TRICHODERMA-PLANT INTERACTIONS FOR SUSTAINABLE CROP PRODUCTION UNDER ORGANIC FARMING SYSTEMS

Abstract

Trichoderma is one of the most versatile bio-control agents, ubiquitous in soil, multifaceted, with tremendous potential for use in organic farming systems. Since the time of its discovery, *Trichoderma* has been found to be of considerable importance in various facets of agriculture as well as industry. The industrial applications revolve around the production of various types of enzymes by different species of *Trichoderma*. However, it has more often been used as a bio-control agent, particularly for the management of soil borne diseases, though it has also been reported to be effective against foliar pathogens. It has multiple modes of action, viz., mycoparasitism, antibiosis, competition and induced systemic resistance. An important characteristic of *Trichoderma* is its bio-stimulant activity. *Trichoderma* has been found to stimulate the various growth parameters like root growth, shoot growth, flower and fruit production and total yield, in addition to disease management. In the present scenario, *Trichoderma* can be integrated with the various agricultural operations for sustainable crop production. This is particularly so because *Trichoderma* has been found efficient for soil bio-remediation and can improve the quality of soil which in turn increases the quality of yield. Thus, it is highly recommended that *Trichoderma* be incorporated in the schedule for sustainable organic farming system as it combines many benefits like management of diseases, bio-stimulant action for crop growth and soil bio-remediation.

Keywords: *Trichoderma,* bio-control agents, ubiquitous in soil,

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I. INTRODUCTION

One of the greatest discoveries of the century, from an agriculturist point of view, is perhaps the discovery of the uses and benefits of *Trichoderma.* It was first described by Persoon in 1794 (Persoon, 1794), but due to difficulties in morphological identification, it was not until 1969 that a unified concept for the identification was initiated (Rifai, 1969; Samuels, 2006). By 2006, more than 100 phylogenetically different species had been defined. Nowadays, safe identification of *Trichoderma* can be done with the help of an oligonucleotide barcode (TrichOKEY) and a customized similarity search tool (TrichoBLAST) from online web resource www.isth.info (Kopehinskiy *et al*., 2005). There is a wide variation in the different species of *Trichoderma,* starting from colony morphology, pigmentation, colony color, color of spores, etc. upto the branching pattern and molecular characteristics.However, most of the *Trichoderma* species are characterized by easy isolation, rapid growth, mostly green conidia of various shapes and highly branched conidiophore structure (Gams and Bissett, 1998). Currently, up to 50 new species are recognised per year with the help of revolutionary molecular methods (Cai and Druzhinina, 2021). From its first use in 1932 by Weindling (Weindling, 1932; Weindling and Fawcett, 1936), this fungus has proved to be effective against a vast number of pathogens which include fungi, bacteria, nematodes and even viruses. It produces a wide array of enzymes that are industrially important and have been commercially exploited for the production of cellulases, xylases and other enzymes (Sperandio and Filho, 2021; Passos *et al.,* 2018). It has also been used for the bioremediation of problem soils (Tripathi *et al.,* 2013; Dacco *et al.,* 2020). However, currently we shall be focussing on the bio-control aspect of Trichoderma.

