

---

## REVIEW

# *Trichoderma*: A way for rice health management

---

**ARUP KUMAR MUKHERJEE**

*Molecular Plant Pathology Laboratory, Division of Crop Protection, ICAR-National Rice Research Institute, Cuttack-753006*

---

Received : 21.03.2023

Accepted : 18.06.2023

Published : 25.09.2023

---

*Trichoderma* spp. are the best biocontrol agents, as more than 60% of the enlisted biofungicides utilized in present agribusinesses are based on *Trichoderma*. Plant–*Trichoderma*–pathogen is a complex community having multiple mechanisms. Seed bio-priming with *Trichoderma* strains isolated from tree bark, reduced the mean germination time, enhanced the seedling vigour and total chlorophyll content which could be related to the higher yield observed in rice varieties. This investigation demonstrates that *Trichoderma* strains obtained from tree bark could be considered to be utilized for the sustainable health management of rice crop. Recent methodologies based on molecular science can easily identify, clone, sequence, and express the activity of the genes and can observe their capacities and functions in the biocontrol system. Herein we present the utilization of *Trichoderma* strains collected from tree barks for rice plant growth, its health management and paddy straw degradation. The aforementioned variables are required to enhance their efficiency and applications and also demonstrate the possibilities for development of strains of *Trichoderma* spp.. *Trichoderma* isolated from tree bark is a novel strain for the preparation of rice straw compost and its value addition. The isolate produces high amount of straw degrading enzymes like cellulase, xylanase and laccase. There is 20% of weight reduction of rice straw during composting through *Trichoderma* within 30 days. The rice straw compost mediated by *Trichoderma* is rich in nutrients like N, P, K and promoted germination, seedling vigour and growth of rice plant. We also conclude that apart from growth promotion, enriched compost imparted intrinsic stress tolerance to rice by producing higher amount of defense enzymes like catalase, peroxidase and superoxide dismutase. In the present-day scenario, 60-70 million tonnes of rice straw burning in India is a huge economic loss in addition to the associated problems of air pollution. The *Trichoderma* mediated-straw manure could be promoted as one of the viable options to reduce straw burning. However, large scale field level evaluation is recommended to commercialise this product for the benefit of farmers.

**Keywords:** *Trichoderma*; vigor index; stress responsive enzyme; antioxidant genes; *Trichoderma* mediated rice straw compost; defense enzymes; biocontrol agent; rice straw management

---

## INTRODUCTION

The number of inhabitants on the planet is expanding quickly and it is normal that the total populace will be around 9.6 billion out of 2050. To accomplish food security for all, the development of food should be expanded to 70% by 2050. Yields ought to be safeguarded from biotic stresses to accomplish this objective. This ought to be finished in a more eco-accommodating and reasonable way, possibly by utilizing certain biocontrol agents (BCA).

Different BCA like bacteria, fungi, and viruses are being utilized habitually for the administration of illnesses in various yields (Abraham *et al.* 2013). Genus *Trichoderma* is convincing as a biocontrol operator against different pathogens (Swain *et al.* 2021, Shasmita *et al.* 2022). The essential normal territory of *Trichoderma* is generally viewed as soil or plant rhizosphere, despite the fact that most extreme variety of these species occurs over-the-ground (Druzhinina *et al.* 2011). With the growing threats to nature and to our food security, assurance of *Trichoderma* spp. as a BCA has been anticipating centrality in giving security for plant assurance and improvement (Swain and Mukherjee, 2020). *Trichoderma* spp. likewise actuates plant development by the production of different phytohormones and initiates plant supplements for better harvest. *Trichoderma* spp.

isn't just showcased as a biopesticide, biofertilizer, and development advertiser, yet in addition utilized as a supplement solubilizer and natural matter decomposer (Mukherjee *et al.* 2021). There are only several reports on the evaluation of *Trichoderma* as a biocontrol expert got from over the ground domains (Jahagirdar *et al.* 2019).

Practically 60% of fungal BCA market is shared by *Trichoderma* spp. (Whipps and Lumsden, 2001) however, there are critical difficulties to explore. The mode of action of *Trichoderma* spp. may be attributed to (a) Generation of trichodermin, trichothecenes, trichorzianins, or gliotoxins (Mukherjee *et al.* 2013); (b) Seeking sustenance and space (Celar, 2003); Antibiosis (Swain and Mukherjee, 2020, Shasmita *et al.* 2022); (d) Mycoparasitic capacities—a relationship in which one living fungus goes about as a supplement hotspot for another (Punja and Utkhede, 2003).

