Agricultural Reviews, 39(1) 2018 : 48-54
Print ISSN:0253-1496 / Online ISSN:0976-0539

AGRICULTURAL RESEARCH COMMUNICATION CENTRE
www.arccjournals.com

Trichoderma as an efficacious bioagent for combating biotic and abiotic stresses of wheat-A review

O.P. Gangwar* and Akanksha P.K. Singh[1]

ICAR-Indian Institute of Wheat and Barley Research,
Regional Station, Flowerdale, Shimla-171 002, Himachal Pradesh, India.

Received: 07-11-2017 Accepted: 16-01-2018 DOI: 10.18805/ag.R-1770

ABSTRACT

Several environmental stresses are the major hindrances in achieving the attainable yield in wheat crop. The actual losses due to biotic stresses is estimated in the range of 26-29%, however, abiotic stresses have more adverse effects on crop yield and are responsible for about 70% of yield reduction worldwide. Agrochemicals are widely considered as an effective management strategy for wheat crop diseases and insect pests but they adversely affect the human and animal health due to accumulation of chemical residues in the soil, plant tissues and grains. Hence, there is a need for alternate management strategies to protect crop plants against various stresses. Species of the genus *Trichoderma* are economically important as biocontrol agents, serving as a potential alternative to agrochemicals for overcoming the biotic and abiotic stresses. The importance of *Trichoderma* in alleviating the myriad of biotic and abiotic stresses of wheat is discussed in this review article.

Key words: Bioagent, Biotic stress, Disease, *Trichoderma*, Wheat.

Importance of wheat (*Triticum aestivum* L.) as staple food is well known as nearly 35% of the world population depends on wheat and demand for wheat is expected to grow faster than for any other major crop (Pingali, 1999). Over the next four decades, the world's population is forecast to increase by 2 billion people to exceed 9 billion people by 2050. It has to be achieved with less land and resources through genetic, physiological and agronomic interventions, precision breeding for improving varietal elasticity, new initiatives for climate change monitoring and crop modelling for advance yield forecasts (Sharma *et al.*, 2015). The current major challenges facing future wheat production in India are increasing heat stress, dwindling water supplies for irrigation, a growing threat of new virulence of diseases such as wheat rusts and leaf blight (Joshi *et al.*, 2007). Modern farming practices, with their reliance on agrochemical pest and disease control, are responsible for considerable pollution and can have harmful effects on human health (Haggag *et al.*, 2015). In this scenario, application of antagonistic micro-organisms for diseases and pests management can be considered as a viable alternative method. Among the fungal antagonists, *Trichoderma* species are known since the early 1930s as potential biological agents for managing a myriad soil and airborne diseases, enhancing the plant growth and combating with different biotic and abiotic stresses. Fungi of the genus *Trichoderma* are soilborne, green-spored ascomycetes that can be found all over the world. The teleomorphic (sexual) stage is known by the generic name *Hypocrea*, whereas the anamorphic or mitosporic (asexual) stage is called *Trichoderma*. Up to now, more than 1100 *Hypocrea / Trichoderma* strains have been identified from 75 molecularly defined species and all the species tested to possess mycoparasitic potential against *Alternaria alternata, Botrytis cinerea* and *Sclerotinia sclerotiorum* (Druzhinina *et al.*, 2011). Recently, four new species, *Trichoderma asterineum, T. henanense, T. odoratum and T. pseudobritdaniae,* were discovered and described (Qin and Zhuang, 2016). The genome sequencing of *Trichoderma* species has stimulated the development of systems biological approaches, initiated and enhanced whole-genome expression studies and provided unique data for phylogenetic and bioinformatic analyses toward understanding the roles of these opportunists in ecosystems (Mukherjee *et al.*, 2013). *Trichoderma reesei* (*Hypocrea jecorina*) is the first member of the genus whose genome sequenced completely and comprising 9,129 predicted gene models (Martinez *et al.*, 2008). Till date, the genome of seven *Trichoderma* spp. (*T. reesei*, *T. atroviride*, *T. virens*, *T. harzianum*, *T. asperellum*, *T. citrinoviride* and *T. longibrachiatum*) have been sequenced completely. The genomes of *T. atroviride* (teleomorph *Hypocrea atroviridis*) and *T. virens* (formerly *Gliocladium virens*, teleomorph *Hypocrea virens*), were sequenced using a whole genome shotgun approach to approximately eight-fold coverage and further improved using finishing reactions and gap closing. Their genome sizes were 36.1 (*Ta*) and 38.8

*Corresponding author's e-mail: gangwarop@gmail.com
[1]Department of Genetics and Plant Breeding, Narendra Deva University of Agriculture and Technology, Kumarganj, Faizabad-224 229, U.P, India.

Mbp (*Tv*), and thus larger than the 34 Mbp determined for the genome of *Trichoderma reesei* (teleomorph *Hypocrea jecorina*) (Kubicek *et al.*, 2011). Recently, the whole genome of *Trichoderma gamsii* T6085 and *Trichoderma harzianum* B97 have been sequenced (Baroncelli *et al.*, 2016; Compant *et al.*, 2017). The use of *Trichoderma* to combat with environmental stresses that are playing major role in decreasing wheat crop productivity, is the topic of discussion of present review article.

