

Potential of *Trichoderma* species as biofertilizer and biological control on *Oryza sativa* L. cultivation

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ABSTRACT

Rice (*Oryza sativa* L.) is one of the main staples around the world, especially in Asia, the most consuming region. Rice cultivation currently faces many environmental problems caused by the contribution of chemical fertilizers and pesticides. This review is carried out to document the principal findings of *Trichoderma* species application on rice plants. The analysis revealed that different species of *Trichoderma* have been applied in different fields of research on rice plants to increase the absorption of nutrients, soil fertility, tolerance to salinity, plant growth promotion and development with increased yields. Mechanisms include decomposition, mycoparasitism, cellulose degradation, and phosphate solubilizing activity. The potential for antagonistic activity against disease-causing fungi and inhibition of growth of harmful root microflora is demonstrated. This work also suggested that *Trichoderma* can be applied alone or together with other microorganisms to significantly promote the growth and performance of rice plants. Among the species, *T. harzianum* was studied mainly to determine its different roles in rice, followed by *T. asperellum*, *T. viride*, *T. virens* and *T. atroviride*. Therefore, the findings revealed the potential of the *Trichoderma* species as a possible biofertilizer and biological control for rice cultivation worldwide.

Keywords: rice, biocontrol agent, growth parameters and yield

Potencial de especies de *Trichoderma* como biofertilizante y control biológico en el cultivo de *Oryza sativa* L.

RESUMEN

El arroz (*Oryza sativa* L.) es uno de los principales alimentos básicos en todo el mundo, especialmente en Asia, la región más consumidora. El cultivo de arroz en la actualidad enfrenta muchos problemas ambientales causados por el aporte de fertilizantes químicos y plaguicidas. El objetivo de este trabajo de revisión fue documentar los principales hallazgos sobre el empleo de especies de *Trichoderma* en el cultivo de arroz. Este análisis reveló que diferentes especies de *Trichoderma* se han aplicado en diferentes campos de investigación sobre plantas de arroz para aumentar la absorción de nutrientes, la fertilidad del suelo, la tolerancia a la salinidad, promoción del crecimiento y desarrollo de las plantas con incremento en los rendimientos. Entre los mecanismos se menciona la descomposición, el micoparasitismo, la degradación de celulosa y la actividad solubilizadora de fosfatos. Se demuestra el potencial de actividad

antagonista contra hongos causantes de enfermedades y la inhibición del crecimiento de la microflora perjudicial de la raíz. Este trabajo también sugirió que *Trichoderma* puede aplicarse solo o junto con otros microorganismos para promover significativamente el crecimiento y el rendimiento de las plantas de arroz. Entre las especies, *T. harzianum* se estudió principalmente para determinar sus diferentes roles en el arroz, seguido de *T. asperellum*, *T. viride*, *T. virens* y *T. atroviride*. Por lo tanto, los hallazgos revelaron el potencial de las especies de *Trichoderma* como un posible biofertilizante y control biológico para el cultivo de arroz en todo el mundo.

Palabras clave: arroz, agente de biocontrol, parámetros de crecimiento y rendimiento

INTRODUCTION

Among the major food crops, rice (*Oryza sativa* L.) serves as the staple food in terms of area under cultivation, production and consumer preference catering to more than half of the population of the world including two third of Indian population (Bishwajit *et al.*, 2013; Huang *et al.*, 2014).

India is the second largest producer and patron of rice production in the international level (Singh *et al.*, 2018). However, the production of this crop is progressively restricted by varied environmental stresses in Asia (Dar *et al.*, 2013).

Similarly, world rice production is significantly reduced by drought because of unpredictable and uneven rain throughout the growing season (Crosson, 1995). Therefore, the crises of food demands for improved farming practices resulting in enhanced rice production, particularly in areas that are highly susceptible to varied types of environmental stresses (Singh and Singh 2017).

Due to massive application of chemical fertilizers, it directly or indirectly causes different environmental pollutions (Khan, 2018). The use of chemical fertilizers and pesticides lead to system damage through emergence of resistant pathogens as well as soil toxicity due to persistent heavy metals (Habibah *et al.*, 2011; Doni *et al.*, 2014a). Hence, there is a need to promote the use of biofertilizers that are environment friendly (Banayo *et al.*, 2012).