*Trichoderma* spp. produces auxins that are chargeable for plant blossom and root improvement in each harmonious and pathogenic correspondence with plants (Swain *et al.* 2022). An astonishing impact on plant improvement has been shown for a few *Trichoderma* optional metabolites. Koninginins 6-pentyl- $\alpha$ -pyrone, trichocaranes A-D, harzianopyridone, cyclonerodiol, harzianolide, and harzianic corrosive are cases of worsens that influence plant improvement in an extensively subordinate manner (Swain and Mukherjee, 2020). To comprehend the plant development advancement movement, rice seeds were bio primed with the *Trichoderma* strains. Bio priming will help in expansion in colonization, multiplication, and foundation of BCA on the seed surface. Subsequently, it can support seedling energy and will actuate foundational protection from biotic and abiotic stresses (Singh *et al.* 2020). Plant-microorganism communications arrangement by far off, unmistakable, and grouped microbial affiliations will generally affect different normal helpful foundational changes in the articulation level of plant qualities that encode for proteins to detoxify reactive oxygen species (Swain *et al.* 2018).

Faster decomposition of rice straw can be achieved by inoculating microorganisms, like ligno-cellulolytic microbes (Sarangi *et al.* 2021). *Trichoderma* produces high levels of several biomass degrading enzymes like cellulase and xylanase (Juturu and Wu, 2014). These enzymes degrade cellulose and

hemicellulose, respectively. Lignin was degraded by ligninolytic enzymes into simpler phenyl rings (Sancez, 2009). Compost vaccinated with *Trichoderma* spp., could complement the soil nutrients and increase yield (Islam *et al.* 2014; Sarangi *et al.* 2021). *Trichoderma* mixed compost improved the yield of chili fruit as compared to chemical fertilizer (Hock *et al.* 2014). Rice straw compost can increase crop yield by 4-9%, as the compost contains 1.7-2.1% of nitrogen, 1.5% of phosphorous, 1.4-1.6% of potassium, apart for being rich in available silicon (Marecik *et al.* 2018). Similar observations on rice straw compost on sustainable agriculture were reported by various authors (Islam *et al.* 2014; Siddiquee *et al.* 2017; Sarangi *et al.* 2021). Accordingly, *Trichoderma* spp. could be considered as a potential natural decomposing specialist that can create good quality of compost. Most of the *Trichoderma* spp. is isolated from soil or plant rhizosphere. It has been reported that the diversity of this genus is mostly on the above ground parts (Druzhinina *et al.* 2011; Swain *et al.* 2018; Mukherjee *et al.* 2021)

### **Capacity of *Trichoderma* strains for biological control and its mechanism**

Mycelial growth of *Rhizoctonia solani*, *Sclerotium oryzae*, *Sclerotium rolfsii*, and *Sclerotium delphinii* were inhibited by 98.33–100.00, 18.75–84.17, 14.17–66.67, and 56.67–76.25%, respectively as reported by Swain *et al.* (2021). *Trichoderma erinaceum* (CRRIT-2), *Trichoderma atroviride* (CRRIT-3), *Trichoderma hebeiensis* (CRRIT-15), *Trichoderma parareesei* (CRRIT-16) overgrew *R. solani* within 3 days. In case of *S. delphinii*, CRRIT-15, CRRIT-2 exhibited more than 70% inhibitory effect whereas all other strains were able to colonize in between 58 and 63% of the medium surface. *T. hebeiensis* (CRRIT15) and *T. erinaceum* (CRRIT-2) were superior antagonists against four rice pathogens. Biocontrol potential of these isolates can be correlated with prussic acid (HCN) production. The highest quantity of HCN was produced by CRRIT-15 (0.37  $\mu\text{g/mL}$ ) which was significantly higher as compared to other isolates. Many species of *Trichoderma* were accounted for as biocontrol specialists for a wide range of plant pathogens (Abdollahi *et al.* 2012; Kumar *et al.* 2012; Swain *et al.* 2018). Mycoparasitism is clearly one of the mechanisms for biocontrol action of *Trichoderma* (Mukherjee *et al.* 2013). Besides mycoparasitism, release of

prussic acid has been proposed as a significant antifungal component. Cyanide produced by microbes may act as an inhibitor to soil borne pathogens without any harm to the host plant (Noori and Saud, 2012). Hence, for the management of soil borne pathogens, the prussic acid produced by *Trichoderma* spp. played a vital role. Biocontrol potential of *Trichoderma* spp. mainly depends on the host plant, agro climatic conditions and nutrient availability (Mukherjee *et al.* 2013). *T. hebeiensis* and *T. parareesei* from the above ground part have been explored as potential biocontrol for the first time by Swain *et al.* (2021).

