Caliphate Journal of Science & Technology (CaJoST)

ISSN: 2705-313X (PRINT); 2705-3121 (ONLINE)

Review

Article Info

Received: 24th April 2021

Revised: 22th July 2021

Accepted: 25th July 2021

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Cite this: *CaJoST,* 2021, 2, 196-205

Roles of *Trichoderma species* as a Potent Biochemical Agent for Sustainable Farming Practice: A Mini Review

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In the past few decades, fungi have attracted many scientists globally to develop an interest in using *Trichoderma species* and other related fungi specifically for organic farming purposes. *Trichoderma spp.* as an endophytic and saprophytic fungi found in diverse natural habitats such as soil, compost, plant roots, leaves, woods and so forth. They play a crucial role in different agricultural processes similar to the synthetic counter parts for the improvement of crop yield. In this mini review, numerous findings from old of 1989 to the recent of 2021 signifying the several researches as well as mechanisms in which *Trichoderma spp.* operate which are very crucial for the agricultural development and sustainability in providing cheaper, safer, healthier and nutritious produce as well as provision of environment free of contaminants. In this review it was gathered that these fungi could be one of the promising species that can burst farming practice when use as biofertilizer

Keywords: Ecosystem, Crop yield, Organic farming, Sustainability, *Trichoderma spp*.

1. Introduction

Trichoderma species are endophytic and saprophytic in nature that is found to have been playing a vital and diverse role in the agricultural field and other essential fields of human endeavour (Woo *et al.,* 2014). There are many species of Trichoderma but the notable ones amongst them include: *Trichoderma harzianum*, *Trichoderma viride* and *Trichoderma atroviride*; some of the strains are also available and still researches are underway to find more of them (Lee *et al.,* 2016). These amazing fungi are available in diverse sources such as soil, compost, plant roots, leaves and can grow saprophytically on bark, wood and some other substrates (Zeilinger *et al.,* 2016).

Agriculture, now the most challenging field in human endeavour in the global perspective that require more robust attention (Nchuchuwe & Adejuwon, 2012). One of the challenges is the crop production and yield which defend on the agricultural input of chemicals like synthetic fertilizers and pesticides to improve the soil fertility for more production outcome and eventually, these processes of applying chemicals were found to have more detrimental effect to the environment and to the final consumers (Massah & Azadegan, 2016). The chemicals such as fertilizers, insecticides and pesticides which eventually lead to the environmental contamination in soil, air and water respectively.

In this new era of modern research, the use of microorganisms as a replacement of the chemical usage for more crops production is now in focus; with the priority focus on *Trichoderma species* that were known to have every potentiality in providing better, safer and qualitative feedback compared to chemical methods of application (Ajmal *et al.,* 2018). In this paper, we specifically focus on some important benefits associated with *Trichoderma species* in relation to agriculture and more reviews are needed for other benefits that can be derived from this amazing fungal species or other microbial species that can serve similar purpose.

