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REVIEW ARTICLE

An overview of multifaceted role of *Trichoderma* spp. for sustainable agriculture

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ABSTRACT

The excessive use of chemical fertilizers and pesticides have caused several negative impacts on the environment and human health. They degrade soil fertility, build up resistance on pathogens, inhibit microbial activities and also enhance greenhouse gas emission. It is impossible and inappropriate to control plant pathogens by using chemical pesticides alone. Emphasize should be given towards organic fertilizers and pesticides to attain sustainability in agriculture. The use of *Trichoderma* is slowly increasing in the recent years among progressive farmers as an alternative to chemical fertilizers and pesticides. Slow rate of multiplication and colonization, susceptible to biotic and abiotic stresses, incomplete elimination of pathogens and high cost are the major problems behind its poor adoption among the farmers. To overcome these challenges different strains of *Trichoderma* should be identified which can multiply and colonize rapidly, least affected by environmental conditions and having wide host range on pathogens. In addition, farmers should be made aware about the importance of *Trichoderma* in agriculture through various extension facilities for its wide scale adoption. *Trichoderma* can be the viable and sustainable alternative which acts as biofertilizer, bioremediator and biocontrol agent. Nevertheless, the use of *Trichoderma* is limited on research activities and its application at farmers' level is not yet satisfactory. Thus, this study based on critical analysis of the research works from worldwide researchers aims to reveal the present scenario of the use of *Trichoderma*, its importance, modes of action, methods of application and multiplication, challenges for wide scale adoption and its appropriate solutions.

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INTRODUCTION

An indiscriminate use of chemicals in the name of intensive agriculture has degraded the quality of soil and the environment as well as brought several negative impacts to the human health. They build up resistance in pathogens against chemicals and also bring risk to non-targeted organisms. Furthermore, the heavy use of chemicals in agriculture contributes to greenhouse gas emission and loss of biodiversity (Nicolopoulos-Stamati, 2016). Thus, it is a high time to seek such agricultural practices or techniques which are safe to environment and human health to achieve sustainability in agriculture. Sustainable agriculture is such a holistic prospective that aims success in whole farming considering environmentally friendly, quality of human as well as animal life, minimum economic costs and minimum risk to all contribution that farmer makes to their society (Norman *et al.*, 2000). Abo- Elyousr *et al.* (2014) reveals that key to food security for this rapidly increasing world's population is sustainable agriculture. Thus, to adopt sustainable agriculture at first we have to minimize heavy use chemicals and emphasize should be given towards organic fertilizers and pesticides. In this regard, *Trichoderma* can be the appropriate bio-agent that plays a vital role to achieve the goal of sustainable agriculture. It has multipurpose uses, it can be applied as bio-fertilizer, bio-control agent and bio-remediator. Thus, it has a great potential in sustainable agricultural approaches like Integrated Pest

Management (IPM), Integrated Nutrient Management (INM) and organic farming.

Trichoderma are asexual fungi and reproduced by chlamydospores, ascospores and can survive to all pH ranges of soil with optimum temperature of 25-35°C (Shah and Afiya, 2019). It is very dominant to all fungus and it has high outbreak capacity. Usually it is found with plant roots as symbiont and dominant fungus and is considered as antagonist to other fungi. Benitez *et al.* (2004) reports that *Trichoderma* has high capacity to compete with other microbes by producing iron chelating compounds, which absorb soil iron compounds and makes other microbes deficit to iron and by making more acidic soil environment which is unfavourable to other pathogenic microbes. Antibiosis, competition and mycoparasitism are the important features of *Trichoderma* through which it inhibits the growth of other pathogenic microbes through the biosynthesis of targeted metabolites like growth regulators, enzymes, antibiotics and siderophores (Sood *et al.*, 2020). There are about 89 species of *Trichoderma* genus distributed worldwide and most of them have practical importance in agriculture. *Trichoderma* has been used in agriculture for a long time. The antagonistic activity of *Trichoderma* against most of the pathogens was known since 1920s (Harman, 2006). Similarly, nowadays, the use of *Trichoderma* to control soil as well seed borne plant pathogens and as a biofertilizer is increasing. Nevertheless, its adoption rate is lower as compared to chemical fertilizers and pesticides. Its adoption at *farmer's* level all over the world is not yet satisfactory. There may be certain challenges for its adoption equal to or more than the level of chemical fertilizers and pesticides and those challenges are necessary to be identified. Thus, this study aims to reveal the multipurpose uses of *Trichoderma*, its mode of action and methods of application along with its challenges for wide scale adoption and to provide appropriate ways to overcome those challenges through critical analysis of the situation.