1. ***Trichoderma* for the Management of Fungal Diseases:** Adnan *et al.,* (2019) recently reviewed the status of management of fungal diseases by *Trichoderma* with focus on management via taxonomy, important strains, biodiversity and mode of action. In case of *Trichoderma-Fusarium* interaction, it was observed that both of these fungi recognise each other by sensing their volatile compounds (VCs) and in response produce their own VCs to inhibit the VCs produced by the other fungus (Li *et al.,* 2018). *T. longibrachiatum*and *T. asperelloides*produce soluble metabolites that can inhibit or kill *Magnaporthiopsis maydis,* the causal agent of late wilt of maize, besides improving the seedlings' wet biomass and total yield improvement through increase in various growth parameters (Degani and Dor, 2021). Mendez *et al.,* (2020) found that *T. asperellum*induces systemic defences against *Sclerotium cepivorum*in onion plants under tropical climatic conditions. The endophytic *Trichoderma* reduces colonization of *Phaeoacremonium minimum* and protects the plant by limiting the development of grapevine trunk disease (Carro *et al.,* 2020). Based on in vitro diagnostic assay and analysis of metabolite fractions, Tomah *et al*., (2020), deduced that *T. virens* HZA14 could cause colony collapse and degradation of *Phytophthora capsici.* Besides, different species of *Trichoderma* were found effective against foliar blight of onion, powdery mildew and black spot of rose, tomato root rot, postharvest anthracnose of chilli, peanut brown root rot, common bean damping off, tomato vascular wilt and early blight(Shahnaz *et al.,* 2013; Amin *et al.,* 2018; Kashyap, *et al.,* 2020; Boat *et al.,* 2020; Carino *et al.,* 2020; Ruangwong*et al.,* 2021; Erazo *et al.,* 2021) and many other diseases to name a few.

2. ***Trichoderma* for the Management of Bacterial Diseases:** Khan *et al.,* (2020) found that the secondary metabolites (SMs) from different *Trichoderma* isolates produced severe morphological changes, such as rupturing of the bacterial cell walls, disintegration of cell membrane and cell content leaking out of phytopathogenic bacteria *Ralstonia solanacearum* and *Xanthomonas compestris.* Konappa *et al.,* (2018) also found that the application of *T. Asperellum* isolates delayed wilt caused by *R. solanacearum*, decreased the disease incidence, increased fruit yield, and improved plant growth promotion of tomato. However, Yan and Khan (2021) suggested that the secondary metabolites of *T. harzianum*could be utilized as low cost and environment friendly alternative for sustainable management of bacterial wilt of tomato. *Trichoderma* was also found beneficial for the management of bacterial spot of tomato caused by *Xanthomonas perforans*(Chien and Huang, 2020). A consortium of *Bacillus subtilis* and *T. harzianum*effectively suppressed common scab of potato caused by *Streptomyces* spp. and increased tuber yield as a result of primary colonization (Wang *et al.,* 2019). The growth of *Erwinia carotovora*was reduced by *Trichoderma* spp. resulting in reduced disease incidence of potato tuber soft rot (Sulaiman*et al.,* 2020). However, Morán-Diez *et al*. (2020) reported that *Trichoderma* spp. are not able to control the fully pathogenic strain of *Pseudomonas syringae*pv. *tomato.*

3. ***Trichoderma* for the Management of Viral Diseases:** The management of viral diseases by *Trichoderma* spp. is mostly through the induction of systemic resistance. *T. hamatum* was found to promote plant growth, induce resistance and boost innate immunity against tobacco mosaic virus (TMV) infection (Abdelkhalek *et al.,* 2022). The release of salicylic acid by *Trichoderma* bioagents may result in the suppression of pepper leaf curl virus (PeLCV) (Rochal *et al.,* 2021). In some cases, metabolites like trichorzins may inhibit viral infections like cucumber mosaic virus infection of cowpea. *T. asperellum*could also control cucumber mosaic infections in cucumber by inhibiting the virus and induction of systemic resistance (Tamandegani *et al.,* 2021). *T. harzianum* can also been used as a bio-control agent for the management of papaya ringspot virus (Etim *et al.,* 2022). Jaddawi *et al.,* (2019) suggested that tomato seedlings are protected from cucumber mosaic virus through stimulation of plants to produce pathogenesis related proteins, whereas, Taha *et al.,* (2020) evaluated the ability of 6-pentyl-α-pyrone (6PP) isolated from *Trichoderma koningii*for the induction of systemic resistance in tobacco against tobacco mosaic virus. Nigirpexin E, an azaphilone, derived from *T. afroharzianum*was found to have anti-tobacco mosaic virus activity (Xie*et al.,* 2022).