2. Biocontrol and Cell wall degrading potential

Evidences in the literature have demonstrated the effectiveness of *Trichoderma species* on the enhancement of crop yield due to the pathogenicity combat of these fungal species which lead to their commercialization and now attracting the global attention toward the benefits. Although scientific research did not provide full details of mechanisms for which it operates, but it believes that some of the mechanisms of action of these *Trichoderma species* against a wide set of microbes like fungi, bacteria and virus to some certain cases indicate how effective are the *Trichoderma spp.* in biocontrol potentiality (Zeilinger *et al.,* 2016). The author observed that the synthesis of bioactive compounds such as peptaibiotics in the cell is very crucial on the survival of both mycoparasites and saprotrophic species of *Trichoderma* for defence and colonization. Cuesta *et al.,* (2012), described both species of *Trichoderma* and *Streptomyces species* produce antibiotics and clearly showed the antagonistic and chitinolytic activities against phytopathogens. In a related literature, where six *Trichoderma species* were tested against the soil-borne pathogens *Rhizoctonia solani*, *Sclerotium rolfsii*, *Sclerotinia sclerotiorum,* the isolates exhibit the inhibitory effect upon dual culture with *Trichoderma species* where *T. viride* strains had more significant effect over *T. harzianum* strain (Amin *et al*., 2010), likewise when tested against *Fusarium species* (Küçük, 2017). The biocontrol potential of eleven some species of *Trichoderma* isolates were assessed against *M. Phaseolina* a soy bean pathogen of which two strains strains of *T. Harzianum* (T7 and T14) emerged the best for inhibiting pathogen growth (Khaledi & Taheri, 2016). Similarly, *Trichoderma viride* and *Trichoderma harzianum* were described as the most potent biocontrol agent and are commercially available as biocides against plant pathogens (Ghahfarokhi & Goltapeh, 2010; Unarngam *et al*., 2020; Alvarado-Marchena & Rivera-Méndez, 2016). Also, *T. asperillum* demonstrates high antagonistic property towards *Fusarium oxysporum f. sp. Lycoperci* (FOL) (El-Komy *et al.,* 2015). Other species known as *Trichoderma gamsii* isolated from a healthy plant root of *Panax notoginseng*, identified as non-pathogenic to its host plant, with ability of producing volatile organic compounds (Chen *et al.,* 2016). Therefore, these features are of utmost importance for the *Trichoderma species* in successful combat against the fungal and bacterial related plant pathogens through antagonistic interactions (Degenkolb *et al.,* 2015). Similarly, a combination of two beneficial fungi like *Trichoderma spp*. and *Mycorrhizae* produced the best growth and decrease the wilt disease in pigeon pea (Dehariya *et al.,* 2015). Sometimes this depends on the plant type, density and probably the species of the microbes that colonized the roots of such plants. For instance, upon application of different concentrations of *Trichoderma harzianum* was experimentally reported to have increased seed germination, seedling survival and growth against *Festuca arundinaceaschreb., Lespedeza cyrtobotryaMiq., Dianthus barbatus var. asiaticus Nakai*, and *Parthenocissus tricuspidata* (Wang *et al.,* 2016). Recently, the use of *Trichoderma spp* for pest control and disease management were reported (Poveda, 2021; Mistra & Ansari, 2021).

One of the main reasons of the *Trichoderma species* serving as biocontrol agent is due its ability to secrete enzymes of carbohydrates, lipids and proteins degradation. It was reported that *Trichoderma species* produce lytic enzymes that serve as an antifungal against the pathogenic fungi (Rajeswari, 2014). The secretion of antifungal enzymes and chitinolytic action of *Trichoderma* isolates of *T. viride, T. harzianum* and *T. hamatum* were screened and tested; with the *T. viride* identified to be the most potent fungal antagonist against *Fusarium oxysporum, Aspergillus niger* and *Sclerotum rolfsii* as well as secretion of the main cell wall degrading enzymes like: protease, chitinase and β-glucanase (Goltapeh & Danesh, 2006). Therefore, the ability of *Trichoderma species* as a bio fertilizer producing power is mainly due to the secretion of degradative enzymes. It was believed that the agricultural waste decomposition also improves the soil fertility which is solely due to the action of microbial degradative enzymes. Some of the activities that Trichoderma exhibit are as a result of these secretions. For instance, the use of *Trichoderma species* as biological control agents were due to their ability to secrete hydrolytic enzymes which include chitinases and glucanases which are among the cell wall degrading enzymes of phytopathogenic fungi against nematodes and insects (González *et al.,* 2012). Report shows that, upon isolation of fifty fungal species from fouled soil in oil refinery which was screen for its ability to secrete xylanase enzyme from one of the strain identified as *Hypocrea lixii* and was tested to have the potentiality in utilizing sludge of sunflower oil as the sole source of carbon and eventually high content of xylanase was traced (Sakthiselvan, Naveera & Partha, 2014). It was demonstrated that the alginate pellets formulated from three isolates of *Trichoderma species* and the comparison were made for the *in vitro* chitinase and also β-1,3-glucanase synthesis in which the addition of the dried fungal mycelium increases the fold of chitinase and β-1,3-glucanase (El-Katatny *et al.,* 2003). In a related finding, assessment for the induction of chitinases and glucanases enzymes was demonstrated using different strains of *Trichoderma* upon cultured in liquid media containing different inducers, the highest level of enzymes activities of both chitinase and glucanase were reported (Prasetyawan & Sulistyowati, 2018). As a result, *Trichoderma spp*. are used in the current industrial trends for enzymes production, antibiotics, biofuels and other metabolites; therefore, more researches are required to enhance their efficiency and more safety for the application (Błaszczyk et al., 2014). Application of