Methodology

This paper is the outcome of secondary sources of data gleaned through various literatures including books, journal articles and different websites. Required data were assembled and the graph was generated to show the recent trends in the use of synthetic fertilizers and pesticides. Related literatures were analysed thoroughly to reveal the multifaceted role of *Trichoderma* in agriculture, its challenges for wide scale adoption and their suitable solutions.

Trichoderma as an alternative to chemical fertilizers and pesticides

If all the farmers were well-known about the negative impacts of chemicals and benefits of *Trichoderma* in agriculture, then ofcourse, their choice might be *Trichoderma*. *Trichoderma* is cheap as well as eco-friendly and thus it is beneficial to the farmers. *Trichoderma* is being heavily used to control many plant pathogens like viruses, fungi, nematodes, bacteria and many higher plant parasites (Bigirimana *et al.*, 1997). Due to its long-term persistence on soil as well as other parts it is widely used and its application is much more extended (Hanada *et al.*, 2009). It also helps in the improvement of plant growth, development and yield along with stem length, thickness and chlorophyll content (Hossain and Akter, 2020). Sachdev and Singh (2020) found that by the interaction of *Trichoderma* and plant, volatile chemicals are produced that helps to control insects. Residues of chemical pesticides persists in soil for a time destroying soil ecosystem and increasing toxicity to plants. In contrast to chemicals, *Trichoderma* has potential to minimize or destroy toxic compounds in soil and metabolize a variety of high and low molecular weight polycyclic aromatic hydrocarbons (Yao *et al.*, 2015). *Trichoderma* not only inhibits pathogen population but also have capacity to develop resistance and enhance many physiological activities in plants. It minimizes the use of chemical NPK fertilizers, increases the uptake of micronutrients and also helps in solubilisation of phosphates (Kamala, 2018). Nutrients of chemical fertilizers are quickly lost either by leaching or volatilization but persistence of *Trichoderma* occurs for long time in soil. Considering all these points we can confirm that *Trichoderma* can be the viable and sustainable alternative to chemical fertilizers and pesticides.

Present scenario of the use of *Trichoderma* in agriculture

The use of *Trichoderma* in agriculture is gaining momentum in these recent years. Hundreds of researches have been carried out to understand the role of *Trichoderma* as biofertilizer, bioremediator and biocontrol agent. *Trichoderma* is mostly used by progressive farmers who have knowledge about the importance *Trichoderma* and harmful effects of chemical pesticides in agriculture. The rate of use of synthetic fertilizers and pesticides is increasing at slow rate as compared to the last decade as presented in Figure 1. This slow rate of increase is due to the high rate of use of biofertilizers and botanical pesticides

Uses of *Trichoderma* in agriculture

***Trichoderma* as biofertilizer:** *Trichoderma* makes nutrients available to the plants through different biological processes. In contrast to synthetic fertilizers, they improves soil properties and microbial activities. They can maintain soil fertility for longer period as compared to chemical fertilizers. They can be applied alone or along with other chemical and biofertilizer in the field. Haque *et al.* (2012) reported that the application of 50% Nitrogen fertilizer and 50% *Trichoderma* enriched biofertilizer can increased the yield of mustard and tomato upto 108.36% and 125.45% over control condition respectively. Similarly, Doni *et al.* (2017) observed increased plant height, photosynthetic rate, chlorophyll content, stomatal conductance, and tiller and panicle numbers of rice with the application of *Trichoderma* enriched biofertilizer in SRI system. Moreover, *Trichoderma* has the potential to increase the availability of micronutrients to the plants. Khan *et al.* (2017) found that