### ***Trichoderma as a decomposer***

Cellulase activity of fungal isolates with EI values of more than 1.5 were considered to be potential cellulase producers (Florencio *et al.* 2012; Saroj *et al.* 2018). *T. harzianum* CEN 139, *T. sp.* 104 NH and *T. harzianum* CEN 155 exhibited 1.74, 1.72, and 1.61 EI value for cellulase activity, respectively (Florencio *et al.* 2012). According to Swain *et al.* (2021) CRRIT-15 exhibited the highest xylanase activity, i.e., 1.68 EI value followed by *Trichoderma* strains CRRIT-27 and CRRIT-2. All the strains exhibited positive reddish-brown zones around the fungal colonies indicating laccase activity. Monssef *et al.* (2016) examined 24 fungal isolates for the production laccase enzyme and found only *T. harzianum* could produce the enzyme. These results confirmed that many of *Trichoderma* spp. with cellulase activity could also be a good source of laccase (Gochev and Krastanov, 2007). CRRIT-15 showed maximum endoglucanase activities, i.e., 0.75 IU/mL whereas CRRIT-22 isolate showed lowest endoglucanase activities (i.e., 0.53 IU/mL). Similarly, CRRIT-15 and CRRIT-3 showed maximum total cellulase activities, i.e., 2.59 and 2.13 IU/mL, respectively. Besides, CRRIT-15 released maximum xylanase activity of 201.35 nkat/mL followed by CRRIT-2 195.89 nkat/mL (Swain *et al.* 2021). Among four isolates, CRRIT-15 showed 12.60 IU/mL of laccase activity followed by CRRIT-3 9.85 IU/mL of activity (Sarangi *et al.* 2021). Earlier Druzhinina *et al.* (2011) reported that *T. reesei* is a major source of hydrolytic enzymes like cellulase and hemicellulase. *Trichoderma* sp. 104 NH, *T. harzianum* CEN 139, and *T. harzianum* CEN 155 exhibited 1.72, 1.74, and 1.61 EI value and 0.23, 0.27, and 0.22 IU/mL of endoglucanase activity, respectively (Florencio *et al.* 2012). Lee *et al.* (2011) reported *T. harzianum* isolated from post-

harvest rice straw possesses 0.095 IU/mL of endoglucanase activity and 0.222 IU/mL of total cellulase activity. Similarly, Pathak *et al.* (2014) reported *T. harzianum* isolated from soil, rotting wood, and manure from different locales of northern India possesses 1.28 IU/mL endoglucanase and 0.37 IU/mL of total cellulase activity. So, both the isolates NRRIT26 and NRRIT-27 seem to be a very good potential cellulase and xylanase producer and they may be used as a better option for the preparation of rice straw compost as compared to the previous reports. According to Pathak *et al.* (2014) 100.2 IU/mL of xylanase activity was observed in the case of *T. harzianum* collected from various location of northern India. NRRIT-26, i.e., *T. reesei* showed highest xylanase activity as compared to the other three isolates that can be considered as the best candidate for rice straw compost (Swain *et al.* 2021). Swain *et al.* 2021 reported the creation of laccase enzyme in all the *Trichoderma* isolates isolated from tree bark. *Trichoderma* are adapted well to rice straw and they could be utilized to degrade straw as reported by previous researchers (Kang *et al.* 2004). Overall, the isolate, CRRIT-15 released the highest number of enzymes as compared to other isolates. Hence, it may be used as a candidate for the preparation of rice straw compost in an economically way. The *Trichoderma* inoculated straw was decomposed at a faster rate as compared to the non-inoculated one. Among the seven *Trichoderma* strains, NRRIT-15, CRRIT-2, and NRRIT-27 could be able to produce compost from rice straw at a faster rate (Sarangi *et al.* 2021 and Swain *et al.* 2021). The loss of weight of the rice straw was 20.95, 18.27, and 18.57%, respectively, after 60 days when treated with NRRIT-15, CRRIT-2, and NRRIT27 (Swain *et al.* 2021). These enzymes decomposed the rice straw at a faster rate. Similarly, the C/N ratio did not vary between 30 and 60 days. So based on these data, Swain *et al.* (2021) concluded that the compost is generally stable after 30 days of incubation. As *Trichoderma* mediated rice straw compost has a low C/N ratio in *in vitro* condition, the technique can be extended to field conditions which will improve organic matter along with fertility of the soil.

### ***Trichoderma as a growth promoter for rice crop***

Auxins play a critical role for both the plant growth and root development. The quantity of IAA

synthesized by various *Trichoderma* strains in the broth ranged from 19.19 to 46.28 µg/mL (Swain *et al.* 2021). The highest IAA was produced by CRRIT15 (46.28 µg/mL) which was significantly higher followed by CRRIT2 (42.38 µg/mL). Quantitative assessment of soluble phosphate concentrations in Pikovskaya's broth varied from 297.49 to 435.42 µg/mL. CRRIT15 may be treated as the best inducer of phosphate mobilization as it exhibited higher phosphate solubilization capacity in Pikovskaya's broth. The amount of inorganic phosphate solubilized was 435.42 µg/mL. Parameters related to seed vigor and seed germination of different *Trichoderma* dressed seeds varied from 2.13–4.13 days (Mean germination time), 2166.67–3413.33 (Vigor index-I) and 11.00–18.33 (Vigor index-II), respectively in variety Satabdi (Swain *et al.* 2021). A similar trend was also found in the case of the Annapurna rice variety (Swain *et al.* 2018). Physiological parameters among the treatments significantly varied in both the varieties. Absolute chlorophyll content went from 4.61 to 18.78 mg/g in the Annapurna rice variety. Seed biopriming with beneficial microbes have been reported by several workers for their ability to mitigate biotic stress in an efficient way (Singh *et al.* 2020). During biopriming, antagonistic PGPR increases on the seed surface, thereby defending the plant from pathogen attack and enabling it to be sustained under various stress conditions (Rajput *et al.* 2019). In the field study, all the strains of *Trichoderma* controlled the plant growth along with various agronomical parameters (Mukherjee *et al.* 2014). The highest yield (31.14g/hill) was recorded from CRRIT-15 followed by CRRIT-16 and CRRIT-13 (Swain *et al.* 2021). Similar trends were observed in case of the Satabdi rice variety. Mukherjee *et al.* (2021) reported higher total chlorophyll content, plant vigor in direct seeded rice treated with *Trichoderma*. Previously Mukherjee *et al.* (2013 & 2018) explained the role of *Trichoderma* as a plant growth promoter. The enhancement of seed vigor parameters may be due to the production of phenolic compounds and secondary metabolite namely harzianolide by *Trichoderma* spp. (Cai *et al.* 2013). This result was also found in case of chickpea and wheat (Zhang *et al.* 2019). All these positive impacts of vigor property helped the plant in uptake and mobilization of nutrients for a longer time, which leads to a better yield (Sarangi *et al.* 2021). Among the secondary metabolites, IAA (auxin) helps in plant growth and