Chemical fertilizer is harmful to living beings and specially, adversely affects the microbial population present in the ecosystems (Khan and Singh, 2015). It is therefore essential to develop an integrated nutritional support policy to supplement and build smart fertilizer

application with the addition of adequate eco-friendly resources. Utilization of microorganisms has been hypothesized to play vital role in mitigating stress and thereby enhancing yields in rice (Man and Ha, 2006; Zaidi *et al.*, 2018).

Besides, beneficial microorganisms have been reported to be involved in maintaining agricultural production, protecting the ecosystem and decreasing the use of chemical fertilizers (Adesemoye and Kloepper, 2009). For instance, soil bacteria such as *Pseudomonas* and *Azospirillum* are known to alleviate abiotic stresses in numerous crop species including rice (Vejan *et al.*, 2016).

On the other hand, *Trichoderma* is amongst the foremost extensively researched microbes and is primarily recognized for its mycoparasitic activities and also helps plants to reduce stress through induction of morphological, physiological and organic changes (Ji *et al.*, 2012; Mukherjee *et al.*, 2013; Doni *et al.*, 2014d). The first description of *Trichoderma* dates back to 1794 (Person, 1794) and these ubiquitous fungi have tremendous impact on human life and ecosystem functionality (Felix *et al.*, 2014).

Trichoderma are one such free-living fungi which are highly interactive in root, soil and foliar environments (Harman *et al.*, 2004) and are available to natural growers as large variety of *Trichoderma*-based biopesticides that may be useful for the management of plant diseases (Singh *et al.*, 2014). It is also reported that *Trichoderma* enhance root growth, promotes plant growth, improves seedling vigour, promotes plant development, increases absorption of nutrients, helps seed germination under adverse soil conditions, imparts tolerance to abiotic stresses, secretes phosphate-

solubilizing enzymes and phytohormones, improves yield parameters and represses growth of harmful root microflora Harman *et al.*, 2004; Shores and Harman, 2008; Mastouri *et al.*, 2010; Shukla *et al.*, 2012; Hermosa *et al.*, 2012; Chen *et al.*, 2013; Pandey *et al.*, 2016; Swain *et al.*, 2018).

Besides, *Trichoderma* species (*T. virens*, *T. viride*, *T. harzianum*) are involved in decomposition, mycoparasitism and even in polyose degradation (Samuels, 1996; Harman *et al.*, 2004; Druzhinina *et al.*, 2006; Jiang *et al.*, 2011).

In addition, some *Trichoderma* species (*T. harzianum*, *T. asperellum*, *T. atroviride*, *T. gamsii*, *T. hamatum*, *T. koningii*, *T. lignorum*, *T. parceanamosum*, *T. polysporum*, *T. virens* and *T. viride*) are well recognized as biofungicides in agricultural practices (Verma *et al.*, 2007; Woo *et al.*, 2014). Integrated disease management by using biocontrol agents (BCAs) is precious to sustainable agriculture and it helps to reduce crop losses caused by plant pathogens using natural mechanisms involving numerous modes of action including antibiosis, mycoparasitism, antagonism and induced resistance. Scientists are striving to identify potential strains of BCA that upon combination may result in a synergistic response. Much of the published work claiming synergy showed antagonistic relations among BCAs (Xu *et al.*, 2011).

In rice cultivation several papers reports the use of *Trichoderma* species with different applications. For this reason, the present review is carried out to document the principal findings of *Trichoderma* species application on rice plants.

Effect of *Trichoderma* on yield enhancement of rice

Different species of *Trichoderma* showed beneficial effects on soil application (Cuevas *et al.*, 1995; Cuevas *et al.*, 2001; Cuevas *et al.*, 2005; Cuevas, 2006) (Table 1, Table 2, Table 3). Doni *et al.* (2017) reported that System of Rice Intensification (SRI) with the application of *T. asperellum* showed yield components with highest panicle number, spikelets per panicle and more filled grains on rice plants as compared to other

treatments. These effects were established by measuring the physiological and growth parameters.

In this sense, Khadka and Uphoff (2019) described many benefits of *Trichoderma* inoculation for improving crop production which includes growth and yield enhancement and the alleviation of biotic and abiotic stresses. They also evaluated the effects of *Trichoderma* inoculation of rice plants under SRI management compared with transplanted and flooded rice plants and the results indicated significantly better performance ($P=0.01$) associated with *Trichoderma* inoculation in terms of grain yield and other growth-contributing factors, compared to non-inoculated rice cropping.