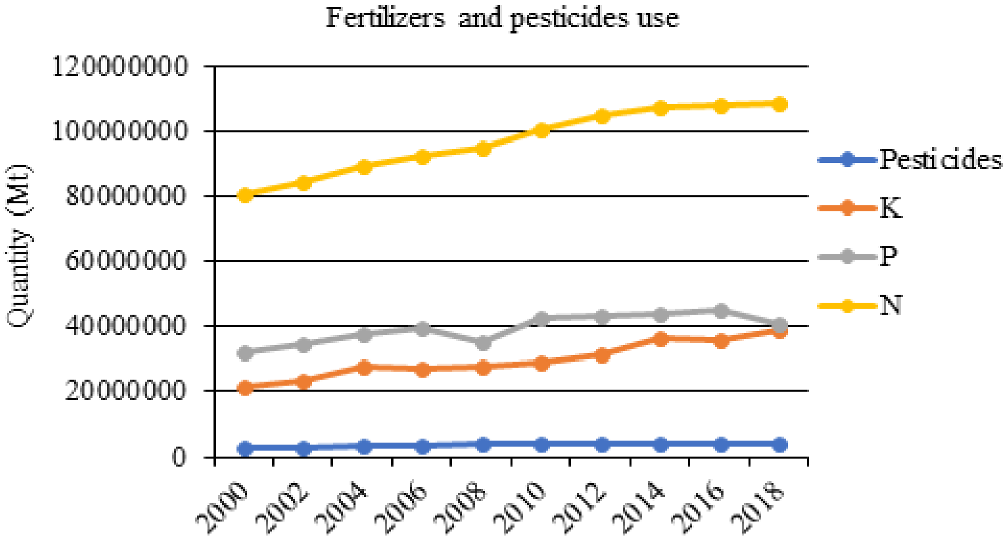

Figure 1. *Trends in synthetic fertilizers and pesticides use in agriculture during 2000-2018 (Source: FAO, 2020).*

Table 1. Bioremediation of pollutants by different species of *Trichoderma*.

S.N.	Pollutants	*Trichoderma* sps.	Result	Reference
1	Lead (Pb), Chromium (Cr)	*T. viride*	Uptake of 9.14 mg/g of lead and 2.55 mg/g of Chromium	Kumar *et al.* (2017)
2	Olive oil mill waste water	*T. viride*	66% removal of organic carbon and 50% removal of phenolic compounds	D'Urso *et al.* (2008)
3	Benzo [a] Pyrene	*T. reesei*	54% removal of B [a] P after 12 days of incubation	Yao *et al.* (2015)
4	Bromoxynil	*T. harzianum and T. Viride*	The remaining amount of Bromoxynil were 0.63 ppm and 1.56 ppm when incubated with *T. Viride* and *T. harzianum* respectively out of 100 ppm (initial concentration)	Askar *et al.* (2007)
5	Carbendazim and Mancozeb	*T. spp.*	36% degradation of Mancozeb and 25% degradation of Carbendazim during 15 days of incubation	Ahlawat *et al.* (2010)
6	Copper (Cu)	*T. atroviride*	50-85% of Cu adsorption during in vitro experiment	Yazdani *et al.* (2009)
7	Diesel oil	*T. reesei* H002	Degradation of 98.78% of petroleum hydrocarbon during 40 days of incubation at 25 degree Celsius	Nazifa *et al.* (2018)
8	Zinc (Zn)	*T. atroviride*	47.6 – 64% adsorption and 30.4 – 45% absorption of Zn	Yazdani *et al.* (2010)
9	Cadmium (Cd)	*T. asperellum*	76.17% removal of Cadmium	Mohsenzadeh and Shahrokhi (2014)
10	2,4,6- trinitrotoluene (TNT)	*T. viride*	Degrade TNT into a major compound i.e. 5-(hydroxymethyl)- 2- Furancarboxaldehyde and a minor compound i.e. 4- propyl benzaldehyde	Alothman *et al.* (2020)

minerals like K, Cu, Fe and Zn contents in roots zone were significantly higher with 100% *Trichoderma* enriched biofertilizer than the recommended dose of NPK while computing after 60 days of transplantation of tomato plant. *Trichoderma* enriched biofertilizers are twice more effective in increasing the yield parameters of brinjal than farmyard manure (FYM) of the same dose (Hossain and Akter, 2020). Wang *et al.* (2017) revealed that viable and nonviable *T. Viride* could decreased ammonia volatilization upto 42.21% and 32.42% respectively as compared to urea. Thus, apart from maintaining soil structure, improving microbial activities and soil fertility, *Trichoderma* spp. can increase fertilizer use efficiency and consequently control environmental pollution.