T. viride on the solid state fermentation process on grape marc and wine lees; after 10 days, the important enzymes for the cell wall degradation (chitinase, pectinase and β-glucanase) of varying concentrations were produced and are also predicted for their involvement in protecting the plants from disease and are eco-friendly (Bai *et al.,* 2008). Also, *Trichoderma reesei* was described as the major source of hemicelluloses and cellulases used in various industries for the production of biofuels due to the presence of biosynthetic pathways leading to the synthesis of secondary metabolites but mechanisms for their secretion still not clear (Martinez *et al.,* 2008). The secretion of the enzymes seems not to affect the secretion of other beneficial metabolites. Because, when an in *vitro* study of *Trichoderma species* against *Rhizoctonia solani* was conducted it revealed that enzymatic activities of *Trichoderma species* which include chitinase, cellulase, lipase, protease and phosphate solubilisation capability had shown a positive response for inhibition of the pathogen's growth as well as synthesis of growth hormone (Rahmansyah, 2014).

3. Bio fertilizer and phosphate solubility

The major limiting factor that affects the crop yield among the farmers in developing countries globally is the issue of soil fertility and thus, maintaining the soil quality could subside the problems concerning land degradation, soil infertility as well as a rapid decline in crop production for better farming practice (Mohammadi & Sohrabi, 2012). In a similar review as reported previously, the author stated that; bio fertilizers are a product of cells of certain different types of beneficial microorganisms that consist of important components of nutrients which play a key role in soil protection, crop productivity and sustainability of the ecosystem. Some microorganisms that are often used as biofertilizers are nitrogen fixers, phosphorus and potassium solubilize (Mohammadi & Sohrabi, 2012). Augmentation of some certain beneficial fungi contribute immensely in achieving a desired goal such as application of *Mycorrhizae* and *Trichoderma species* on dry land increased the growth and weight of both fresh and dry bulb of red onion significantly as previously reported (Sakthiselvan, Naveena & Partha, 2014). Improving the fertility and more conducive soil, some of the microbes were identified as thermo-tolerant and capable of solubilizing phosphate compounds such as the bacteria and fungi which were isolated from varying compost plants and bio fertilizers; with the exception of *Streptomyces thermophiles* J57 that lacked pectinase, all of the isolates possessed ; chitinase, CMcase, pectinase, protease, nitrogenase and lipase activities and all were able to solubilize phosphate containing compounds such as calcium phosphate, Israel rock phosphate among others (Chang & Yang, 2009).

The study was conducted to assess the effect of the application of different doses of chemical fertilizer (potassium fertilizer) K_2O along with *Pochonia chlymydosporia* and *Trichoderma harzianum* for the management of disease caused by nematodes (*Meloidogyne incognita*); upon addition of double doses of K_2O fertilizer along with the two fungi (*P. chlymydosporia* and *T. harzianum*) that served as bio fertilizer enhanced the plant growth and reduced the population of galls in a roots system (Hisamuddin, 2014). Therefore, the ability of *Trichoderma species* as a bio fertilizer producing power is mainly due to the secretion of the degradative enzymes. In another finding, the Trichoderma enhances cell wall degradative enzymes as well as availability of phosphorus in the soil (Saravanakumar *et al.,* 2016). It was believed that the agricultural waste upon decomposition and decay can also improve the soil fertility which is solely due to the action of microbial degradative enzymes.