Trichoderma promotes growth, increases rice grain as well as vegetable yield even with minimal mineral fertilizer application due to better mineral accessibility (especially P and Zn) to plants. For example, sowing of seed after osmopriming with 3% ZnSO₄ and biopriming with *Trichoderma* and then application of sulphur fungicide at 20 days after sowing documented for improving seedling establishment and increasing grain yield of Boro rice (Rahman *et al.*, 2015).

Another example is the application of *Trichoderma* species with composted rice straw in conjunction with 70% NPK. It was found to be economically efficient i.e., benefit cost ratio was highest among all treatments. The nutrient content (organic carbon, available N, P and exchangeable K) in the rice soil was improved significantly with *Trichoderma* as compared to the other conventional application by the dose of farmers (burnt rice straw with 100% NPK alone). The combination of *Trichoderma* with 70% NPK and burnt rice straw reduced inorganic fertilizer cost while increasing grain yield, benefit cost ratio and soil fertility (Son *et al.*, 2013). Application of the combination of *T. harzianum* with NPK treatments efficiently worked for conservation of soil nutrients under rice ecosystem through proper decomposing method, concurrently enhancing soil microorganisms that are beneficial for plant growth and productivity (Man *et al.*, 1999; Sannathimmappa *et al.*, 2015).

Table 1. Effect of *Trichoderma* spp. strains applied in *Oryza sativa* L. cultivation.

No.	Rice cultivar	Significant findings	Country	References
1	OM 1490	Reducing 30% of inorganic fertilizer cost, increased grain yield, benefit cost ratio and improve soil fertility.	Vietnam	Son <i>et al.</i> (2013)
2	Local rice cultivar	Increased plant resistance to disease, especially basal stem roots diseases and wilt disease.	Indonesia	Suparno <i>et al.</i> (2016)
3	MRQ74	Increased rice growth components.	Malaysia	Doni <i>et al.</i> (2014)
4	GJS04-217	Potential applicability in the improvement of the crop.	Brazil	Chagas <i>et al.</i> (2015)
5	PB-1121	For the management of nematode in rice crop.	India	Kumar <i>et al.</i> (2017a)
6	Neda	To control sheath blight of rice.	Iran	Naeimi <i>et al.</i> (2010)
7	Natural Jhingora rice	Reducing disease severity and increasing grain yield over control.	India	Khan and Sinha (2007)
8	Paddy seedlings	Biocontrol agents in rice against <i>Rhizoctonia solani</i> .	India	Anitha and Das (2011)
9	IR 64	Increasing grain yield, association of higher microbial colonization apart of these also reduced sheath blight disease of rice.	Vietnam	Man <i>et al.</i> (1999)
10	IR64	Increased rice yield.	Vietnam	Man and Ha (2006)
11	MRQ74	Increased rice seedling growth, germination rate, vigour index and speed of germination.	Malaysia	Doni <i>et al.</i> (2014)
12	MTU 7029	Gained higher biomass yield.	India	Nongmaithé <i>et al.</i> (2017)
13	MRQ74	Improving rice physiological process.	Malaysia	Doni <i>et al.</i> (2014)
14	Karuna and Sahabgadhyan	Recorded better crop growth and highest yield both under biotic and abiotic stresses.	India	Swain <i>et al.</i> (2018)
15	IR-50	Enhanced root and shoot growth also to control sheath blight of rice and wilt of tomato	India	Balasubramanian <i>et al.</i> (2014)
16	Swarna, Swarna Sub-1, IR-64, DRR-42	Ability for enhancing, root development and water productivity and effective in improving soil moisture availability and thus increased plant establishment.	India	Kurrey <i>et al.</i> (2018)
17	NLR-34449	Highly effective against sheath blight pathogen.	India	Prasad and Kumar, (2011)
18	MRQ74	Potential to enhance rice physiological processes and growth.	Malaysia	Doni <i>et al.</i> (2014)
19	Pusa 1121	Effective against brown leaf spot disease of rice.	India	Kumar <i>et al.</i> (2016)

Antagonistic effect of *Trichoderma* in rice disease management

Trichoderma species has been shown antagonism effect on the causal agents of several diseases in rice *in vitro* and in field

assays. *Trichoderma* have long been recognized as biocontrol agents are highly interactive in root, soil and foliar environments and produce a variety of compounds that induce localized and systemic resistance responses in plants (Table 1, Table 2, Table 3, Table 4).

Table 2. Effect of *Trichoderma harzianum* strains applied in *Oryza sativa* L. cultivation.