potentially increases the root length as well. Laboratory studies have emphasized the role of plant growth promoting fungi as auxin producers and biocontrol operators (Hossain *et al.* 2007; Contreras-Cornejo *et al.* 2009) in plant development. This key hormone was synthesized by the fungus *Trichoderma* in symbiotic as well as in pathogenic interactions (Gravel *et al.* 2007). Similarly, plants can only uptake and mobilize essential micronutrients if they are solubilized by microbes (Rudresh *et al.* 2005). *Trichoderma* spp. can deliver phosphate from mineral crude materials as plant accessible structures (Dunaitsev *et al.* 2008). It was observed that *Trichoderma* isolates demonstrated higher capacity to solubilize the phosphate as they additionally displayed great reactions to plant growth promotion action after direct seed treatments (Swain *et al.* 2022). *Trichoderma* as plant symbionts for updated supplement take-up, extended root and shoot advancement, improved plant influence and biotic/abiotic stress flexibility have been widely discussed (Harman, 2011).

#### **Improvement of plant resistance by the enunciation of stress responsive enzymes**

Inside and out higher verbalization of the enzymes related to stress was seen in *Trichoderma* seed treated plants when appeared differently in relation to untreated plants against the rice assortments (Mukherjee *et al.* 2018; Shasmita *et al.* 2019, Mukherjee *et al.* 2021, Swain *et al.* 2021, Shasmita *et al.* 2021; 2022). CRRIT-15, and CRRIT-2 treated root and shoots of rice assortment Annapurna and Satabdi had exceptionally higher PER, SOD, PPO, and TP activity contrasted with other treatment (Swain *et al.* 2021). Also, catalase action was higher in CRRIT15 and CRRIT-2 treatment in both root and shoot. In blend with their immediate impact on the pathogen structure and action, *Trichoderma* spp. has additionally been found to invigorate plant resistance mechanisms (Yedidia *et al.* 2001). Successful *Trichoderma* strains can instigate a more grounded reaction in the plant contrasted with pathogen-triggered immunity by creating an assortment of microorganisms related molecular patterns (MAMPs), for example, hydrophobins, expansin-like proteins, metabolites, and catalysts like catalase, peroxidase, and superoxide dismutase, having direct antimicrobial activity (Vargas *et al.* 2008). *Trichoderma* can likewise improve ETI by causing a quicker reaction

(preparing), or initiate it by discharging exacerbates that, similarly as with some pathogen molecules, are explicitly perceived by plant cell receptors (Bailey *et al.* 1993). In the present exploration, the stress enzymes expressed in a higher amount in *Trichoderma* treatments rather than the control group. Mohapatra and Mittra (2017) and Swain *et al.* (2018) documented that *Trichoderma* spp. triggered the fabrication of antioxidant enzymes in wheat and rice seedlings, respectively. *Trichoderma* isolates were accounted to help fundamental defense reactions through different catalysts (Ma<sup>3</sup>olepsza *et al.* 2017). PPO is engaged with the plant guard system against pathogens by catalyzing the oxidation of phenols to quinines in an oxygensubordinate way (Daw *et al.* 2008). An increase in defense enzymes activity (Mandal *et al.* 2013) and TP content (Mandal *et al.* 2013) in plants with a reaction to pathogen assault has also been previously reported.