Effect of *Trichoderma* on alleviating biotic stresses of wheat crop: The biotic stresses are most serious constraints to wheat production in India and would continue to be a major challenge in achieving the goal sustainable food security. For instance, the recent outbreak of wheat blast in Bangladesh poses a real threat to wheat crop in India. Wheat blast is caused by the fungus *Magnaporthe oryzae* and first reported in 1985 from Brazil's Parana state. The fungus strikes the heads of wheat, which are difficult for fungicides to reach (Callaway, 2016). Although, common wheat may be attacked by a large number of diseases and pests, less than 20 diseases and about five insect or mite pests are of major significance. Some of these have a global distribution and occur in most wheat growing areas, whereas others are restricted to certain geographic regions or climatic zones (McIntosh, 1998). Among the diseases and pests of wheat that have potential to reduce grain yield, wheat rusts, powdery mildew, spot blotch, cereal cyst nematode, aphids have been remained economically important and challenging despite the widespread use of host resistance and pesticides. Since, biotic stresses have major effects on agricultural production and achieving the goal of food security, sustainable strategies for disease management are necessary in order to minimize the use of pesticides in agriculture. In this regard, biological control using natural enemies like *Trichoderma* has been accepted as an eco-friendly, technically appropriate, economically viable and socially acceptable method of pest management (Routray *et al*., 2016). Biological controls lean to be highly specific and have different mode of action which includes, parasitism, predator, antibiosis, competition for site and nutrition, as well as by inducing the resistant in plants against pathogen, including induced systemic resistance (Kamal *et al.,* 2015). *Trichoderma* strains combat with biotic stresses (phytopathogens, nematode or insects) mainly by mycoparasitism or by competing for nutrients and space (rhizosphere competence), promoting plant growth and plant defensive mechanisms and production of antibiotics and enzymes (Fig. 1). Earlier, it was considered that antibiosis and mycoparasitism were the primary mechanisms of biocontrol, but now a phenomenon/mechanism known as induced systemic resistance has been discovered and considered to be more important. Weindling (1932) first showed that *Trichoderma* species have biocontrol potential

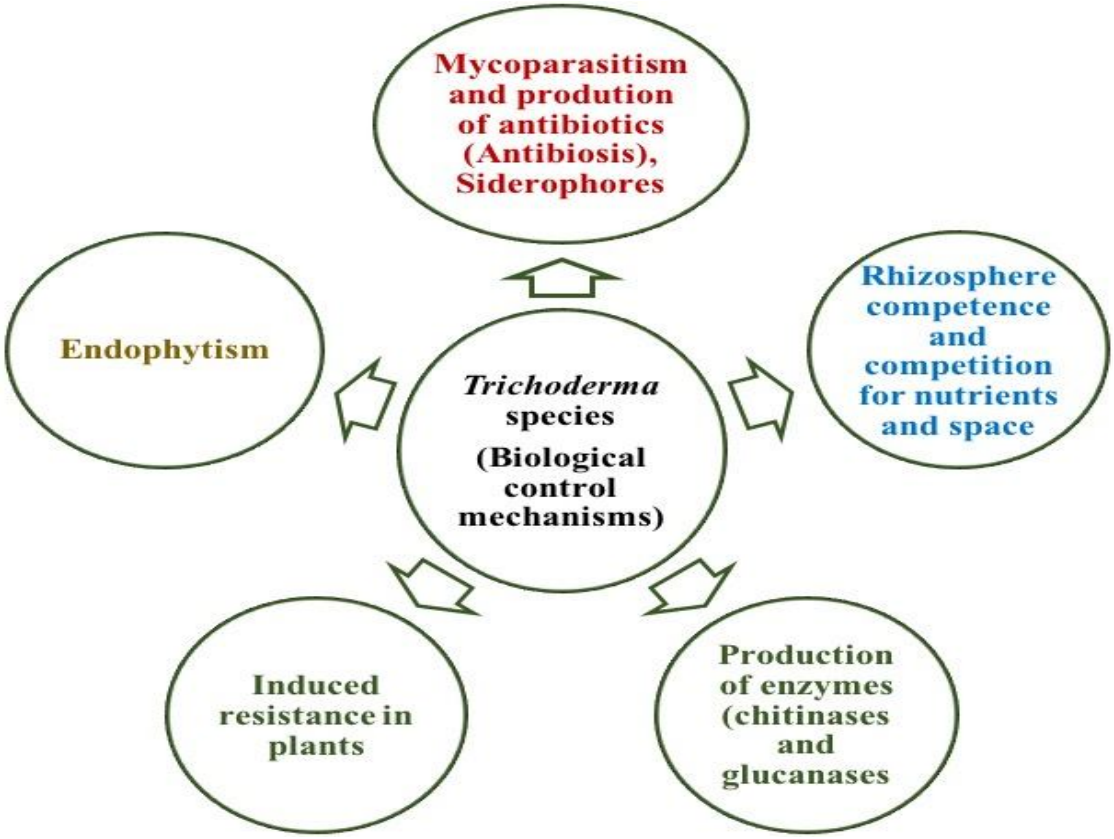


Fig 1: Different mechanisms employed by *Trichoderma* species to overcome the biotic stresses