No.	Rice cultivar	Significant findings	Country	References
1	Kalanamak-3131	Salinity tolerant.	India	Rawat <i>et al.</i> (2012)
2	Kalanamak 3131	Delay in the drought responses of rice plants.	India	Shukla <i>et al.</i> (2012)
3	Pant Dhan-4	Significantly reduced the disease severity and incidence of sheath blight.	India	Khan and Singh (2015)
4	BRRI dhan28	Improved seedling establishment and increase grain yield of dry direct seeded Boro rice.	Bangladesh	Rahman <i>et al.</i> (2015)
5	JGL-1798	Increased rice productivity and enhancing soil microorganisms beneficial for plant growth and productivity.	India	Sannathimmappa <i>et al.</i> (2015)
6	Sugandh Dhan-17, Pusa Basmati-1, Kalanamak 3131	Resulted in significantly increased in plant height before and after drought stress.	India	Pandey <i>et al.</i> (2016)
7	Kernel	Enhances salt tolerance of rice also lowered the H ₂ O ₂ concentration reducing the damaging effect of Reactive oxygen species (ROS) within plants.	Pakistan	Yasmeen and Siddiqui (2017)
8	Sahbhagi Dhan and Swarna-Sub1	Enhanced the yield and yield parameters as well as enhanced the productivity of rice in rain fed area also.	India	Zaidi <i>et al.</i> (2017)
9	Jyothi	Superior plant growth parameters (plant height, root length, grain yield etc.).	India	Narasimhamurthy <i>et al.</i> (2017)
10	Kali kamod	Synergistic against Rice Blast.	India	Jambhulkar <i>et al.</i> (2018)
11	BU dhan 1	Significant increase in N uptake and enhance the yield of rice.	UK	Khan (2018)

Gomathinayagam *et al.* (2009) suggested that *T. viride* has a potent antagonistic activity against the pathogen which causes brown spot disease in rice (*Cochliobolus miyabeanus*). *Trichoderma* spp. are able to increase plant resistance to disease, especially in case of basal stem rot disease (*Sclerotium oryzae*) as well as wilt disease (*Xanthomonas* sp.) and it also plays a significant role as decomposer to provide plant nutrients (Man and Ha, 2006; Suparno *et al.*, 2016). Consortium of Rhizobacteria and mycorrhiza with *Trichoderma* spp. notably reduced the infection of blast (*Magnaporthe grisea* Herbert) and brown spot disease (*C. miyabeanus*) in upland rice crops (Taufik *et al.*, 2016; Kumar *et al.*, 2016).

It is also an effective biological control agent against soil-borne fungal pathogens. *Trichoderma* spp. increases resistance against Bakanae disease of MR219 rice by increasing resistance to the pathogen *Fusarium fujikuroi* (Ng *et al.*, 2015). Rice blast disease caused yield losses throughout the world but *Trichoderma* individually or in mixed inoculums with *Bacillus subtilis* Cohn gave the best reduction in pre-post damping off disease infection caused by rice blast fungus *M. grisea* (Ali and Nadarajah, 2014). Combined application of *Pseudomonas fluorescens* Migula and *Trichoderma* species showed significant role in plant growth enhancement and management of blast of rice (Subhalakshmi and Devi, 2017; Jambhulkar *et al.*, 2018).

Table 3. Effect of different *Trichoderma* species strains applied in *Oryza sativa* L. cultivation.

No.	Rice cultivar	Microorganisms	Significant findings	Country	References
1	NARDI 108	<i>T. viride</i>	Promoting crop growth, grain and straw yields of rice and controlling the sheath blight disease.	India	Mathivanan <i>et al.</i> (2005)
2	PSB rc 34	<i>T. pseudokoningii</i>	Increased yield and effective biological control agent against soil-borne fungal pathogens.	Philippines	Cuevas (2006)
3	BRS Tropical	<i>T. asperellum</i>	Reduced sheath blight progression rate and increasing yield and grain weight.	Brazil	França <i>et al.</i> (2015)
4	MTU 7029	<i>T. viride</i>	Most effective treatment against sheath blight.	India	Pal <i>et al.</i> (2015)
5	Pusa Sugandh 5 (Pusa 2511)	<i>T. viride</i>	Improvement of rice quality and decreased rice production costs, with savings of 50% in N application.	India	Adak <i>et al.</i> (2016)
6	MRQ74	<i>T. asperellum</i>	Enhanced the macronutrient N, P and K.	Malaysia	Doni <i>et al.</i> (2017)

