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TRICHODERMA: ITS ECOPHYSIOLOGY, MECHANISM OF BIOCONTROL AND APPLICATION METHODS

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A R T I C L E I N F O

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A B S T R A C T

Chemically managed plants impose environmental risks to humans and environment. Using biological approaches to control plant diseases is a more effective and environment friendly alternative. The biological approach to plant disease refers to controlling disease by using organisms like fungi, bacteria and viruses. This can be done by introduction or utilization of resident antagonistic living organisms. Biological control can be achieved through different forms of interactions between organisms and the interactions includes hyperparasitism, antibiosis, commensalism, neutralism, and competition. Various biocontrol agents commonly used against plant pathogens are Trichoderma harzianum, Trichoderma hamatum, Trichoderma viride, Trichoderma koningii, Gliocladium virens, Gliocladium roseum, Paecilomyces liiacinus, Coniothyrum minitans, Bacillus subtilis, Bacillus polymyxa, and Pseudomonas fluorescens.

1. INTRODUCTION

Chemically managed plants impose environmental risks to humans and environment. Using biological approaches to control plant diseases is a more effective and environment friendly alternative. The biological approach to plant disease refers to controlling disease by using organisms like fungi, bacteria and viruses (O'Brien, 2017). This can be done by introduction or utilization of resident antagonistic living organisms. Biological control can be achieved through different forms of interactions between organisms and the interactions includes hyperparasitism, antibiosis, commensalism, neutralism, and competition. Various biocontrol agents commonly used against plant pathogens are *Trichoderma harzianum*, *Trichoderma hamatum, Trichoderma viride*, *Trichoderma koningii*, *Gliocladium virens*, *Gliocladium roseum*, *Paecilomyces liiacinus*, *Coniothyrum minitans*, *Bacillus subtilis*, *Bacillus polymyxa*, and *Pseudomonas fluorescens* (Tyśkiewicz *et al*., 2022).

The most important genera against soil pathogens are *Trichoderma*, *Pseudomonas* and *Bacillus* (Guo *et al*., 2004; Huang *et al*., 2015). *Trichoderma* is found to be an effective biocontrol agent especially for soil borne pathogens like *Rhizoctonia solani, Sclerotium rolfsii, Phythium aphanidermatum, Fusarium oxysporum,* and *Gaeumannomyces graminis* under both field and greenhouse conditions (Chet & Inbar, 1994; Basim *et al*., 1999). The *Trichoderma* spp. have a positive effect on plant growth through hydrolysis of cellulose in soil, increases plant defense mechanism, mineral solubilization and improvement in root morphology, enabling roots to cover large volume of soil (Junaid *et al*., 2013; Timila *et al*., 2015).

2. *TRICHODERMA*: ITS BIOCONTROL POTENTIAL AND ECOPHYSIOLOGY

Trichoderma spp., the promising antagonistic fungi are established in agriculture use. These are classified as an anamorphic Hypocreals, belonging to Ascomycetes (Esposito & Da Silva, 1998). Conidiophores are highly branched and produce lateral side branches that may be paired or not. Phialides are formed on the conidiophore main axis or at the tip. The conidiophore with paired branches takes a shape of pyramid in some species (Samuels & Hebbar, 2015). Watanabe (1985) found *T. hamatum, T. harzianum, T. koningii, T. pseudokoningii* and *T. viride* having strong antagonistic potential against soil borne pathogens. They show antagonistic activity under both *in vitro* and *in vivo* conditions by competing for nutrients and space, antibiosis, mycoparasitisam, promoting plant growth and plant defense responses (Brotman *et al*., 2010). Seema and Devaki (2012) reported antangonistic effects of *T. harzianum* and *T. viride* and found significant suppression of mycelial growth and sclerotia formation of pathogen, *R. solani*. Similarly, the seedling mortality of groundnut was also significantly reduced by seed treatment with various isolates of *Trichoderma* spp. (Biswas & Sen, 2000). Freeman *et al*. (2004) reported various isolates of *Trichoderma*, including *T. harzianum* isolate T-39 significantly reduced anthracnose (*Colletotrichum acutatum*) and grey mould (*Botrytis cinerea*) in strawberry under greenhouse and *in vitro* conditions. Pastrana *et al*. (2016) reported preventive and curative application of *T. asperellum* totally avoided incidence of crown and root rot caused by *F. solani* at the same level as application of carbendazim. Similarly, incidence of charcoal rot caused by *M. phaseolina* reduced up to 65% under field conditions and up to 44% in a growth chamber with application of *Trichoderma*. Amin *et al*. (2010) tested six isolates of *Trichoderma* against three different soil borne pathogens namely *R. solani* (isolates from tomato), *Sclerotinia sclerotiorum* (causing web blight of beans) and *S. rolfsii* (causing collar rot of tomato) under *in vitro* conditions and found that maximum inhibition (71.41%) in *R. solani* by *T. viride* (Tv-2) followed by *T. viride* (Tv-1) and *T. harzianum* (Th-1). *T. viride* (Tv-1) showed best antagonist inhibiting 67.91 and 66.21% over control in *S. rolfsii* and *S. sclerotiorum*, respectively. They also found that all the *Trichoderma* isolates significantly inhibited sclerotia production in all three tested pathogens. *Trichoderma* is also effective against Stemphylium blight of lentil. Subedi *et al*. (2014) reported percentage disease control and percent yield increase were higher in *T. viride* i.e. 42.14% and 58.80% respectively. *T. viride* also showed high compatibility with fungicides (potassium phosphonate and fosetyl aluminium) and incompatibility with fungicides (carbendazim, hexaconazole, potassium phosphonate + hexaconazole mixture and captan + hexaconazole mixture) (Dhanya *et al*., 2016).