#### **Seed biopriming with *Trichoderma* actuates antioxidant gene expression in rice plants**

Plants have created solid cell antioxidant molecular systems because of the utilization of biocontrol specialists like *Trichoderma* (Rejeb *et al.* 2014; Swain *et al.* 2018 and Mukherjee *et al.* 2021), however the initiation and articulation of these genes change under plant organism communication conditions (Singh *et al.* 2020). Albeit, both organism-treated and non-treated plants were developed under typical development conditions. Swain *et al.* (2021) investigated the plant molecular reactions as far as the outflow of prominent defense (PAL and DEFENSIN) and antioxidant (POX, LOX, and PR-3) genes following microbial inoculation. They observed multifold over expression of genes in both the strains. However, *Trichoderma* seed biopriming caused >2-fold up regulation of every gene in both the rice varieties. Besides, CRRIT-15 exhibited the highest level of fold expression (i.e., >3) of all the genes as compared to control one. CRRIT-16 and CRRIT-2 treatment performed the second highest level of fold expression (i.e., >2.5) by following CRRIT-15. Seed biopriming with beneficial microbes have been accounted for their capacity to relieve biotic stress in an effective way. During the process of seed biopriming, antagonistic plant growth promotive activity increases on the seed surface, hence not only defending the plant from pathogen attack but also promoting the plant growth (Mukherjee *et al.* 2018 and Swain *et al.* 2018). Co-vaccination of *Paenibacillus polymyxa*

and *Rhizobium tropici* mitigated drought in common bean (*Phaseolus vulgaris* L.) (Figueiredo *et al.* 2008). Swain *et al.* 2021 explained that *Trichoderma* treated plants exhibited an increase in total phenol content, catalase content, peroxidase content, superoxide dismutase content and expression of defense gene (POX, LOX, PAL, DEFENSIN, and PR-3) as compared to control one. This further authenticates the induction of growth responses and defense response in rice up on application of *Trichoderma* in rice seeds. Plant phenolics are normally framed in light of both biotic and abiotic stress through enactment of phenyl propanoid pathway and include in cellulase, lignin, xylanase, and biosynthesis (Swain *et al.* 2022). Thus, PPO catalyzes phenolics, exacerbating the production of quinines through a secondary reaction, which further prompts the arrangement of an earthy colored complex polymer, melanin; a physical hindrance to microbe ingress (Taranto *et al.* 2017). As per the report of Swain *et al.* 2021 the *Trichoderma* strains exhibited higher total phenol content, PPO activity as compared to the control one. Besides, CRRIT-15, CRIT-16, and CRRIT-2 out-performed the others. This suggests a synergistic effect of *Trichoderma* in induction of plant growth and defense in rice varieties. Notwithstanding these, acceptance of different development promotive genes and antioxidant agent responsive genes mitigates oxidative stress in plant cells. Our outcomes are validated with Singh *et al.* (2013) in which they revealed improved movement of PAL, PPO, PO, and SOD content in chickpea treated with *Pseudomonas*, *Trichoderma*, and *Rhizobium*. Contrasting these discoveries and our outcomes prompts the presumption that stronghold of rice with microbial inoculants characteristically balanced molecular components to give resilience against ROS scavenging in a manner to making plants fortified against stress difficulties. Rice seed biopriming of *Trichoderma* could, accordingly, become a proficient methodology for raising yield for better profitability and resistance against stress conditions (Sarangi *et al.* 2021).

#### **CONCLUSION**

With the expanding risks to nature and to our food security, selection of *Trichoderma* spp. as a biological control agent (BCA) has been assuming significance in providing security for plant protection and growth. To achieve this, unexplored

parts of the world should be investigated to locate appropriate and efficient *Trichoderma* strains to function extraordinarily as biocontrol agents. Different species of *Trichoderma* are engaged in biocontrol action, and their mechanisms of activity are outstanding in their qualities, as has been seen and reported. Most of the *Trichoderma* strains defined in literature were isolated from the soil or rhizosphere, but very few are isolated from the above ground aerial parts. The rice seed treatment with *Trichoderma* strains not only promoted germination, seedling vigor, and growth of the plant, but also increase the level of gene expression related to plant defense. Apart from growth promotion these strains imparted intrinsic stress tolerance to rice by producing a higher amount of defense enzymes like catalase, peroxidase, superoxide dismutase, polyphenol oxidase, and total phenolics content as evidenced by the expression of their respective genes. So many investigations try to fill the gap by isolating and identifying above ground *Trichoderma* strains for rice health management. Two strains, namely *T. hebeiensis* and *T. erinaceum* may be promoted in sustainable crop management for their beneficial role. The genes isolated from these biocontrol specialists have been found to assume a basic function in biocontrol actions, with the assistance of genetic engineering procedures to progressively enumerate more valuable genes that should be found to enhance farming for ourselves and the future. Epic discoveries will then show the advances and reception of *Trichoderma* as a BCA to help in the improvement of our harvests and in overcoming infestations.