T. harzianum and *T. viride* are potential biological control agents and there are significant differences between these two fungi in controlling brown spot disease (*C. miyabeanus*) in rice plants (Gomathinayagam *et al.*, 2012). *Trichoderma* spp. isolates found in the commercial product Trichoplus JCO were capable of solubilizing phosphate in substance, suggesting its potential pertinence in the improvement of the crop (Chagas *et al.*, 2015). Kannahi *et al.* (2016) studied the efficacy of various isolates of *T. viride*, *T. virens*, *T. harzianum* and *T. reesei* against fungus by dual culture methodology under various *in vitro* conditions and found that each one of the isolates of *Trichoderma* species showed antagonistic activity. Kumar *et al.* (2017a) found that *Trichoderma* can be applied to crops with agrochemicals for controlling of root-kont nematode (*Meloidogyne graminicola*). França *et al.* (2015) demonstrated that mixed isolates of *T. asperellum* used during seed treatment and foliar spray efficiently increased yield and grain weight in cultivated rice under flooded conditions while minimizing the incidence of rice sheath blight (*Rhizoctonia solani* J.G.Kühn).

Numerous researchers reported that different *Trichoderma* sp. like, *T. harzianum* (Khan and Sinha, 2007; Shahram *et al.*, 2010),

Trichoderma sp. (Man *et al.*, 1999; Naeimi *et al.*, 2010; Prasad and Kumar, 2011; Balasubramanian *et al.*, 2014) and *T. viride* (Mathivanan *et al.*, 2005; Pal *et al.*, 2015) were successful in controlling sheath blight of rice (*R. solani*). *T. harzianum* with *P. fluorescens* helped in reducing nematode population by producing some special structure which contained toxins and alkaloids that killed eggs, juvenile stage and also inhibited growth and activity of nematodes (Narasimhamurthy *et al.*, 2017). Jambhulkar *et al.* (2018) showed that the combined application of *T. harzianum* with *P. fluorescens* increased efficacy and consistency of the two biocontrol agents to impart a synergistic response against rice blast disease.

The formulations must maintain the antagonists in a viable form in the environment as long as it is necessary for the mode of action to be expressed and favours survival of biocontrol agents in the environment (Joshi and Raut, 2005). Although *Trichoderma* isolates of T8 and T21 exhibited moderate degree of antagonistic activity in dual culture experiments, these isolates provided higher antagonistic values against *M. grisea* that indicates an effective mycoparasitism against infective agent in soil (Bell *et al.*, 1982; Harman, 2000; Schuster and Schmoll, 2010;

Table 4. Effect of *Trichoderma* strains combined with other microorganism in *Oryza sativa* L. cultivation.

No.	Rice cultivar	Microorganisms	Significant findings	Country/Region	References
1	G98-135	<i>T. harzianum</i> <i>T. viride</i>	Potential biological control agents for controlling brown spot disease in rice plants.	South America	Gomathinayagam <i>et al.</i> (2009)
2	G98-135	<i>T. harzianum</i> <i>T. viride</i>	Potential biological control agents in controlling brown spot disease in rice plants.	South America	Gomathinayagam <i>et al.</i> (2012)
3	PSB Rc18	<i>Azospirillum</i> , <i>Trichoderma</i> , unidentified <i>Rhizobacteria</i>	Significant yield increase	Philippines	Banayo <i>et al.</i> (2012)
4	MR219	<i>Trichoderma</i> spp., <i>B. subtilis</i>	Effective in inhibiting <i>Magnaporthe grisea</i>	Malaysia	Ali and Nadarajah (2014)
5	CO-43	<i>Trichoderma</i> species	Antagonistic potential of four species against <i>Ustilagoideae virens</i> after 9 days and 12 days of incubation period.	India	Kannahi <i>et al.</i> (2016)
6	Bakala	<i>Trichoderma</i> sp. <i>Rhizobacteria</i> and Mycorrhiza	Prepared consortium (with <i>Trichoderma</i> spp.) significantly reduced the infection of blast and brown spot diseases, during the vegetative and generative phases of upland rice crop.	Indonesia	Taufik <i>et al.</i> (2016)
7	Rice var. KD	<i>P. fluorescens</i> <i>Trichoderma</i> sp.	Plant growth promotion and control of Blast of rice.	India	Subhalakshmi and Devi (2017)
8	Pusa basmati-1121	<i>Trichoderma</i> spp. <i>P. fluorescens</i>	Inhibits the blast disease of rice.	India	Kumar <i>et al.</i> (2017b)