II. MODES OF ACTION

Until recent past, it was believed that *Trichoderma* induces its action by way of mycoparasitism or by the production of antibiotics. It has now been shown that it, in fact, exerts a multipronged strategy for the management of plant pathogens. *Trichoderma* has multiple modes of action and attacks its target through many tactics. These may be direct like competition for nutrients or space, parasitisation of the pathogen, release of antibiotics or production of a cascade of cell wall degrading enzymes that may directly affect the pathogenic population. There is also an indirect mechanism, that is induction of systemic resistance and plant growth promotion. A brief account of the various mechanisms employed by *Trichoderma* species is provided in Table 1.

Table 1: Modes of action employed by *Trichoderma* against different plant pathogens

S. No.	Title	Pathogen	Mode of Action	Reference
1.	*Trichoderma viride* cellulase induces resistance tothe antibiotic pore-forming peptide alamethicinassociated with changes in the plasmamembrane lipid composition of tobaccoBY-2 cells	-	Antibiosis	Aidemark *et al.,* 2010
2.	Appraisal of Combined Applications of *Trichodermavirens* and a Biopolymer-Based Biostimulant onLettuce Agronomical, Physiological, and QualitativeProperties under Variable N Regimes	-	Biostimulation	Rouphael *et al.,* 2020
3.	The 4-phosphopantetheinyl transferase of *Trichoderma virens*plays a role in plant protection against *Botrytis cinerea*through volatile organic compound emission	*Botrytis cinerea*	Volatile Organic Compounds	Cornejo *et al.,* 2014
4.	*Trichoderma harzianum*T6776 modulates a complexmetabolicnetwork to stimulate tomato cv. Micro-Tom growth	-	Plant growth stimulation	Fiorini *et al.,* 2016
5.	Biological control of foliar pathogens by means of *Trichoderma harzianum* and potential modes of action	*Botrytis cinerea, Pseuperonosporacubensis, Sclerotinia sclerotiorum*and *Sphaerothecafusca*	Local and systemic induced resistance, production of enzymes	Elad, 2000
6.	*Trichoderma hamatum*: Its hyphal interactions with*Rhizoctonia solani* and*Pythium* spp.	*Pythium* spp. and*Rhizoctonia solani*	Mycoparasitism	Chet *et al.,* 1981

7.	Inhibition of plant pathogenic fungi by endophytic *Trichoderma* spp. through mycoparasitism and volatile organic compounds	*Sclerotinia sclerotiorum*-TSS, *Sclerotium rolfsii*-CSR and *Fusarium oxysporum*-CFO	Volatile Organic Compounds	Rajani *et al.,* 2021
8.	Inhibitory Mechanism of *Trichoderma virens* ZT05 on *Rhizoctonia solani*	*Rhizoctonia solani*	Hyperparasitim and antibiosis	Halifu *et al.,* 2020
9.	Biological characteristic and biocontrol mechanism of *Trichoderma harzianum*T-A66 against bitter gourd wilt caused by *Fusarium oxysporum*	*Fusarium oxysporum*	H2 O2 burst and callose deposition, as well as increasing antioxidant enzymes activities	Zhang *et al.,* 2020
10.	Mechanism antagonism of *Trichoderma viride* against several types of pathogens and production of secondary metabolites	*Alternaria solani, Fusarium oxysporum, Rhizoctonia solani,* and *Sclerotium rolfsii*	Competition and mycoparasitism	Muhibbudin *et al.,* 2021
11.	*Trichoderma asperellum* T42 induces local defense against *Xanthomonas oryzae*pv. *oryzae*under nitrate and ammonium nutrients in tobacco	*Xanthomonas oryzae*pv. *oryzae*	oxidative burst-mediated defense	Singh *et al.,* 2019
12.	Systemic inducing resistance against late blight by applying antagonist *Trichoderma viride*	*Phytophthora infestans*	Systemic Induced resistance	Purwantisari *et al.,* 2018
13.	Bioactive Secondary Metabolites from *Trichoderma* spp. against Phytopathogenic Fungi	-	Secondary metabolites	Khan *et al.,* 2020
14.	*Trichoderma viride* Controls *Macrophominaphaseolina*	*Macrophominaphase*	DNA disintegrati	Khan *et al.,* 2021