## REFERENCES

- Abdollahi, M., Rahnama, K., Marabadi, M., Ommati, F., Zaker, M. 2012. The *in vitro* efficacy of *Trichoderma* isolates against *Pythium aphanidermatum*, the causal agent of sugar beet root rot. *J. Res. Agri. Sc.* **8**: 79–87.
- Abraham, A., Philip, S., Jacob, C.K., Jayachandran, K. 2013. Novel bacterial endophytes from *Hevea brasiliensis* as biocontrol agent against *Phytophthora* leaf fall disease. *Biocontrol* **58**: 675–684.
- Cai, F., Yu, G., Wang, P., Wei, Z., Fu, L., Shen, Q., Chen, W. 2013. Harzianolide, a novel plant growth regulator and systemic resistance elicitor from *Trichoderma harzianum*. *Plant Physiology and Biochemistry* **73**: 106–113.
- Celar, F. 2003. Competition for ammonium and nitrate forms of nitrogen between some phytopathogenic and antagonistic soil fungi. *Biological Control* **28**: 19–24.
- Contreras-Cornejo, H.A., Macias-Rodríguez, L., Cortés-Penagos, C., López-Bucio, J. 2009. *Trichoderma virens*, a plant beneficial fungus, enhances biomass production and promotes lateral root growth through an auxin-dependent mechanism in *Arabidopsis*. *Plant Physiol.* **149**: 1579–1592.
- Daw, B.D., Zhang, L.H., Wang, Z.Z. 2008. Salicylic acid enhances antifungal resistance to *Magnaporthe grisea* in rice plants. *Aust. Plant Pathol.* **37**: 637–644.
- Druzhinina, I.S., Seidl-Seiboth, V., Herrera-Estrella, A., Horwitz, B.A., Kenerley, C.M., Monte, E., Mukherjee, P.K., Zeilinger, S., Grigoriev, I.V., Kubicek, C. P. 2011. *Trichoderma*: the genomics of opportunistic success. *Nature Reviews Microbiology* **9**: 749–759.
- Dunaitsev, I.A., Kolombet, L.V., Zhigletsova, S. K., Bystrova, E.V., Besaeva, S.G., Klykova, M.V., Kondrashenko, T.N. 2008. Phosphate releasing microorganisms with antagonistic activity against phytopathogenic microorganisms. *Mikologiyai Fitopatol.* **42**: 264–269.
- Figueiredo, M.V.B., Buritya, H.A., Martínez, C.R. and Chanway, C.P. (2008). Alleviation of drought stress in the common bean (*Phaseolus vulgaris* L.) by co-inoculation with *Paenibacillus polymyxa* and *Rhizobium tropici*. *Applied Soil Ecol.* **40**: 182–188. <https://doi.org/10.1016/j.apsoil.2008.04.005>.
- Florencio, C., Couri, S., Farinas, C.S. 2012. Correlation between agar plate screening and solid state fermentation for the prediction of cellulase production by *Trichoderma* strains. *Enzyme Res.* doi:10.1155/2012/793708.
- Gochev, V.K., Krastanov, A.I. 2007. Isolation of Laccase producing *Trichoderma* Species. *Bulgarian J. Ag. Sc.* **13**: 171-176.
- Gravel, V., Antoun, H., Tweddell, R.J. 2007. Growth stimulation and fruit yield improvement of greenhouse tomato plants by inoculation with *Pseudomonas putida* or *Trichoderma atroviride*: possible role of indole acetic acid (IAA). *Soil Biol. Biochem.* **39**: 1968–1977.
- Harman, G.E. 2011. Multifunctional fungal plant symbionts: new tools to enhance plant growth and productivity. *New Phytologist* **189**, 647–649.
- Hock, O., Subramaniam, G., Abdullah, F.B. 2014. Effect of *Trichoderma*-infused compost on yield of chili plants. Presented at International Conference on Advances in Environment, Agriculture & Medical Sciences (ICAEM'14), 16–17 November 2014. Lumpur, Kuala
- Hossain, M., Sultana, F., Kubota, M., Koyama, H., Hyakumachi, M. 2007. The plant growth-promoting fungus *Penicillium simplicissimum* GP17-2 induces resistance in *Arabidopsis thaliana* by activation of multiple defense signals. *Plant Cell Physiol.* **48**: 1724–1736.
- Islam, M.A., Mostafa, M.G., Rahman, M.R. 2014. Conversion of solid organic waste into compost using *Trichoderma* spp. and its application on some selected vegetables. *Int. J Environ Waste Manag* **14**:211–221.
- Jahagirdar, S., Kambrekar, D.N., Navi, S.S. and Kunta, M. 2019. Plant Growth-Promoting Fungi: Diversity and Classification. In: Jogaiah S., Abdelrahman M. (eds) *Bioactive Molecules in Plant Defense*. Springer, Cham. [https://doi.org/10.1007/978-3-030-27165-7\\_2](https://doi.org/10.1007/978-3-030-27165-7_2).
- Juturu, V., Wu, J.C. 2014. Microbial cellulases: engineering production and applications. *Renew. Sustainable Energy Review* **33**:188-203.
- Kang, S.W., Park, Y.S., Lee, J.S., Hong, S.I., Kim, S.W. 2004. Production of cellulases and hemicellulases by *Aspergillus niger* KK2 from lignocellulosic biomass. *Bioresource Technol.* **91**: 153-156.
- Kumar, K., Amaresan, N., Bhagat, S., Madhuri, K., Srivastava R. C. 2012. Isolation and Characterization of *Trichoderma* spp. for Antagonistic Activity against Root Rot and Foliar Pathogens. *Ind. J. Microbiol.* **52**: 137–144.
- Lee, S., Jang, Y., Lee, Y.M., Lee, J., Lee, H., Kim, G.H., Kim, J.J. 2011. Rice straw-decomposing fungi and their cellulolytic and Xylanolytic enzymes. *J. Microbiol. Biotech.* **21**: 1322-1329.
- Ma<sup>3</sup>olepsza, U., Nawrocka, J., Szczech, M. 2017. *Trichoderma virens* 106 inoculation stimulates defense enzyme activities and enhances phenolics levels in tomato plants leading to