Alfredo and Aleli, 2011). The antagonism of *Trichoderma* species is widely explored and this fungus provides advantages to guard roots from disease and pathogen attack. *Trichoderma* has ability to supply noxious substrate in growth media. The *Trichoderma* have antagonism and saprobe traits to plant pathogens (Suparno *et al.*, 2016). The antagonistic property of *Trichoderma* sp. and *P. fluorescens* was determined against rice sheath blight (*R. solani*). On co-culturing, growth of the antagonists was noticed in individual media whereas growth of *R. solani* was suppressed (Anitha and Das, 2011).

Dennis and Webster (1971) observed in a study that *T. viride* significantly decreased sheath blight infection and increased grain yield in rice. *Trichoderma* inoculants into

sheath blight plagued rice straw also resulted in decline of the extent of infestation caused by *Rhizoctonia solani* (Nagamani and Mew, 1987; Man and Noda, 1997). In another study, Baby and Manibhushanrao (1993) reported 25% increase in growth of rice plants after application of antagonists to soil. Patel and Mukhopadhyay (1997) found that spraying of fungal antagonists increased the grain weight in rice. The application of *Trichoderma* or different *Trichoderma* formulations like *T. harzianum* exhibited significant reduction of the disease as compared to various formulations (Table 2) and among bioagents, *T. harzianum* was found to be the best in managing sheath blight (*R. solani*) giving 48.2% and 30.0% reduction in disease severity and incidence, respectively (Khan and Sinha, 2007). Nevertheless, Sarkar *et al.*

(2014) documented that the use of bioagents, including *Trichoderma* sp., for brown spot management was not so effective than the traditional application of fungicides although *in vitro* experiment showed some promise in controlling the pathogen.

Singh and Sinha (2009) demonstrated enhancement in the growth of rice crop after seed treatment with *T. harzianum* and *Pseudomonas fluorescens* (Table 4) which might be attributed to the enhanced nitrogen uptake and drought tolerance as a result of the bio control treatments. *Trichoderma* species facilitated production of growth hormones like auxins and gibberellins which supported root growth and increased water absorption capacity from soil (Contreras-Cornejo *et al.*, 2009; Martínez-Medina *et al.*, 2011).

Effect of *Trichoderma* on stress tolerance activity

T. harzianum strain is known for enhancing the yield and yield attributes of stress tolerant rice varieties (Zaidi *et al.*, 2018) (Table 2). Application of *T. harzianum* enhanced salt tolerance of maize (*Zea mays* L.) and rice through higher inhibitor activities and high amino alkanolic acid content. This is not only due to the physiological parameters but also due to the reduction in H₂O₂ concentration, hence minimizing the damage created by reactive oxygen species (ROS) inside plants (Yasmeen and Zamin, 2017).

Shukla *et al.* (2012) unconcealed an immensely vital result of treatment with rice root dip in drought tolerant isolates of *T. harzianum* to alleviate drought stress. *Trichoderma* treatment relieved the strain condition, considerably improved length and contemporary weight of shoot and root, increased leaves range, leaf area, photosynthetic pigment content, and reduces stress levels (Rawat *et al.*, 2012).

On the other hand, Pandey *et al.* (2016) found that *T. harzianum* down regulated the expression of Aquaporin, LOC_Os06g12310 gene expression of PSD-17 rice genotype under drought condition and its interaction improved drought.

Potent phosphate solubilizing activity that trends to increase soil fertility

Kapri and Tewari (2010) have documented the ability of *Trichoderma* to solubilized phosphate by releasing phosphatase enzymes, thereby enhancing soil fertility and plant growth.

In other study, Chagas *et al.* (2015) also found that the plant growth was considerably hyperbolic in presence of natural phosphate stirred by *Trichoderma* immunization when compared to plant growth management in absence of *Trichoderma*. Application of composted rice straw with *Trichoderma* spp. helped to maintain soil pH between 4.2 and 4.51, which was not toxic to rice plant growth and the nutrient content in the rice soil. Organic carbon, available N, P and exchangeable K was also improved considerably as compared to the conventional application by the farmers dose burnt rice straw + 100 % (100N-60P₂O₅-30 K₂O kg ha⁻¹) reported by Son *et al.* (2013).