by virtue of possessing mycoparasitic properties. The first mycoparasitism related gene (Prb1) was cloned from *T. harzianum*, gene encoded product was purified and biochemically characterized as a serine proteinase, a hydrolytic enzyme (Geremia *et al.*, 1993). These fungi produce a number of secondary metabolites involved in various activities including the recently determined role in the activation of plant resistance to biotic stresses and growth promotion. In the rhizosphere, the exchange and recognition of signaling molecules by *Trichoderma* and plants may alter physiological and biochemical aspects in both.

For example, several *Trichoderma* strains induce root branching and increase shoot biomass as a consequence of cell division, expansion and differentiation by the presence of fungal auxin-like compounds. Furthermore, *Trichoderma*, in association with plant roots, can trigger systemic resistance and improve plant nutrient uptake (Contreras-Cornejo *et al.*, 2016). Growth promoting ability of *Trichoderma harzianum* (Th3) was demonstrated in wheat cultivar Raj 3765 at farmer's field in Jaipur and Kota district of Rajasthan. Its application enhances rootlets, tillers, grains weight and grain yield significantly (Sharma *et al.*, 2012). Currently more than 60% of all registered biopesticides are *Trichoderma*-based because of the capability of these fungi to invade and destroy other fungi or nematode (Verma *et al.*, 2007).

The rust diseases are among the most important of wheat diseases because of its widespread prevalence and airborne nature of pathogens. The bio-efficacy of *T. harzianum* was tested against *Puccinia triticina* (leaf rust) on two susceptible genotypes Morocco and Sids-1 of wheat under greenhouse and open field conditions. It was shown that spraying the plants of both the genotypes with the tested bioagent decreased leaf rust severity, increased spike weight, grains weight/spike and 1000 kernel weight significantly, compared with control and also elevate the resistance of susceptible genotypes (El-Sharkawy *et al.*, 2015).

Fusarium head blight (FHB) or Scab is another one of the most important diseases of wheat, caused by *F. graminearum* especially in humid growing areas of North America, China, central and Eastern Europe and South America. The most serious consequence of FHB is the contamination of wheat grain and its products with mycotoxins like deoxynivalenol (DON), endangering the animal and human health. *Trichoderma gamsii* T6085 is a promising beneficial isolate whose effects consist of growth inhibition of the main agents causing *Fusarium* head blight, reduction of mycotoxin accumulation, competition for wheat debris, and reduction of the disease in both the lab and the field (Baroncelli *et al.*, 2016). In field trials, *Trichoderma* stain TrichC70 was found effective in increasing the seedling emergence by 10.9%, dry weight by 51.7%, yield by 11.0% and reducing root rot severity by 51.7%. These effects were at par that of the registered fungicide Vitaflo-280 used as the positive control in the field trials. The results indicate that *Trichoderma* stain TrichC70 may be used as an alternative to fungicide seed treatments to alleviate the detrimental effect of the seed-borne phase of FHB in wheat (Xue *et al.*, 2017). However, Yadav *et al.* (2015) showed that application of *Trichoderma harzianum* significantly reduced the spot blotch disease (*Bipolaris sorokiniana*) incidence but was less effective compared to chemical control. The effectiveness of four *Trichoderma harzianum* strains and one *T. koningii* strain in reducing the incidence and severity of the leaf blotching of wheat caused by *Septoria tritici* with two formulation, spore suspension and the coated-seed technique, was studied under field conditions. At the tillering stage, all of the treatments tested effectively reduced the incidence or the severity of the disease compared to the control and none of the treatments tested caused a significant decrease of the disease at the heading stage. These results indicated that the antagonism was effective at an early stage of the disease only. *Trichoderma harzianum* isolates T4 and T2 showed the greatest effectiveness for controlling disease, with similar reduction values to that shown by the fungicide (Folicur) application treatment (Perello *et al.*, 2009). Stocco *et al.* (2016) characterized 240 isolates of *Trichoderma harzianum* from the Argentine wheat regions by means of molecular techniques and selected 37 strains which reduced the severity of Septoria leaf blotch ≥ 50%. These 37 native strains of *T. harzianum* are important in biocontrol programs and could be advantageous for the preparation of biopesticides adapted to the agroecological conditions of wheat culture. *Trichoderma* and *Muscodor* species have been widely evaluated for their capacity to produce a wide range of volatile metabolites (FVOCs- volatile organic compounds produced by fungi) that can be used as biocides against plant pathogens. FVOCs produced by the endophytic fungus *Muscodor albus* inhibited the germination of the teliospores of *T. indica* that cause wheat karnal bunt (Schalchli *et al.*, 2014). Another important wheat disease, Tan spot, is a stubble-borne, splash-dispersed disease and problematic in the USA and Australia and some regions of Nepal. Endophytes from wheat cultivars isolated in Buenos Aires province, Argentina, were assessed for their potential as biocontrol agents against *Pyrenophora tritici-repentis*, the causal agent of tan spot of wheat. Among the endophytes, *T. hamatum* significantly reduced the average disease severity on all three leaves compared to the control under greenhouse conditions (Larran *et al.*, 2016). In an experiment, the efficacy of six isolates of *T. harzianum* and one isolate of *T. koningii* against tan spot disease was assessed under field conditions in Argentina. The application of six of the treatments on wheat plants significantly reduced disease severity by 16 to 35% in comparison with the control. Disease control provided by isolate T7 was similar to that provided

by the fungicide tebuconazole 250 EC treatment (56% reduction) (Perello *et al.*, 2008).