***Trichoderma* as bioremediator:** Bioremediation refers to the degradation of pollutants present in the environment by using potential bioagents. The accumulation of chemical residue is increasing day by day in the environment causing a great loss of biodiversity and has also brought serious health hazards to human beings. Application of *Trichoderma* can be the sustainable and viable solution in this regard. The different species of *Trichoderma* as a bioremediator to various pollutants are presented in the Table 1.

***Trichoderma* as bio control agent:** The bio control action of *Trichoderma* against various diseases of crops along with experimental conditions and results are summarised in Table 2.

Methods of application of *Trichoderma*

The fungicidal nature of *Trichoderma* makes it an effective biological control agent for the control of plant pathogenic fungi. Single strain of *Trichoderma* may not be effective for all the diseases. So, at the time of application, mixing of other bio-control agents along with *Trichoderma* results in better control of the related diseases (Bhattacharjee and Dey, 2013).The most common and effective methods of applying *Trichoderma* are seed and seedling treatment, soil treatment and foliar application.

Seed and seedling treatment: Seed treatment with biocontrol agents is considered as effective method of controlling seed/soil borne pathogens. According to BCA (2018), wetting of the seeds before treating with *Trichoderma* followed by the mixing of treated seeds in a plastic box or sheet helps in improving the resistance of plants against diseases. According to Mastouri *et al.* (2010), when seeds treated with *T. harzianum* were exposed to physiological, biotic, or abiotic stresses, the positive response to the treatment was noticed.

Table 2. Biocontrol action of *Trichoderma* against different crop diseases.

S.N.	Plant	Disease	Pathogen	*Trichoderma* species	Experiment condition	Result	Reference
1	Sugarcane (*Saccharum officinarum*)	Pineapple disease	*Creatocystis paradoxa*	*T. harzianum* IMI- 392432	In vitro	63.80% inhibition of radial growth when culture plug was at the margin and 80.82% radial growth inhibition when culture plug was away from margin	Rahman *et al.* (2009)
2	Bean (*Phaseolus vulgaris)*	Root rot	*Rhizoctonia solani*	*T. asperellum*	In vitro and greenhouse	In vitro: lowered disease incidence (19.3%) In green house: only 30.5% of incidence	Asad *et al.* (2014)
3	Cacao (*Theobroma cacao*)	Black-pod	*Phytophthora palmivora*	*T. martiale* ALF247	In vivo	Progressive decrease in disease severity with increase in inoculum concentration	Handa *et al.* (2009)
4	Grapes (*Vitis venifera*)	Esca	*Phaemoniella chlamydospora*	*T. harzianum*	In vivo	Treated plant did not show necrosis or black goo	Marco *et al.* (2004)
5	Broad leaves and coniferous trees	Brown root rot	*Phellinus noxius*	*T. asperellum* TA	In vitro	The size of *Phellinus noxius* colonies was reduced from 7.3% to 15.8% than that of control	Chou *et al.* (2019)
6	Maize (*Zea mays*)	Stalk rot	*Fusarium graminearum*	*T. asperellum* ZJSX5003	In vitro and in vivo (greenhouse)	Disease reduction of 71%	Li *et al.* (2016)
7	Coconut (*Cocos nucifera*)	Black rot	*Ceratocystis paradoxa*	*T. sp*	In vitro	More than 60% growth inhibition of pathogen on the 7^{th} day of incubation in dual culture	Kannangara *et al.* (2016)
8	Cocoyam (*Colocasia esculenta*)	Root rot	*Pythium myriotylum*	*T. asperellum*	In vitro and in vivo	Above 60% growth inhibition in vitro. 50% reduction of infection in vivo.	Mbarga (2012)
9	Sugar beet (*Beta vulgaris*)	Leaf spot	*Cercospora beticola*	*T. hermatum* (Ba8/86, Ba9/86, Ba12/86)	In vitro and in vivo	Maximum (63.5%) inhibition of mycelial growth by Ba9/86. 100% inhibition of conidia germination by Ba8/86. Ba9/86 and Ba8/86 were effective in controlling pathogen under field condition.	Galletti *et al.* (2008)
10	Beans (*Phaseolus vulgaris*)	Damping off	*Pythium aphanidermatum*	T105 strain	In vitro and in vivo (greenhouse)	In vitro: maximum inhibition (only 4.16% disease severity) In green house condition: 82.86% reduction of disease incidence.	Kamala and Indira (2011)
11	Rice (*Oryzae sativa*)	Brown leaf spot	*Bipolaris oryzae*	*T. harzianum*	In vitro and In vivo (field)	In vitro: 48% inhibition if pathogens after 6 days. In field condition: *Trichoderma harzianum* has lowest (2.5%) disease severity and lowest disease incidence (46.9%) on 21^{st} day of incubation.	Abdel-fattah *et al.* (2007)