4. Macro/Micro Nutrients

Nutrients are required by every living matter be it plant, animal or microbes. All nutrients are either classified as macro or micronutrients depending on the quantity requirement. In the plant Carbon, Nitrogen, Sulphur and Phosphorus are referred to as macro elements for macronutrient synthesis while Zinc, Copper, Molybdenum, Manganese are called microelements for micronutrients supplement. In the plant, all the macronutrients are automatically made in the process called photosynthesis which are referred as autotrophs. But in the case of micronutrients/elements, plants compete around their niche. Such microelements are crucial to plant growth and health. Related work had been published where some *Trichoderma species* serve as nutrients supplement booster on plants. Ülker *et al.,* (2011), reported that certain elements such as Ca^{2+} and Mn^{2+} have the potential of enhancing lipases activities. Experimental prove shows that; application of *Trichoderma species* on citrus orchard trees with deficiency in some certain nutrients had shown a significant increase in nitrogen (N) and manganese (Mn) supplement (Haris *et al.,* 2016). Another evidence of cyanobacteria-based inoculant interacts with the rice plant (*Oryza sativum L.*) leads to the supplementation of micronutrients such as Zn, Mn, Cu and Fe (Adak *et al.,* 2016). Li *et al.,* (2015), prove the nutritional supplementation was noticed while using *Trichoderma species* against tomato plant in a copper (Cu) deficient soil but nutrients uptake was enhanced on the soil with phosphate due to their phosphate solubilizing potentials. Similarly, composted kitchen waste using *Trichoderma harzianum* was observed to have improved the growth, yield and the nutritional quality of the tomato (*Lycopersicon esculentus* Mill.) (Molla *et al.,* 2012). Thus, improvement of the nutrients synthesis in addition to that of the photosynthesis process and its uptake will lead to the early harvest of the product within a limited period. Another impressive habit of this fungus that contributes to the better yield is the exhibition of resistivity to certain abiotic factors.