Take-all of wheat caused by *Gaeumannomyces graminis* f. sp. *tritici*, is the most important root disease of wheat worldwide. *Trichoderma virens* isolates T96, T65, and Trichodermin B (commercial product) were more effective in reducing the Take-all disease severity by 25 to 55% in greenhouse conditions (Zafari *et al.*, 2008). *Heterodera avenae* is a devastating plant pathogen that causes significant yield losses in many crops, but there is a lack of scientific information whether this pathogen can be controlled effectively using biocontrol agents. According to Zhang *et al.* (2014), in greenhouse, *T. longibrachiatum* inoculation decreased *H. avenae* infection in wheat (*Triticum aestivum*) significantly. Observations with microscopes revealed that after mutual recognition with cysts, the spore of *T. longibrachiatum* germinated with a large number of hyphae, and reproduced rapidly on the surface of cysts. Meanwhile, the cysts surface became uneven, with some cysts producing vacuoles, and the others splitting. Finally, the cysts were dissolved by the metabolite of *T. longibrachiatum*. Sahebani and Hadavi (2008) showed that different concentrations (10^2–10^8 spores/ml) of *T. harzianum* BI decreased nematode infection (*Meloidogyne javanica*) and decreased nematode egg hatching level significantly, compared to control. It is apparent from above discussion that *Trichoderma* bio-formulations (bio-pesticides) applied either as a seed bio-priming, in soil, root dip or foliar spray, efficiently lessen the severity of biotic stresses. Even, in few instances, some strains of *Trichoderma* showed disease management efficacy at par of chemical control.

Several *Trichoderma* species like *T. harzianum, T. viride, T. asperellum, T. longibachiatum, T. pseudokoningii, T. reesei* have emerged as an efficient candidate for the synthesis of silver or gold nanoparticles (Ahluwalia *et al.*, 2014; Mishra *et al.*, 2014; Devi *et al.*, 2013; Vahabi *et al.*, 2011). The efficacies of nanoparticles have been demonstrated in the management of plant diseases. For instance, damping-off caused by *F. graminearum* was reduced by different concentrations of Zirconium oxide nanoparticles in tested wheat cultivars. The higher inhibition rate of fungi (50%) and spores 55.102% were found at 200mg/ml concentration of Zirconium oxide nanoparticles. However, silver nitrate nanoparticles (10mg/ml) caused reduction in fungal and spores with inhibition rate 52.083, 57.142mg/ml respectively (Jallil and Numan, 2016).

Effect of *Trichoderma* on alleviating abiotic stresses of wheat crop: Abiotic stress includes high and low temperature, salinity, drought, flooding and heavy metals. These stresses reduced the yield of crops, depending on the type of crop and stress period. In many semi-arid and arid regions of the world, crop yield is limited due to increased rate of soil salinity. Salinity and drought are the two most complex stress tolerances to breed for as the type (combinations of drought and salinity), timing in relation to plant growth stage and intensity of stress can all vary considerably, which have severely affected plant growth and biomass production since long (Haggag *et al.*, 2015). It is estimated that abiotic environmental stresses are responsible for about 70% of yield reduction of crops in production. The abiotic stress factors that most commonly influence plant performance include deficiencies or excesses of water (drought and flooding), extremes of irradiance, excessively low or high temperature, or deficiencies or excesses of several nutrients, including macro and micronutrients, high salinity (i.e. excesses of Na^+, Cl^-, So_4^{2-}), and extremes of soil pH. Abiotic stresses may also include mechanical stresses (e.g. wind, hail, mechanical impedance of root growth in compacted soils, and wounding and stresses associated with toxic, manmade chemicals, including gaseous pollutants (sulfur dioxide, nitrogen oxides, ozone), heavy metals and xenobiotics i.e. herbicides (Rhodes and Nadolska-Orczyk, 2001). Drought primarily causes a decrease in plant height, spike number and grain weight. By contrast, heat stress causes an increase in aborted spikes and a decrease in grain numbers. In reproductive tissues, drought primarily impacts pistil development, whereas heat stress primarily impacts pollen development. Tolerance of wheat crop to salt, drought, water stress, low and high temperature, heavy metals is enhanced via overexpression of specific stress related genes.

Various species of *Trichoderma* are capable to induce abiotic stress tolerance, improve plant growth and vigor, solubilize plant nutrients, and bioremediate heavy metals and environmental pollutants (Lorito *et al.*, 2010; Shoresh *et al.*, 2010; Hermosa *et al.*, 2012).