- lowered *Rhizoctonia solani* infection. *Biocontrol Sc. Tech.* **27**: 180-199.
- Mandal, S., Kar, I., Mukherjee, A.K., Acharya, P. 2013. Elicitor-induced defense responses in *Solanum lycopersicum* against *Ralstonia solanacearum*, *Sc. World J.* <https://doi.org/10.1155/2013/561056>
- Marecik, R., Blaszczyk, L., Marecik, R.B., Cyplik, A.P. 2018. Screening and identification of *Trichoderma* strains isolated from natural habitats with potential to cellulose and xylan degrading enzyme production. *Pol J Microbiol* **67**:181–190.
- Mohapatra, S., Mittra, B. 2017. Alleviation of *Fusarium oxysporum* induced oxidative stress in wheat by *Trichoderma viride*. *Archives of Phytopathology and Plant Protection* **50**: 84-96.
- Monsef, Rehan. Abd. A. Hassan., Enas, A., Ramadan, M.E. 2016. Production of Laccase enzyme for their potential application to decolorize fungal pigments on aging and paper parchment. *Ann. Agricult. Sci.* **61**: 145-154.
- Mukherjee, A.K., Sampath, Kumar A., Kranthi, S., Mukherjee, P.K. 2014. Biocontrol potential of three novel *Trichoderma* strains: isolation, evaluation and formulation. *3 Biotech* **4**: 275–281.
- Mukherjee, A.K., Swain, H., Adak, T., Chattopadhyaya, K. 2018. Evaluation of *Trichoderma* based product 'RiceVit' in farmers field of Chandol, Kendrapada, Odisha. *NRRI NEWSLETTER*, **39**: 20-21.
- Mukherjee, A.K., Adak, T., Swain, H., Behera, S., Dangar, T.K., Dhua, U., Jena, M., Bagchi, T.B., Bhattacharyya, P., Kumar A. 2021. A multi-use composition for biocontrol of plant pathogen infestation and growth enhancement. Patent No- 383679
- Mukherjee, P.K., Horwitz, Benjamin A., Singh, Uma Shankar, Mukherjee, M., Schmoll, M. 2013. *Trichoderma*: Biology and Applications, CAB International, UK ([www.cabi.org](http://www.cabi.org)).
- Noori, M.S.S., Saud, H.M. 2012. Potential plant growth-promoting activity of *Pseudomonas* spp. isolated from paddy soil in Malaysia as biocontrol agent. *J. Plant Pathol. Microbiol.* **3**: 10.4172/2157-7471.1000120.
- Pathak, P., Bharadwaj, N., Singh, A.K. 2014. Production of crude cellulase and xylanase from *Trichoderma harzianum* PPDDN10NFCCI-2925 and its application in photocopier waste paper recycling. *Appl. Biochem. Biotech.* **172**: 3776-3797.
- Punja, Z.K., Utkhede, R.S. 2003. Using fungi and yeasts to manage vegetable crop diseases. *Trends in Biotech.* **21**:400–407.
- Rajput, R.S., Singh, P., Singh, J., Vaishnav, A., Ray, S., Singh, H.B. 2019a. *Trichoderma* mediated seed biopriming augments antioxidant and phenylpropanoid activities in tomato plant against *Sclerotium rolfsii*. *J. Pharmacogn. Phytochem.* **8** : 2641–2647.
- Rejeb, I.B., Pastor, V., Mauch-Mani, B. 2014. Plant responses to simultaneous biotic and abiotic stress: molecular mechanisms. *Plants (Basel)* **3**: 458–475. <https://doi.org/10.3390/plants3040458>
- Rudresh, D.L., Shivaprakash, M.K., Prasad, R.D. 2005. 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.* **51**: 217–222.
- Sancez, C. 2009. Lignocellulosic residues: Biodegradation and bioconversion by fungi. *Biotech. Advance* **27**: 185-194.
- Sarang, S., Swain, H., Adak, T. et al. 2021. *Trichoderma*-mediated rice straw compost promotes plant growth and imparts stress tolerance. *Environ. Sci. Pollut. Res.* **28**: 44014–44027. <https://doi.org/10.1007/s11356-021-13701-3>.
- Saroj, P., Manasa, P., Narasimhulu, K. 2018. Characterization of thermophilic fungi producing extracellular lignocellulolytic enzymes for lignocellulosic hydrolysis under solid state fermentation. *Bioresource and Bioprocess* **31**: <https://doi.org/10.1186/s40643-018-0216-6>.