	through its DNA disintegration and Production of Antifungal Compounds	*olina*	on and secondary metabolites	
15.	*Trichoderma asperellum* T76-14 Released Volatile Organic Compounds against Postharvest Fruit Rot in Muskmelons (*Cucumis melo*) Caused by *Fusarium incarnatum*	*Fusarium incarnatum*	Volatile Organic Compounds	Intana *et al.,* 2021
16.	Biological control of *Fusarium oxysporum* f. sp. *ciceri*and *Ascochyta rabiei* infecting protected geographical indication Fuentesaúco-Chickpea by *Trichoderma* species	*Fusarium oxysporum f.* sp. *ciceri*	Directly and by induction of local and systemic resistance	Poveda, 2021
17.	Morphological and protein alterations in *Sclerotinia sclerotiorum* (Lib.) de Bary after exposure to volatile organic compounds of *Trichoderma* spp.	*Sclerotinia sclerotiorum*	Volatile Organic Compounds	da Silva *et al.,* 2020
18.	*Trichoderma* Isolates Inhibit *Fusarium virguliforme* Growth, Reduce Root Rot, and Induce Defense-Related Genes on Soybean Seedlings	*Fusarium virguliforme*	mycoparasitism and induction of defense-related genes in plants	Pimentel *et al.,* 2020
19.	Mycelial Inhibition of *Sclerotinia sclerotiorum* by *Trichoderma* spp. Volatile Organic Compounds in Distinct Stages of Development	*Sclerotinia sclerotiorum*	Volatile Organic Compounds	da Silva *et al.,* 2021
20.	In vitro biocontrol potential of *Trichoderma pseudokoningii*against *Macrophominaphaseolina*	*Macrophominaphaseolina*	Disintegration of DNA	Khan and Javaid, 2020

III. FORMULATIONS OF TRICHODERMA

For successful biological control, the bio-control agent used must be highly efficient; ease of mass production of highly effective and viable propagules; delivery systems should aid the BCA giving it a competitive edge without loss of viability; economical; cost effective; protection against microbial contamination; long shelf life (Harman, 1991; Harman *et al.,* 1991). Besides, it should have high rhizosphere competence and added advantage of promotion of plant growth for increased acceptance among the farming community.Most of the times BCAs are formulated as liquid formulations or solid formulations. Both have their own advantages and disadvantages. Liquid formulations allow for optimization of biomass production and quality with ease of preparation but their acceptability among the farming community is low. Solid formulations can be prepared on agricultural waste materials like sawdust, wheat, rice or maize straw, spent compost, vermicompost, etc. but they are bulky and need larger space for production and packaging. Further, popularization of BCAs is very low among the farming community and only 2 % biopesticides are available in the market (Kumar *et al.,* 2014). Out of these 60% are *Trichoderma* based products (Pintaric, 2019). The different types of formulations available in the market are based on talc, vermiculite, pesta granules, alginate prills, press mud, coffee husk based, oil based or based on different low cost agricultural waste materials.