Trichoderma spp. can enhance crop productivity by virtue of both enhanced decomposition of biomass and improving uptake of inorganic fertilizers (Mehetre and Mukherjee, 2015). The systemic fungal endophytes isolated from pioneer plants on salinized soil have the potential to confer tolerance to agriculturally and horticulturally important plants grown in arid environments (Azad and Kaminskyj, 2016). Though, biocontrol is only a subset of the advantages that effective endophytic *Trichoderma* strains can confer. They can also promote growth and induce resistance to a variety of abiotic stresses, including water deficit, temperature, salt and osmotic stress (Zaidi *et al.*, 2014). *Trichoderma* spp. exist either in the rhizosphere or on plant roots. They form a symbiotic relationship with the host plant. In the existence of the relationship, the proteome and transcriptome of plants change as a consequence of the interaction of *Trichoderma* metabolites or plant colonization. Alleviation of damage by reactive oxygen species (ROS), water-use efficiency and secretion of phytohormonal analogues are the three mechanisms employed by the fungi in enhancing plant growth under drought stress or other

abiotic stresses (Chepsergon *et al.*, 2014). *Trichoderma harzianum* exerted a positive effect only on wheat plants subjected to water deficit. The population growth rate reached its highest level in the presence of plants under conditions of water deficit. These results confirm the occurrence of a mutualistic interaction between wheat and *T. harzianum* (Donoso *et al.*, 2008). This mutualistic mechanism between wheat and *T. harzianum* under water deficit facilitate in mitigation of the effect of drought. Salinity is one of the most important abiotic stresses that limit crop growth and productivity. Rawat *et al.* (2011) showed that salinity tolerant isolates of *T. harzianum* have efficiency to reduce the severity of the effects of salinity by strengthening the plant stand. The treated plants showed lower accumulation of MDA (Malondialdehyde) content whereas proline content and phenolics were higher under both non-saline and saline conditions.

The growth and development of crop needs optimum ratio of micronutrient in soil. Deficiency of micronutrients in soil affect the plant growth leads to severe loss in the productivity and yield. To alleviate Zn deficiency a study on combined application of micronutrients zinc, chelating agents, (ethylene diamine tetra acetic acid, EDTA) and biofertilizer (*Trichoderma* spp.) showed better response in terms of growth and yield of wheat under polyhouse conditions compared to Zn alone (Giri and Pandey, 2016). Colonization of five drought tolerant isolates of *Trichoderma* by seed biopriming enhanced drought tolerance of wheat plants as it delayed drought induced changes like stomatal conductance, net photosynthesis, chlorophyll fluorescence and greenness of plants. Drought stress from 4 to 13 d increase the concentration of many stress induced metabolites in wheat leaves, while *Trichoderma* colonization caused a decrease in proline, MDA and H_2O_2 contents and an increase in phenolics concentration. Among different *Trichoderma* isolates, Rani Th-14 induced maximum drought tolerance as treated plants recorded only 20-40 per cent wilting even at 13 days drought stress (Rawat *et al.*, 2016). In the open field trials, there was a significant reduction in grain yield of winter wheat by 24.3% and 7.7%, during the first and second growing season, respectively, compared to the coated seeds with *Trichoderma* (Colla *et al.*, 2015). The application of *Trichoderma* can improve the crop performance of wheat in a sustainable way under abiotic stresses.

FUTURE THRUSTS

- The regulation pattern of differentially expressed genes, individually or in group form, may help researchers to study different pathways and functions at the cellular and molecular level. By intervention of molecular biology, we can easily isolate, characterize, clone, sequence and express the functions of these genes and can study their functions and role in the biocontrol mechanism (Sharma *et al.*, 2011). These studies can provide a lot of useful information to unravel the mystery of abiotic/ biotic stresses in wheat or other important crop plants.
- Genome sequencing data of important *Trichoderma* species would facilitate in better understanding of mycoparasitism and thereby the development of improved biocontrol strains for efficient and environmentally friendly protection of plants.
- Transgenic approaches are one of the many tools available for modern plant improvement programs. Gene discovery and functional genomics projects have revealed multitudinous mechanisms and gene families, which confer improved productivity and adaptation to abiotic/ biotic stresses (Jewell *et al.*, 2010). Moreover, the stress related genes from the different sources can be cloned and used for developing transgenic wheat. The production of transgenic plants by genetic engineering allows a much faster progress. Adopting the transgenic wheat is feasibly one of the way to overcome various environmental stresses and breaking the yield barrier. Pragmatically, it was shown by Rana *et al.* (2012) that Genes encoding a endochitinase (chit42) and a chitosanase (harcho) from *T. harzianum*, if co-transformed in wheat plants, then, they enhance the tolerance to the powdery mildew pathogen (*Blumeria graminis* f.sp. *tritici*).
- The information on the efficacy of *Trichoderma* spp. in mitigating the terminal heat losses, interaction among the pathogen-antagonist-wheat plants or antagonist with abiotic stresses like frost, chemical toxicity, radiation, application of nanoscience for overcoming biotic and abiotic stresses, transferring the stress related genes from different sources into wheat by genetic engineering, is scanty or not available. These are some researchable issues in wheat and a clarion call for breaking the yield barrier for world food security.