- Shasmita, Swain HK, Naik, S.K., Mukherjee, A.K. 2019. Comparative analysis of different biotic and abiotic agents for growth promotion in rice (*Oryza sativa* L.) and their effect on induction of resistance against *Rhizoctonia solani*: A soil borne pathogen. *Biological Control.* **133**:123-133. DOI:10.1016/j.biocontrol.2019.02.013
- Shasmita, Samal, P., Naik, S., Mahapatra, P.K., Mukherjee, A.K. 2021. Improved Photosystem II and Defense Enzymes activity in Rice (*Oryza sativa* L.) by Biopriming against *Xanthomonas oryzae* pv. *oryzae*. *Function. Plant Biol.* **48**:298-311 <https://doi.org/10.1071/FP20221>
- Shasmita, Swain, B.B., Mohapatra, P.K., Naik, S.K., Mukherjee, A.K. 2022. Biopriming for induction of disease resistance against pathogens in rice. *Planta* **255**:113. <https://doi.org/10.1007/s00425-022-03900-8>
- Siddiquee S, Shafawati SN, Naher L 2017. Effective composting of empty fruit bunches using potential *Trichoderma* strains. *Biotech. Rep.* **13**:1–7.
- Singh, D.P., Singh, V., Shukla, R., Sahu, P., Prabha, R., Gupta, A., Sarma, B.K., Gupta, V.K. 2020. Stage-dependent concomitant microbial fortification improves soil nutrient status, plant growth, antioxidative defense system and gene expression in rice. *Microbiol. Res.* **239**: 126538.
- Singh, P., Singh, J., Ray, S., Rajput, R.S., Vaishnav, A., Singh, R.K., Singh, H.B. 2020. Seed biopriming with antagonistic microbes and ascorbic acid induce resistance in tomato against *Fusarium* wilt. *Microbiol. Res.* **237**: 126482.
- Swain, H., Adak, T., Mukherjee, A.K., Mukherjee, P.K., Bhattacharyya, P., Behera, S., Bagchi, T.B., Patro, R., Shasmita, Khandual, A., Bag, M.K., Dangar, T.K., Lenka, S., Jena, M. 2018. Novel *Trichoderma* strains. isolated from tree barks as potential biocontrol agents and biofertilizers for direct seeded rice. *Microbiol. Res.* **214**: 83-90.
- Swain, H., Mukherjee, A. K. 2020. Host–Pathogen–*Trichoderma* Interaction. In: "*Trichoderma*" Springer, Singapore, PP-149-165. [https://link.springer.com/chapter/10.1007/978-981-15-3321-1\\_8](https://link.springer.com/chapter/10.1007/978-981-15-3321-1_8).
- Swain, H., Adak, T., Mukherjee, A.K., Sarangi, S., Samal, P., Khandual, A., Jena, R., Bhattacharyya, P., Naik, S.K., Mehetre, S.T., Baite, M.S., Kumar, M.S., Zaidi, N.W. 2021. Seed Biopriming With *Trichoderma* Strains Isolated From Tree Bark Improves Plant Growth, Antioxidative Defense System in Rice and Enhance Straw Degradation Capacity. *Front. Microbiol.* **12**:633881. doi: 10.3389/fmicb.2021.633881.
- Swain, H., Naik, S.K., Mukherjee, A.K. 2022. Utilization of Arbuscular Mycorrhizal Fungi to Boom the Efficiency and Product Nature of Horticultural Crops. In: Nayak, S.K., Baliyarsingh, B., Singh, A., Mannazzu, I., Mishra, B.B. (eds) *Advances in Agricultural and Industrial Microbiology*. Springer, Singapore. [https://doi.org/10.1007/978-981-16-9682-4\\_7](https://doi.org/10.1007/978-981-16-9682-4_7)
- Taranto, F., Pasqualone, A., Mangini, G., Tripodi, P., Miazzi, M., Pavan, S., Montemurro, C. 2017. Polyphenol oxidases in crops: biochemical, physiological and genetic aspects. *Int. J. Mol. Sc.* **18**: 377.
- Vargas, W.A., Djonovic, S., Sukno, S.A., Kenerley, C.M. 2008. Dimerization controls the activity of fungal elicitors that trigger systemic resistance in plants. *J. Biochem. Chem.* **283**:19804–19815.
- Yedidia, I., Srivastva, A.K., Kapulnik, Y., Chet, I. 2001. Effect of *Trichoderma harzianum* on microelement concentrations and increased growth of cucumber plants. *Plant and Soil* **235**: 235–242.
- Zhang, S., Xu, B., Gan, Y. 2019. Seed treatment with *Trichoderma longibrachiatum* T<sub>6</sub> Promotes Wheat Seedling Growth under NaCl Stress through activating the Enzymatic and Non-enzymatic antioxidant defense system. *Int. J. Mol. Sc.* **20**: 3729. DOI:10.3390/ijms20153729.