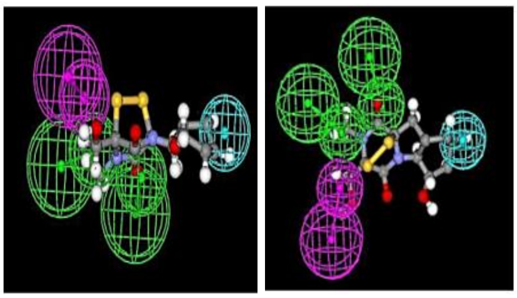
5. Trichoderma and Systemic Resistance

The induction of systemic resistivity to a plant is an interesting and added advantage for a plant to possess such an opportunity. In agriculture, one of the selection criteria that is required for most of the farming practices, especially in a warm temperate region, is the plant with resistance capability to abiotic stresses such as disease and drought. This is a natural phenomenon. But in some plants, the resistivity is intrinsic and therefore, external factors are needed to make it active. Some microorganisms were known to possess such potentialities as such, they act as elicitors and hence are called bio elicitors. *Trichoderma species* are among the successful bio stimulants that enhance the plant growth, induce disease resistance in plants and long-lasting use in horticulture due to the activation of mitogen *(*López-Bucio, Pelagio-Flores & Herrera-Estrella, 2015). Even though other fungi can perform a similar role like Rhizosphere fungi. It was revealed that; *Rhizosphere* of fungi native possesses the potentiality for growth promotion as well as induction of resistance in sunflower when tested against *Plasmoparahalstedii* thereby reducing the severity of the mildew disease (Nagaraju *et al.,* 2012). Some of the microbes were believed to induce such resistivity either directly or indirectly due to the secretion of certain secondary metabolites. Many root-associated mutualists such as *Trichoderma*, *Bacillus*, *Pseudomonas* as well as *Mycorrhiza species* are able to sensitize the immune system of the plant and renders defence indirectly (Pieterse *et al.,* 2014).Carmona-Hernandez *et al.,* (2019), made the assertion that; the defence response experienced by some plants is as a result of over-production of certain enzymes and other metabolites. *Trichoderma harzianum* upon interaction with maize plant; it was noticed that over 300 different proteins were up-regulated and notably among them include the enzymes involved in carbohydrate metabolisms like glucanases and chitinases and other proteins that are associated with the disease resistance and stress (Harman & Shoresh, 2007). Another evidence emerged that; *Trichoderma species* induce resistance over *Fusarium oxysporum f. spp.* on greenhouse crops which subsequently substantiated the incidence of the disease more especially when applied a week prior to the pathogen's inoculation (Ei-Khallal, 2007; Elsharkawy *et al.,* 2015a). A recent study involving the plant-microbes' interactions; revealed that plants can be able to host microbes which help in modifying and reshaping the rhizosphere microbiomes in order to prevent the plants from pathogens and insects attack thereby recruiting microorganisms that suppress pathogen due to the synthesis of secondary metabolites (Berendsen, Pieterse & Bakker, 2012). In the same vein, *Phoma species* which are a plant growth promoting fungi as well, that induce systemic resistivity on *Colletotrichumorbiculare*; hence suppress the disease in cucumber (Elsharkawy *et al.,* 2015b). Similarly, *Trichoderma spp*. was reported to have induced disease resistance on tomato plant caused by *Fusarium oxysporum f. sp.* (FORL) as it significantly reduces the disease severity (Hibar *et al.,* 2007; Shanmugam, Chugh, & Sharma, 2015). Also in cucumber plant (Koike *et al.,* 2001)

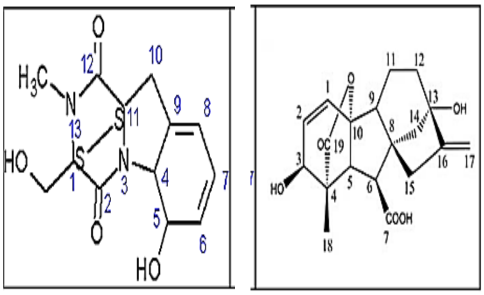
6. Growth Hormone and bio elicitors

Growth promoting efficiency is one of the unique features associated with *Trichoderma spp.* Many findings were published up to the molecular level proving the secretion of growth factor or hormone that is a structural and functional similarity with a popular plant growth hormone known as auxin. The plant hormones are responsible for both roots and shoot elongations. Some are synthetic and others like indole acetic acids (IAA) are naturally produced by the plant. For example, *Trichoderma atroviride* serves as bio elicitor for stimulation of growth and biosynthesis of secondary metabolites around plant roots (Ming *et al.,* 2013). Therefore, secretion of growth hormone by *Trichoderma spp.*and other related microbes will enhance the actions of both synthesizing hormones and burst the growth due to the synergistic effect of the two expected hormones induced in a particular plant. Moreover, when some isolates of *Trichoderma species* were used for the assessment of the germination and seeds vigour in rice (*Oryza sativa L*.) the isolates were discovered to speed up the germination capacity as well as vigour of the rice seeds across the parameters used for such assessment (Doni *et al.,* 2014). For these reasons, the microorganisms like *Trichoderma* definately possess some mechanisms or biosynthetic pathways responsible for the secretion of such important biochemical substances. *Trichoderma harzianum Rifaii* involved in promoting plant growth; in which three possible mechanisms were suggested and these include: medium acidification, synthesis of chelating metabolites as well as redox activity accompanied by solubilisation of the insoluble and sparingly soluble minerals that play a vital role in plant growth (Bezuidenhout, Rensburg & Rensburg, 2012). *Trichoderma asperillum* promote plant growth on maize seedlings more than when treated with 10µL of indole acetic acid (López-Coria, Hernandez-Mendea & Sanchez-Nieto, 2016).