CONCLUSION

The biopesticides treatments have best beneficial effects as in long term compared to chemical fungicide. *Trichoderma* spp. have potential to mitigate the different challenging biotic/ abiotic stresses in wheat and their application safe and cost-effective method. Large-scale application of *Trichoderma* spp. to crops as inoculants would be beneficial in enhancing the crop yield and also substantially reduce the use of chemical fertilizers and pesticides, which often pollute environment and contaminate the foodstuffs. The goal of green agriculture or world food security can be achieved by developing of superior or novel *Trichoderma* strains with improved plant growth promotion traits and transgenic wheat expressing different stress related genes with increased resistance to various abiotic and biotic stresses with the intervention of molecular biology and nanoscience. Certain genes from *Trichoderma* spp. have been identified and transferred to plants for improving biotic and abiotic stress tolerance. Several *Trichoderma* genomes have been sequenced and many are in the pipeline, facilitating high throughput gene analysis and increasing the availability

of candidate transgenes. Through improved plant transformation systems, several genes from these antagonistic fungi or other sources can be transferred into wheat to achieve enhanced biotic/ abiotic stress tolerance. Although, the efficacies of some strains of *Trichoderma* have been shown at par of chemical control, notwithstanding, there is a need to evaluate these effective strains against biotic/ abiotic stresses of wheat at large scale in the field.

REFERENCES

Ahluwalia, V., Kumar, J., Sisodia, R., Shakil, N. A. and Walia, S. (2014). Green synthesis of silver nanoparticles by *Trichoderma harzianum* and their bio-efficacy evaluation against *Staphylococcus aureus* and *Klebsiella pneumonia*. *Industrial Crops and Products.* **55:** 202–206.

Azad, K. and Kaminskyj, S. (2016). A fungal endophyte strategy for mitigating the effect of salt and drought stress on plant growth. *Symbiosis.* **68(1)**: 73-78.

Baroncelli, R., Zapparata, A., Piaggeschi, G., Sarrocco, S. and Vannacci, G. (2016). Draft whole-genome sequence of *Trichoderma gamsii* T6085, a promising biocontrol agent of *Fusarium* Head Blight on wheat. *Genome Announcements.* **4(1)**: e01747-15. (doi:10.1128/genomeA.01747-15)

Callaway, E. (2016). Devastating wheat fungus appears in Asia for first time. *Nature.* **532:** 421-422.

Chepsergon, J., Mwamburi, L. and Kassim, M. K. (2014). Mechanism of drought tolerance in plants using *Trichoderma* spp. *International Journal of Science and Research.* **3(11)**: 1592-1595.

Colla, G., Rouphael, Y., Bonini, P. and Cardarelli, M. (2015). Coating seeds with endophytic fungi enhances growth, nutrient uptake, yield and grain quality of winter wheat. *International Journal of Plant Production.* **9(2)**: 171-189.

Compant, S., Gerbore, J., Antonielli, L., Brutel, A. and Schmoll, M. (2017). Draft genome sequence of the root-colonizing fungus *Trichoderma harzianum* B97. *Genom Announcements.* **5(13):** e00137-17 (doi: 10.1128/ genomeA.00137-17.)

Contreras-Cornejo, H. A., Macias-Rodriguez, L., del-Val, E. and Larsen, J. (2016). Ecological functions of *Trichoderma* spp. and their secondary metabolites in the rhizosphere: interactions with plants. *FEMS Microbiology Ecology.* **92(4)**:1-17 (doi: 10.1093/femsec/fiw036)

Devi, T. P., Kulanthaivel, S., Kamil, D., Borah, J. L., Prabhakaran, N. and Srinivasa, N. (2013). Biosynthesis of silver nanoparticles from *Trichoderma* species. *Indian journal of Experimental Biology.* **51**: 543-547.

Donoso, E. P., Bustamante, R. O., Caru, M. and Niemeyer, H. M. (2008). Water deficit as a driver of the mutualistic relationship between the fungus *Trichoderma harzianum* and two wheat genotype. *Applied and Environmental Microbiology.* **74(5)**:1412-1417.

Druzhinina, I. S., Seidl-Seiboth, V., Herrera-Estrella, A., Horwitz, B. A., Kenerley, C. M., *et al.,* (2011). *Trichoderma*: the genomics of opportunistic success. *Nat. Rev. Microbiol.* **9**: 749–59.

El-Sharkawy, H. H. A., Tohamey, S. and Khalil, A. A. (2015). Combined effects of *Streptomyces viridosporus* and *Trichoderma harzianum* on controlling wheat leaf rust caused by *Puccinia triticina*. *Plant Pathology Journal.* **14 (4)**: 182-188.

Geremia, R. A., Goldman, G. H., Jacobs, D., Ardiles, W., Vila, S. B. *et al*. (1993). Molecular characterization of the proteinase-encoding gene, prb1, related to mycoparasitism by *Trichoderma harzianum*. *Mol. Microbiol.* **8**: 603–613.