Soil treatment: Soil treatment is the most effective method of *Trichoderma* application for the management of soil-borne diseases (Kumar *et al.*, 2014). Colonization can be increased through the application of *Trichoderma* along with some organic matters like FYM, neem powder and/or vermicompost. Addition of the *T. harzanium* to both nursery soil and transplanted soil diversified the microbial community which substantially controlled the fusarium wilt in cucumber (Chen *et al.*, 2012). Hassan (2014) recommended the use of individual *T. harzianum* or the combination with compost material for the effective control of Rhizoctonia root rot of soybean caused by *Rhizoctonia solani*. The soil application of *T. viride* was effective in suppressing the effects of stem rot, seedling blight and root rot disease of Jute (Srivastava *et al.*, 2010).

Foliar application: *Trichoderma* species with ability to suppress many plant pathogenic fungi are also being preferred for reducing the diseases of foliar plant parts. Generally, 10 g of *Trichoderma* mixed with 1 litre of water is sprayed on the aerial parts as foliar application. According to Sawant (2014), the foliar application is mainly used to supress grey mold caused due to infections of *Botrytis cinerea* and powdery mildews on a number of crops and also to improve the shelf life of grapes by the control of downy mildew. An isolate T39 of *T. harzianum* is effective in controlling the foliar pathogens, *B. cinerea*, *Pseudoperonospora cubensis*, *Sclerotinia sclerotiorum* and *Sphaerotheca fusca* in cucumber under commercial greenhouse conditions (Elad, 2000).The foliar application of *Trichoderma* has positive effect on titratable acidity, pH and electrical conductivity of fruits and increases the quality of tomato (Palacios *et al.*, 2019).

Multiplication method of *Trichoderma*

The researchers are exploring the importance of biocontrol agents for the effective management of the plants associated diseases and to promote the growth and development of plants. One of the major limitation related to *Trichoderma* is its production in large quantity. So, the mass production of *Trichoderma* spp. has become a focus of research for searching the alternatives which affect plants comparatively to a less extent than by the use of chemical fertilizers and pesticides. Sabalpara (2014) reports that researchers have attempted for use of varied substrates and techniques for multiplication and introduction of *Trichoderma* into the soil. Different substrates and techniques used for the mass production of *Trichoderma* are categorized into:

Solid state fermentation: Solid state fermentation for the mass multiplication of *Trichoderma* uses the solid based substrates like grains, organic matters and agricultural wastes. According to Bhagat *et al.* (2010), sorgham and wheat were used as the solid substrates for the mass production of *T. viride* and Sorgham was reported to be more effective. Maize was successfully used as the substrate for *T. harzianum* mass production by solid fermentation technique (Pramod and Palakshappa, 2009). According to Palanna *et al.* (2007), FYM, vermicompost, poultry manure, goat manure, decomposed coconut, coir pith was used as the solid substrates for the multiplication of *T. viride* and FYM was found to be the most promising substrate. Wheat straw, paddy straw, shelled maize cob, paper waste, saw dust, sugarcane bagasse, spent straw, wheat bran, rice bran were successfully used as the substrates for the mass production of *T. harzianum* and wheat bran and paddy straw were found to be the most effective (Tewari and Bhanu, 2004).