Improvement of seedling vigor and promotion of seed germination

Trichoderma species that has the ability to promote rice seedling length can be an alternative way to be used in sustainable crop production. The length of shoot and root of the seedling were significantly increased by using *Trichoderma* species in comparison to control (in absence of *Trichoderma* spp.). Auxins produced with the help of *Trichoderma* spp. are able to stimulate root initiation and cell elongation while gibberellins are involved in cell division. Stimulation of production of auxins and gibberellins by *Trichoderma* spp. enhances rice seedling performance during seed germination (Doni *et al.*, 2014b).

Role in decomposition, myco-parasitism and cellulose degradation

Trichoderma spp. are beneficial fungi that are present in substantial numbers in nearly all agricultural soils and in different environments like decaying wood (Harman *et al.*, 1993). It grows typically towards hyphae of different fungi, coil them in a lectin-mediated reaction and degrade the target fungi cell walls by a method called mycoparasitism (Harman *et al.*, 1993).

Microscopic observation suggests that *T. harzianum* produces and excretes mycolytic enzymes that lyse cell membrane during

interaction (Carsolio *et al.*, 1994). The extracellular secretion of 1,3- β glucanases, chitinases and proteinase facilitated by *T. harzianum* play a vital role in biocontrol (Carsolio *et al.*, 1994). The antagonistic process starts with physical contact and *T. viride* is an antagonist of soil-borne fungal pathogens. The enzyme weakens the host cell wall and increases the rate of diffusion of the antibiotics through the cell wall. Upon physical contact the *T. viride* coils around its host where it proceeds with invasive growth. The host hyphae collapse because of loss of turgor pressure (Harman *et al.*, 1993).

Increased absorption of nutrients and soil fertility

T. asperellum is known to increase the ability of plants to absorb the metallic component that may be responsible for higher chemical processes (Harman *et al.*, 2004; De Santiago *et al.*, 2010). *Trichoderma* considerably increased the macronutrient uptake and water acquisition capabilities through promotion of stronger root systems (Doni *et al.*, 2014a). The flexibility of *Trichoderma* to modulate rice plants N, P and K uptake was presumptively because of its capability to supply cellulolytic enzymes, which degrade polysaccharide in soils and releases organic N, P and K within the rice rhizosphere. Jiang *et al.* (2011) reported this ability of *Trichoderma*.

Trichoderma possesses mechanisms to promote plant growth through discharge of indole-3-acetic acid that in turn increases root growth and thereby plays a significant role in nutrient acquisition (Hoyos-Carvajal *et al.*, 2009). The presence of *Trichoderma* in the soil results in the release of mineral elements such as macronutrients (K, P, Ca) and micronutrient (Zn) in the soil which is vigorously absorbed by the plants. Such type of nutrition helps in high dry matter production during vegetative stage and promotes early flowering and fruiting resulting in higher yields (Cuevas, 2006). *Trichoderma* treated plants were able to enhance nutrient uptake, resulting in increased root and shoot growth and improved plant vigour ensuring rapidly growth with enhanced plant greenness due to higher photosynthetic rates, hence increased carbohydrate as well as biomass production (Harman, 2006; Saba *et al.*, 2012). *Trichoderma* species increased the biological nitrogen fixation

in soil and nitrogen uptake capacity of the plant (Dordas and Sioulas, 2008).

Growth inhibition of deleterious root microflora

The information documented by Kumar *et al.* (2017b) showed the effective implementation of *Trichoderma* along with agrochemicals for suppressing root knot nematode development and soil born fungal pathogens during rice cultivation (Table 1). This nematophagous fungus developed some special structures that killed the eggs and juvenile by producing toxins and alkaloids, which hindered the growth and activity of nematodes (Narasimhamurthy *et al.*, 2017).

Enhanced plant development and growth promotion

Several scientific reports revealed that *Trichoderma* isolates induce growth of plants in various environments (Bell *et al.*, 1982; Harman, 2000; Schuster and Schmoll, 2010; Alfredo and Aleli, 2011; Ali and Nadarajah, 2014; Nongmaithem *et al.*, 2017). Therefore, *Trichoderma* species have a positive impact in promoting plant growth and development in rice. This ability could be attributed to several mechanisms (Figure 1). Some of them are mycoparasitism, antibiosis, degradation of toxins, inactivation of pathogenic enzymatic pathways, resistance to pathogens, enhanced nutrient uptake, solubilization, sequestration of inorganic nutrients and enhancement of root hair development (Harman, 2006; Lorito *et al.*, 2010). In this sense, Shukla *et al.* (2012) informed that *T. harzianum* significantly increased the ability of rice plants to tolerate drought stress and increase rice water holding capacity, induced higher leaf number and tiller number. Besides, Kumar *et al.* (2017a) reported that *T. viride* extensively improved the plant growth with respect to height of the plant. Application of *Trichoderma* species with farmer practice revealed a significant increase rice growth components (Doni *et al.*, 2014c; Adak *et al.*, 2016) and higher number of effective tillers over the control (Zaidi *et al.*, 2018). Kurrey *et al.* (2018) also demonstrate that hydrogel and *Trichoderma* enhance the root development and water productivity and those are effective in improving soil moisture availability and thus increased plant establishment.