Giri, P. and Pandey, S. N. (2016). *Trichoderma* spp. and metal chelator enhanced growth and yields in wheat plants by increasing zinc availability. *International Education and Research Journal.* **2(1)**: 66-70.

Haggag, W. M., Abouziena, H. F., Abd-El-Kreem, F. and El Habbasha, S. (2015). Agriculture biotechnology for management of multiple biotic and abiotic environmental stress in crops. *Journal of Chemical and Pharmaceutical Research.* **7(10)**: 882-889.

Hermosa, R., Viterbo, A., Chet, I. and Monte, E. (2012). Plant-beneficial effects of *Trichoderma* and of its genes. *Microbiology.* **158**: 17–25.

Jalill, R. D. A. and Numan, R. S. (2016). Silver nitrate and zirconium oxide nanoparticles as management of wheat damping-off caused by *Fusarium graminearum*. *Journal of Genetic and Environmental Resources Conservat*ion. **4(2)**: 85-93.

Jewell, M. C., Campbell, B. C. and Godwin, I. D. (2010). Transgenic plants for abiotic stress resistance, in *Transgenic crop plants* (eds) Kole C et al, Berlin: Springer-Verlag, 67- 132 pages. (doi: 10.1007/978-3-642-04812-8_2)

Joshi, A. K., Mishra, B., Chatrath, R., Ferrara, G. O. and Singh, R. P. (2007). Wheat improvement in India: present status, emerging challenges and future prospects. *Euphytica.* **157**: 431–446. (doi: 10.1007/s10681-007-9385-7)

Kamal, R., Gusain, Y. S., Kumar, V. and A. K. Sharma, A. K. (2015). Disease management through biological control agents: An eco-friendly and cost effective approach for sustainable agriculture- A Review. *Agricultural Reviews.* **36 (1)**: 37-45.

Kubicek, C. P., Herrera-Estrella, A., Seidl-Seiboth, V., Martinez, D. A. *et al*. (2011). Comparative genome sequence analysis underscores mycoparasitism as the ancestral life style of *Trichoderma. Genome Biology.* **12**: R40 (doi: 10.1186/gb-2011-12-4-r40)

Larran, S., Simon, M. R., Moreno, M. V., Siurana, M. P. S. and Perello, A. (2016).Endophytes from wheat as biocontrol agents against tan spot disease. *Biological Control.* **92**: 17–23.

Lorito, M., Woo, S. L., Harman, G. E. and Monte, E. (2010). Translational research on *Trichoderma*: from 'omics to the field. *Annu. Rev/ Phytopathol.* **48**: 395–417.

Martinez, D., Berka, R. M., Henrissat, B., Saloheimo, M., Arvas, M. *et al.* (2008). Genome sequencing and analysis of the biomass-degrading fungus *Trichoderma reesei* (syn. *Hypocrea jecorina*). *Nat. Biotechnol.* **26**: 553–560.

McIntosh, R. A. (1998). Breeding wheat for resistance to biotic stresses. *Euphytica.* **100**: 19–34.

Mehetre, S. T. and Mukherjee, P. K. (2015). *Trichoderma* improves nutrient use efficiency in crop plants, in *Nutrient Use Efficiency*: *from Basics to Advances* (eds) Rakshit A, Singh, HB, Sen A, India: Springer, 173-180 pages. (doi: 10.1007/978-81-322-2169-2-11)

Mishra, A., Kumari, M., Pandey, S., Chaudhry, V., Gupta, K. C. and Nautiyal, C. S. (2014). Biocatalytic and antimicrobial activities of gold nanoparticles synthesized by *Trichoderma* sp. *Bioresource Technology.* **166**: 235–242.

Mukherjee, P. K., Horwitz, B. A., Herrera-Estrella, A., Schmoll, M., Charles, M. and Kenerley, C. M. (2013). *Trichoderma* Research in the Genome Era. *Ann. Rev. Phytopathol.* **51**: 105–29.

Perello, A., Moreno, V., Monaco, C. and Simon, M. R. (2008). Effect of *Trichoderma* spp. isolates for biological control of tan spot of wheat caused by *Pyrenophora tritici- repentis* under field conditions in Argentina. *BioControl.* **53**: 895–904.

Perello, A. E., Moreno, M. V., Monaco, C., Simon, M. R. and Cordo, C. (2009). Biological control of *Septoria tritici* blotch on wheat by *Trichoderma* spp. under field conditions in Argentina. *BioControl.* **54**: 113–122.

Pingali, P. L. (1999). CIMMYT 1998-99 World Wheat Facts and Trends. Global

Wheat Research in a Changing World: Challenges and Achievements. Mexico, CIMMYT, 46 pages.

Qin, W. T. and Zhuang, W. Y. (2016). Four new species of *Trichoderma* with hyaline ascospores from central China. *Mycol. Progress.* **15(8)**: 811-825.

Rana, I. A., Loerz, H., Schaefer, W. and Becker, D. (2012). Overexpression of chitinase and chitosanase genes from *Trichoderma harzianum* under constitutive and inducible promoters in order to increase disease resistance in wheat (*Triticum aestivum* L). *Mol. Plant Breed.* **3**: 37–49.