Table 2: Some important reviews and rresearchon mass production and formulation of *Trichoderma*in the last ten years

S. No.	Title	Year	Reference
1.	*Trichoderma:* Mass production, formulation, quality control, delivery and its scope in commercialization in India for the management of plant diseases	2014	Kumar *et al.,* 2014
2.	Mass production, formulation, quality control anddeliveryof Trichoderma for plant diseasemanagement	2010	Ramanujam *et al.*, 2010
3.	Advances in Formulation of *Trichoderma* for Biocontrol	2014	Cumagun, 2014
4.	*Trichoderma harzianum*-based novel formulations: potential applications for management of Next-Gen agricultural challenges	2018	Fraceto *et al.,* 2018
5.	*Trichoderma* as biological control agent: Scope and prospects to improve efficacy	2021	Ferreira and Musumeci, 2021
6	Trichoderma-based products and their widespread use in agriculture	2014	Woo *et al.*, 2014
7.	Development of *Trichoderma* sp. formulations in encapsulated granules (CG) and evaluation of conidia shelf-life	2018	Locatelli *et al.,* 2018
8.	Mass production of *Trichoderma harzianum* for managing fusarium wilt of banana	2004	Thangavelu *et al.,* 2004
9.	Prospects of indigenous mass production and formulation of *Trichoderma.*	2006	Jeyarajan, 2006

10.	Mass production of *Trichoderma* spp. and application	2012	Panahian *et al*., 2012
11.	Optimization of culture conditions for mass production and bio-formulation of *Trichoderma* using response surface methodology	2018	Sachdev *et al.,* 2018
12.	Isolation, identification and mass multiplication of *Trichoderma* an important bio-control agent	2013	Babu and Pallavi, 2013
13.	Mass multiplication and shelf life of liquid fermented final product of *Trichoderma viride* in different formulations	2011	Khan *et al*., 2011
14.	Advances in Formulation of *Trichoderma* for Biocontrol	2014	Cumagun, 2014
15.	Optimizing mass production of *Trichoderma asperelloides* by submerged liquid fermentation and its antagonism against *Sclerotinia sclerotiorum*	2020	Rezende *et al.,* 2014
16.	Lowcost carrier material for mass production of *Trichoderma* inoculants	2018	Rini*et al.,* 2018
17.	Mass production and determination of shelf-life of two *Trichoderma* sp. in compost formulation	2022	Fernando and Shehani, 2022
18.	Evaluation and assessment of shelf life of liquid substrates and talc formulation for mass production of native *Trichoderma* spp.	2020	Boblina *et al.,* 2020
19.	Optimization of Culture Conditions and Production of Bio-Fungicides from *Trichoderma* Species under Solid-State Fermentation Using Mathematical Modeling	2021	Malatu *et al.,* 2021
20.	Isolation, identification and mass production of five *Trichoderma* spp. on solid and liquid carrier media for commercialization	2018	Hewavitharana *et al*., 2018
21.	Mass Multiplication of *Trichoderma* in Bioreactors	2020	Prakash *et al.,* 2020
22.	Shelf life studies of different formulations of *Trichoderma harzianum*	2019	Komala *et al.,* 2019
23.	Mass Production and Formulation of Antagonists	2021	Rajeshwari and Appanna, 2021
24.	Development, Production, and Storage of Formulations for Agricultural Applications	2022	Prasad *et al.,* 2022

25.	Quality Control of Fungal Biocontrol Agents with Emphasis on *Trichoderma*	2021	Correa *et al.,* 2021
26.	Effect of physiological parameters on mass productionof *Trichoderma* species	2018	Ghazanfar *et al*., 2018

IV. METHOD OF APPLICATION

The various formulations of *Trichoderma* are applied in various ways. The most common is by seed treatment or soil application. Seed biopriming is the preferred method of control of various soil borne diseases. For treatment of seedlings, seedling dip method for about 20 minutes is followed. Liquid *Trichoderma* is often formulated as pellets, granules or dusts and can be applied to the soil directly or through *Trichoderma* enriched FYM (Ramanujam*et al.,* 2010). Recently, *Trichoderma* has been used for the production of different types of nanoparticles which show high antifungal activity.

V. CONCLUSION

The uses of *Trichoderma* are manywith diverse modes of action, methods of application, production processes, production media and above this is perhaps the most studied and least understood and least utilized fungus. A lot of research has been going on but still lots more needs to be done on the potential of this important fungus.

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