Liquid state fermentation: Liquid state fermentation method of mass production of *Trichoderma* is generally used to produce spores from fungal strains (Waghunde *et al.*, 2016). The liquid fermentation method of mass production is applied for the processes in which soluble materials in water is used for the microbial growth (Kumar *et al.*, 2014). Potato Dextrose Broth, V8 juice and molasses yeast medium were used as the liquid based substrate for the mass multiplication of *T. harzianum* Rifai (Hassan, 2014).

Mode of action of *Trichoderma*

Trichoderma as a biocontrol agent controls the plant disease through different mechanisms. The mode of action to control foliar pathogens may differ from that of the root and soil pathogens. Sometimes involvement of more than one mechanism in the interaction is also observed. The various mode of action employed by *Trichoderma* are described below:

Mycoparasitism: *Trichoderma* species have special ability to parasitize other fungi and involves direct attack of one fungal species (say *Trichoderma*) on another one and the process is called as mycoparasitism. This process involved different complex sequential events from recognition of the fungal strain by *Trichoderma*, effective penetration into the host fungi, attack on cellular machinery to finally killing of the host (Benítez *et al.*, 2005; Waghunde *et al.*, 2016). According to Verma *et al.* (2007), production of various enzymes by species of *Trichoderma* helps in penetration of cell by hydrolysing polysaccharides, β-glucans, cellulose and chitin present in the cell walls of the plant pathogenic fungi. Development of biocontrol strategies were enhanced by the discovery of mycoparasitic ability of *Trichoderma* over other important economic fungi (Harman *et al.*, 2004).

Competition: *Trichoderma* can act as biocontrol agent by growing faster or by using its food source more efficiently than the pathogen which causes comparatively higher crowding of the biocontrol agent and finally taking over the pathogen. This process is referred as nutrient competition. Rhizosphere competence for food and space is also common among *Trichoderma* species. According to Harman (2000), *Trichoderma* species grow readily along with the developing root system of the treated plant when added to the soil or applied as seed treatments. A review Waghunde *et al.* (2016) ascribed regarding the deaths of microorganisms growing near the *Trichoderma* strains and suggested starvation and scarcity of limiting nutrients as the most common cause of death.

Antibiosis: Antibiosis mode of action is a biological interaction mainly observed in between microorganisms in which one is adversely affected. Kucuk and Kivank (2003) stated that *Trichoderma* species have potential to produce number of antibiotics such as trichodernin, trichodermol, harzianun and harzianolide which helps in controlling the plant pathogens. According to Benitez *et al.* (2004), in case of *Trichoderma* the mechanism of antibiosis involves the production of small sized diffusible compounds by *Trichoderma* species called antibiotics that inhibits the growth of other microorganisms. Bhattacharjee and Dey (2014) reported the control of *Pythium* spp. with the use of virdin antibiotic produced by *T. Viride* colonizing Pea seeds.

Induced resistance: The mode of action of *Trichoderma* species involves another mechanism of inducing resistance in the plant when treated with the biocontrol agent. The soil treated with biocontrol agent induced the resistance in leaves against fungal pathogens such as *B. cinerea* and *C. lindemuthianum* though biocontrol agent (T-39) was applied only on the roots. Later, an isolate of *T. harzianum* - T39 when applied into soil was found to be inducing systemic resistance in plants which resulted in reduction of foliar diseases including powdery mildew and also the application of biocontrol agent in the dead cells of roots induced foliar resistance against pathogens (Elad *et al.*, 2000). Other studies like Saksirirat *et al.* (2009) reported the induction of resistance in tomato plant (cv. Sida cultivar) by an isolate of *T. harzianum* (T9) against bacterial spot (*Xanthomonas campestris* pv. vesicatoria) reducing disease incidence upto 69.32% after 14 days of post inoculation. Hoitink *et al.* (2006) suggested the effectiveness of induced systemic resistance in compost amended medium as it helped in the multiplication of *Trichoderma spp.*

Challenges for the adoption of *Trichoderma* over chemicals fertilizers and pesticides