Rawat, L., Bisht, T. S., Kukreti, A. and Prasad, M. (2016). Bioprospecting drought tolerant *Trichoderma harzianum* isolates promote growth and delay the onset of drought responses in wheat (*Triticum aestivum* L.). *Molecular Soil Biology.***7(4)**: 1-15.

Rawat, L., Singh, Y., Shukla, N. and Kumar, J. (2011). Alleviation of the adverse effectsof salinity stress in wheat (*Triticum aestivum* L.) by seed biopriming with salinity tolerant isolates of *Trichoderma harzianum*. *Plant Soil.* **347**: 387–400.

Rhodes, D. and Nadolska-Orczyk, A. (2001). *Plant Stress Physiology*, UK: John Wiley and Sons, 1-7 pages (doi: 10.1038/ npg.els.0001297)

Routray, S., Dey, D., Baral, S., Das, A. P. and Mahantheshwara, B. (2016). Genetic improvement of natural enemies: A review. *Agricultural Reviews*. **37 (4)**: 325-332.

Sahebani, N. and Hadavi, N. (2008). Biological control of the root-knot nematode *Meloidogyne javanica* by *Trichoderma harzianum*. *Soil Biology and Biochemistry.* **40**: 2016–2020.

Schalchli, H., Tortella, G. R., Rubilar, O., Parra, L., Hormazabal, E. and Quiroz, A.(2014). Fungal volatiles: an environmentally friendly tool to control pathogenic microorganisms in plants. *Crit. Rev. Biotechnol.* **36(1)**: 144-152.

Sharma, P., Kumar, P. V., Ramesh, R., Saravanan, K., Deep, S., Sharma, M., Mahesh, S. and Dinesh, S. (2011). Biocontrol genes from *Trichoderma* species: A review. *African Journal of Biotechnology.* **10(86)**; 19898-19907.

Sharma, P., Patel, A. N., Saini, M. K. and Deep, S. (2012). Field Demonstration of *Trichoderma harzianum* as a plant growth promoter in wheat (*Triticum aestivum* L). *Journal of Agricultural Science.* **4(8)**: 65-73.

Sharma, I., Tyagi, B. S., Singh, G., Venkatesh, K. and Gupta, O. P. (2015). Enhancing wheat production- A global perspective. *Indian J. Agr. Sci.* **85(1)**: 3-13.

Shoresh, M., Harman, G. E. and Mastouri, F. (2010). Induced systemic resistance and plant responses to fungal biocontrol agents. *Annu. Rev. Phytopathol.* **48**: 21–43.

Stocco, M. C., Monaco, C. I., Abramoff, C., Lampugnani, G., Salerno, G., Kripelz, N., Cordo, C. A. and Consolo, V. F. (2016). Selection and characterization of Argentine isolates of *Trichoderma harzianum* for effective biocontrol of *Septoria* leaf blotch of wheat. *World J. Microbiol. Biotechnol.* **32**: 49. (doi: 10.1007/s11274-015-1989-9)

Vahabi, K., Mansoori, G. L. and Karimi, S. (2011). Biosynthesis of silver nanoparticlesby fungus *Trichoderma Reesei* (a route for large-scale production of AgNPs). *Insciences Journal.* **1(1)**: 65-79.

Verma, M., Brar, S., Tyagi, R., Surampalli, R. and Valero, J. (2007). Antagonistic fungi, *Trichoderma* spp.: panoply of biological control. *Biochem. Eng. J.* **37**: 1–20.

Weindling, R. (1932). *Trichoderma lignorum* as a parasite of other soil fungi. *Phytopathology.* **22**: 837–45.

Xue, A. G., Guo, W., Chen, Y., Siddiqui, I., Marchand, G., Liu, J. and Ren, R. (2017). Effect of seed treatment with novel strains of *Trichoderma* spp. on establishment and yield of spring wheat. *Crop Protection*. **96**: 97-102.

Yadav, B., Singh, R. and Kumar, A. (2015). Management of spot blotch of wheat using Fungicides, Bio-agents and Botanicals. *African Journal of Agricultural Research*. **10(25)**: 2494-2500.

Zafari, D., Koushki, M. M. and Bazgir, E. (2008). Biocontrol evaluation of wheat take-all disease by *Trichoderma* screened isolates. *African Journal of Biotechnology.* **7 (20)**: 3653-3659.

Zaidi, N. W., Dar, M. H., Singh, S. and Singh, U. S. (2014) *Trichoderma* Species as abiotic stress relievers in plants. In: *Biotechnology and Biology of Trichoderma* (Eds. Gupta *et al.*). Elsevier publication, 515-525 pages (doi: 10.1016/B978-0-444-59576-8.00038-2)

Zhang, S., Gan, Y., Xu, B. and Xue, Y. (2014). The parasitic and lethal effects of *Trichoderma longibrachiatum* against *Heterodera avenae*. *Biological Control.* **72**: 1–8. (doi: 10.1016/j.biocontrol.2014.01.009)