* **2007**, *24*, 123–131. [\[CrossRef\]](#)
117. Locatelli, G.O.; dos Santos, G.F.; Botelho, P.S.; Finkler, C.L.; Bueno, L.A. Development of *Trichoderma* sp. formulations in encapsulated granules (CG) and evaluation of conidia shelf-life. *Biol. Control* **2018**, *117*, 21–29. [\[CrossRef\]](#)
118. Peil, S.; Beckers, S.J.; Fischer, J.; Wurm, F.R. Biodegradable, lignin-based encapsulation enables delivery of *Trichoderma reesei* with programmed enzymatic release against grapevine trunk diseases. *Mater. Today Bio* **2020**, *7*, 100061. [\[CrossRef\]](#) [\[PubMed\]](#)
119. Mitter, E.K.; Tosi, M.; Obregón, D.; Dunfield, K.E.; Germida, J.J. Rethinking crop nutrition in times of modern microbiology: Innovative biofertilizer technologies. *Front. Sustain. Food Syst.* **2021**, *5*, 29. [\[CrossRef\]](#)
120. Fravel, D.R. Commercialization and implementation of biocontrol. *Annu. Rev. Phytopathol.* **2005**, *43*, 337–359. [\[CrossRef\]](#) [\[PubMed\]](#)

121. Esterbauer, H.; Steiner, W.; Labudova, I.; Hermann, A.; Hayn, M. Production of *Trichoderma* cellulase in laboratory and pilot scale. *Bioresour. Technol.* **1991**, *36*, 51–65. [[CrossRef](#)]
122. Al-Taweil, H.I.; Osman, M.B.; Aidil, A.H.; Yussof, W.M. Optimizing of *Trichoderma viride* cultivation in submerged state fermentation. *Am. J. Appl. Sci.* **2009**, *6*, 1284. [[CrossRef](#)]
123. Agosin, E.; Auilera, J.M. Industrial Production of Active Propagules of *Trichoderma* for Agricultural Uses. In *Trichoderma and Gliocladium, Volume 2: Enzymes, Biological Control, and Commercial Application*; Harman, G.E., Kubicek, C.P., Eds.; Taylor & Francis: London, UK, 1998; pp. 205–227.