Martínez-Medina *et al.,* (2014), confirmed the elevation of auxin and decrease in abscisic acid and cytokinins content induced by the isolates that promote plant growth and defence-related metabolites. The molecular docking simulations revealed that *T. harzianum* synthesizes gliotoxin which has a structural identity with the growth hormone gibberellic acids through its receptor (GIDI) and this mimics the structure of gibberellic acid (GA_3) in particular with similar response (Bezuidenhout, Rensburg & Rensburg, 2012). Also, the growth of Arabidopsis seedlings tested *in vivo* upon inoculated with *T. virens* and *T. atroviride* and the result indicated the auxin-related characteristics including the lateral roots stimulation as well as biomass production (Contreras-Cornejo *et al.,* 2009). In a related finding, *Trichoderma viride* and *Trichoderma harzianum* tested against *M. javanica* on tomato plants, the results show that all the densities used for the two fungal species involved in the suppression of nematodes, root galling and also enhanced the growth of the tomato plants (Al-Hazmi & TariqJaveed, 2016).



(a) (b)



(c) (d)

Fig.1: Molecular similarity between (a) Gibberellic Acid (b) Gliotoxin,

Numbered structures for (c) gibberellic acid 3 and (d) gliotoxin (Bezuidenhout, Rensburg & Rensburg, 2012).

7. *Trichoderma spp.* and yield enhancement potentials

The pure *Trichoderma* inoculants or in combination with other beneficial microorganisms enhance the growth of plants which resulted in providing the appreciable yield (Baker, 1989; Harman *et al.,* 2004; Szczech *et al.,* 2017). For instance, combined *Trichoderma spp.* with *Mycorrhizae* and reported the increase in onion growth and the weight of both dry and wet onion bulbs by 63.95% and 55.10% respectively (Made Sudantha, Astiko & Author, 2017). Another report indicated the growth enhancement of red beet and cabbage with huge yield increment (Topolovec-Pintaric, Zutic & Dermic, 2013), tomato yield increment was also documented (Molla *et al.,* 2012; Konappa *et al.,* 2018) and sorghum (López-Bucio, Pelagio-Flores & Herrera-Estrella, 2015) upon application of *Trichoderma species*. However, the notice in the growth begin with the seed germination (Amooaghaie, Saeri & Azizi, 2015; Doni *et al.,* 2014; Mastouri, Bjorkman & Harman, 2010; Srivastava *et al.,* 2010; Toghueo *et al.,* 2016; You *et al.,* 2016), length of the roots (Samolski *et al.,* 2012; Saravanakumar *et al.,* 2016), number of the leaves (López-Coria, Hernandez-Mendea & Sanchez-Nieto, 2016; Made Sudantha, Astiko & Author, 2017; Molla *et al.,* 2012), lateral branches (Srivastava *et al.,* 2010) , chlorophyll content (Shoresh, Harman & Mastouri, 2010; López-Bucio, Pelagio-Flores & Herre-Estrella, 2015; John *et al.,* 2010; Kumar, Manigundan & Amaresan, 2017) to the crop yields. The yield of grape fruit was again increased by two Trichoderma strains (Pascale *et al.,* 2017). Inoculating soil with Trichoderma improved the rice yield cultivated under continues flooding condition (Khadka *et al.,* 2019). *T. harzianum* and

T. hamatum were applied on field study, where *T. harzianum* increased the crop yield of chickpea from 12% to 28% while *T. hamatum* from 12% to 24% respectively.

8. Conclusion

The role of biological agents such as *Trichoderma species* for improvement of agricultural yield cannot be overemphasized considering the above-outlined contributions made by these amazing fungi compiled from several findings which could feasibly represent a viable as well as environmentally benign to human with efficiency similar to that of the synthetic chemicals used for the successful faming processes and more safer to the entire ecosystem, these could save yield from declining, ameliorate the contaminated soil and improve its fertility with time. Therefore, future finding should be focused on health implication upon prolong consumption of the produce obtain on application of these microbes when used as biofertilizers. If found safe for consumption, this could be our future organic fertilizer to replace the chemically synthetic form.

Conflict of interest

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

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