Many articles published on *Trichoderma* have emphasized on the effectiveness and its role in improving the way of practicing agriculture worldwide. But its application in the real agricultural field apart from the field of words is quite limited. Different researchers have studied about biocontrol agents and published thousands of papers on this topic but still the use of bio control agents is limited in commercial agriculture (Harman, 2000). Despite possessing such potentials to change the shape of agriculture as elaborated in different research publications, the actual feasible and economic way of incorporating *Trichoderma* in agriculture field is yet to be found. Topolovec-Pintaric (2019) explained about the low use of bio-control agents like *Trichoderma* in the developing agricultural-based countries. Full-scale production, marketing and registration requirements are unfavourable and the products of biocontrol agents are too expensive to consider their use when compared to chemical use. The major challenge is to use biological agents like *Trichoderma* in a system where chemical fungicides provide a better and more economical fit. Harman (2000) found four major reasons behind the little interest of companies in commercializing the use of biological agents as seed treatment for protecting the seeds. The reasons were (i) availability of highly effective chemical pesticides for protecting the seed; (ii) the available chemicals were less expensive than biologicals; (iii) chemically treated seeds had superior shelf life to biologicals; and iv) effects of chemicals could withstand a wider range of temperatures and other environmental conditions than biologicals. Chemical fertilizers and pesticides are quick in action and can be effective even in short period of time. Also, the pesticides of chemical origin have the ability to eliminate the pest populations completely. On the other hand, *Trichoderma* often takes longer to establish than chemical pesticides and fertilizers and are applicable only in favourable conditions and frequently reduces a pest population to a low level rather than eliminating it completely. Furthermore, the pesticides companies do not want to take risk by investing in commercializing bio control agents as there are already a lot of better market-favoured short term alternatives of bio-control agents.

Recommendation

The success of the use of *Trichoderma* directly depends on its capacity of multiplication and colonization in the given environment, its persistence and time taken for effective action. Thus, further research should be focused on the identification of different strains of *Trichoderma* which are persistent for long period, least affected by environmental conditions, and having high rate of survivability, multiplication and colonization. The research conducted to study and analyse the effectiveness of different strains of *Trichoderma* were done in isolation and being able to encapsulate it in formulations for low scale trial has opened the doors for its further improvements leading to its worldwide adoption. Researchers need to find the ways for its effective formulations for large scale. Atieno *et al.* (2020) noticed the farmer's perception and preference in using the chemical fertilizers instead of biological methods with the hope of improving the yield of crops. Therefore, for the commercialization and wide scale adoption of *Trichoderma*, farmers should be made acknowledged about the benefits of *Trichoderma* over chemical fertilizers and pesticides in controlling the plant diseases and improving the crop yield.

Conclusion

Sustainability in agriculture can only be achieved if emphasizes is given towards organic fertilizers and pesticides. *Trichoderma* is an attractive alternative to chemical fertilizers and pesticides that can be used as biofertilizer, bioremediator and biocontrol agent. Its ability to compete with different other pathogenic organisms has enhanced its use in controlling many plant pathogens like fungi, nematodes, viruses, bacteria etc. Through various mode of actions (mycoparasitism, competition, antibiosis, induced resistance etc.), *Trichoderma* has potentially effective role in controlling plant diseases. *Trichoderma* also assists in absorbing soil nutrients and also has role in increasing the efficiency of chemical fertilizers. It improves soil properties and enhance microbial activities. Different species of *Trichoderma* have been identified as bioremediator of pollutants present in the environment such as heavy metals, petroleum products etc. It has been proved as effective biocontrol agent against different plant pathogens. From these points we can conclude that it has significant potential to achieve the goal of sustainable agriculture. Inspite of having such advantages, it is not widely adopted as compared to chemical fertilizers and pesticides. Slow in action, failure in complete elimination of plant pathogens, high cost and applicable only in the presence of conducive environment are the major challenges for its wide scale adoption. Thus, future research work should be concentrated towards isolation and identification of different strains of *Trichoderma* which are effective against wide range of pathogens, abiotic and biotic stress tolerant and having high rate of multiplication and colonization. Dissemination of knowledge regarding advantages of *Trichoderma* and adverse effects of chemical fertilizers and pesticides should be done at the farmer's level. Furthermore, emphasises should be given towards the approaches like organic farming and integrated pest management (IPM) for the wide scale adoption of *Trichoderma*.

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