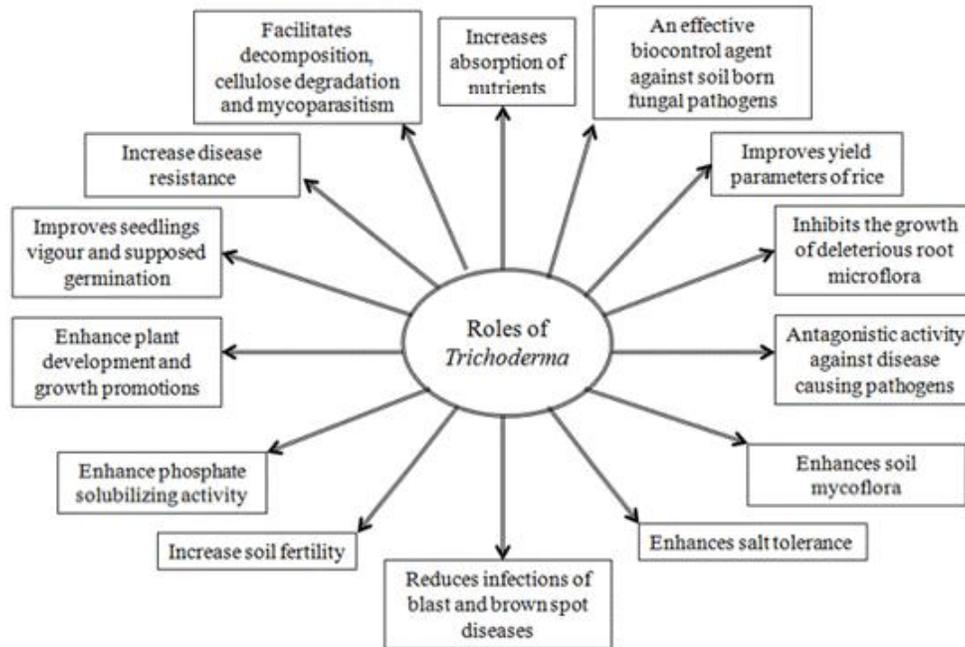


Figure 1. Impact of *Trichoderma* species on soil and plants health during rice cultivation by positively effecting rice plant growth and yield.

CONCLUSIONS

Present review gives an overall involvement of different *Trichoderma* species in improving growth parameters, increasing grain yield, improving soil fertility, decreasing chemical fertilizer use hence reducing the cost involved for fertilization and enhancing economic effectiveness. Present finding suggests that use of *Trichoderma* singly or in combination with other microorganism (biocontrol agents) may be a valuable tool in managing different diseases of rice and it has an effective use in natural abiotic stress tolerance and is one of the best management practices of crop to alleviate stresses occurring in field conditions. Because *Trichoderma* treatments appreciably alleviates the growth parameter effects of hyper salinity, seed bioprimering treatment may be used for getting better plant growth and yield of rice in saline condition. There may be some active metabolites or compounds produced by *Trichoderma* species which stimulate different biological activities of plant. The overall findings reveal *Trichoderma* species to be an effective biocontrol agent that needs to be commercialized throughout the world several formulations are commercialize

around the World. The farmers can use *Trichoderma* species as a biofertilizer or biocontrol because it has no negative effect either on the soil or on the environment. Due to the activities rendered by *Trichoderma* species, it is expected that in near future, exploitation of this fascinating microorganism would be maximized under organic agriculture in rice.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Author contributions

Conceptualization, Investigation and Writing—original draft SD, Resources GC,

Writing—review & editing SSD, Methodology and Formal analysis SRC, Supervision PD and AKS.

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Supplementary material

Table S1. Application of *Trichoderma* spp. as plant growth promoter in rice cultivation. (TableS1.pdf)

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