2.1 Isolation from soil

In 1981, Papavizas used V-8 juice agar as the basal medium for isolation of *Trichoderma* from soil (Papavizas, 1982). Later Papavizas and Lumsden, (1982) developed *Trichoderma* medium E (TME) for isolation of *Trichoderma* from soil. Elad *et al*. (1981) developed a *Trichoderma* selective medium (TSM) for isolation of *Trichoderma* from soil. They used chloramphenicol, pentachloronitrobenzene, p-dimethylaminobenzenediazo, sodium sulfonate and rose-bengal as selective fungal inhibitors. Elad and Chet (1983) further improved TSM medium by adding Captan 50% 2µl/ml which helped to avoid *Fusarium* species. Later, Askew and Laing (1993) modified TSM by adding metalaxyl which suppressed oomycete. However, Williams *et al*. (2003) found captan, was inhibitory to conidial germination of *T. harzianum*.

2.2 Survival in the soil

Trichoderma can abundantly proliferate in various soils and can degrade various organic matters (Papavizas, 1982; Lewis & Papavizas, 1984). They observe that survival of chlamydospore was better than conidia in soil. Lewis and Papavizas (1984) reported that even freshly added conidia declined in the soil and the stable population densities of *Trichoderma* remained is due to survival of chlamydospores. According to Kim *et al*. (1992) with increase in soil depth, the rhizosphere colonizing ability of propagules get reduced. According to Poosapati *et al*. (2014) to adapt to extreme conditions such as high temperatures, some *Trichoderma* produce trehalose, mannose, and raffinose. These sugars are stress protectant and thus *Trichoderma* are able to grow well up to 37-40°C. Some *Trichoderma* spp. are reported to grow in extreme high or low pH, low oxygen (Chovanec *et al*., 2005) and high salinity conditions (Gal-Hemed *et al*., 2011).

2.3 Establishment and proliferation in the soil or rhizosphere

The plant root exudates various organic compounds that affect ecological and biological processes in rhizosphere (Barman *et al*., 2021). Several *Trichoderma* species compete with pathogens for nutrients, space and infection sites on plant roots (Blaszczyk *et al*., 2014). The effectiveness of *Trichoderma* is affected by their biocontrol qualities and their competency in the rhizosphere and plant root colonization (Barman *et al*., 2021). *Trichoderma* introduced on seed must multiply first in the rhizosphere of the host plant to inhibit the pathogen. Biswas and Sen (2000) reported seed treatment with conidial suspension was more effective in reducing disease incidence than soil application. Juliatti *et al*. (2019) stated that seed microbiolization is an important method of application of biocontrol agents since it requires significantly less amount of biological material as compared to the quantity needed for soil application.

2.4 Environmental effects on growth of Trichoderma

2.4.1 Effect of soil type

Trichoderma species are affected by soil pH, moisture and electrical conductivity. According to Wong *et al*. (2002); Singh *et al*. (1998) moist soil conditions is favorable for the antagonistic activity and growth of *Trichoderma*. Similarly, *Trichoderma* spp. are favored by the acidic soils condition. Amir-Ahmadi *et al*. (2017) loam and clay loam reported the best performance of *T. harzianum* in sandy loam soil and loam soil containing 2% organic matter. Soil texture affect the ability of antagonistic fungi to suppress the plant pathogens (Moosavi & Zare, 2015).

2.4.2 Effect of temperature

Temperature is among the important parameters that affect the biomass production of *Trichoderma*. According to Sharma *et al*. (2005) incubation temperature had profound effect on growth of *Trichoderma*. Domingues *et al*. (2016)isolates of *Trichoderma asperellum* (IBLF 897, IBLF 904 and IBLF 914 found that the mycelium of *Trichoderma* grew well at 27 to 32ºC and inhibited at the temperature of 7°C and 42°C. Carro-Huerga *et al*. (2021); Adhikari *et al* (2022) observed that the studied *Trichoderma* strains grew well at 25°C while, some strains showed good response at 35-40°C as well. Di Lelio *et al*. (2021) observed different growth for *T. afroharzianum* and *T. atroviride* at 20 and 25°C, both in *in vitro* and *in vivo* conditions. The lower temperature i.e. 20°C encouraged *T. afroharzianum* growth, whereas *T. atroviride* was abundant at 25°C. According to Klein and Eveleigh (2002); Carro-Huerga *et al*. (2021) the optimum growth temperature for most *Trichoderma* spp. is in the range between 25-30°C and thus are mesophilic in nature. Poosapati *et al*. (2014) observed *T. asperellum*, and *T. harzianum* survived the heat stress, however, with increase of temperature to 37°C, the germination rates of all isolates reduced. The tolerance of *Trichoderma* towards high temperature can be attributed to its ability to accumulate stress protectants. Under stress conditions accumulation of trehalose, mannose and raffinose increase in the cells exposed to stress conditions (Poosapati *et al*., 2014). Under heat stress condition, accumulation of trehalose and mannitol are reported to be necessary for fungal survival and cell protein and structure stability (Daryaei *et al*., 2016)trehalose is accumulated in response to a heat shock or to an oxidative shock. The authors have characterized the A. nidulans tpsA gene encoding trehalose-6-phosphate synthase, which catalyses the first step in trehalose biosynthesis. Expression of tpsA in a Saccharomyces cerevisiae tps1 mutant revealed that the tpsA gene product is a functional equivalent of the yeast Tps1 trehalose-6-phosphate synthase. The A. nidulans tpsA-null mutant does not produce trehalose during conidiation or in response to various stress conditions. While germlings of the tpsA mutant show an increased sensitivity to moderate stress conditions (growth at 45 °C or in the presence of 2 mM H2O2.

3. MODE OF ACTION BY *TRICHODERMA*

Trichoderma spp. are free-living, commonly growing fungi in soil and rhizosphere of various crops (Harman *et al*., 2004). *Trichoderma* can control plant pathogens directly by competition for nutrients, mycoparasitism, production of cell wall degrading enzymes, and production of antibiotics (Harman, 2006) and indirectly by stimulation of plant defense systems (Benítez *et al*., 2004).

3.1. Direct mechanism

3.1.1 Competition for nutrients and space

According to Chet (1987) competition between antagonist and plant pathogen for space and nutrients is a classical mechanism of biological control. One of the most common causes of death of microorganisms are due to starvation. *Trichoderma* are competent for getting limited nutrients resulting in control of fungal plant pathogens (Benítez *et al*., 2004). Generally, filamentous fungi require iron for spore viability and under iron starvation condition, low-molecular-weight ferric-iron specific chelators are excreted to mobilize environmental iron (Eisendle *et al*., 2004). These ferric-iron specific chelators are known as siderophores. Some *Trichoderma* species produce high amount of effective siderophores that chelate iron and absorb them causing starvation of iron to other fungi and stopping their growth (Benítez *et al*., 2004). Based on the chemical nature siderophores are divided into three major groups i.e hydroxamate, catecholate, and carboxylate (Tyśkiewicz *et al*., 2022).

Trichoderma are proficient in mobilization of immobile nutrients and their utilization (Singh *et al*., 2018). Root exude excess amount of sugar, amino acids, iron, vitamins, organic acids and *Trichoderma* compete for these carbon source with other fungi such as *R. solani* and *F. oxysporum* (Sarrocco *et al*., 2009). *Trichoderma* can displace pathogens from a common habitat such as plant tissues, rhizospheres, and phyllospheres by colonizing them (Ghorbanpour *et al*., 2018). The degree of colonization of the host plant by the biocontrol agents depend upon their adaptation to the environmental conditions in which they live and plant colonization strategies (Ghorbanpour *et al*., 2018). Rapid growth and proliferation of *Trichoderma* on substrate determine their aggressiveness (Tyśkiewicz *et al*., 2022). The strain quick in colonizing substrate can quickly eliminate slow growing pathogens (Oszust *et al*., 2020).

3.1.2 Mycoparasitism and cell wall degrading enzymes

Trichoderma is a mycoparasite and has ability to parasitize other fungi such as R. solani, S. rolfsii, S. sclerotiorum etc. The mycoparasitic activity of *Trichoderma* on fungal pathogens starts with prey sensing and growing toward them, adhesion to the host, and intense branching and coiling around them. Also, they can form appressoria-like structure for penetration of the host cells (Moreno-Ruiz *et al*., 2020; Mukherjee *et al*., 2012). After penetration of the host mycelium, *Trichoderma* utilize the intracellular contents of the host (Saba *et al*., 2012). *Trichoderma* species when come in contact with the pathogen cell wall, are triggered to produce many chitinolytic enzymes such as endochitinases, 1,4-β- acetylglucosaminidases, and exochitinases (Benítez *et al*., 2004). β 1,3 glucanases produced by *Trichoderma* hydrolyse β 1,3 glucan present in cell wall of fungal pathogens (Druzhinina *et al*., 2011). According to Vinale *et al*. (2008) volatile secondary metabolites produced by *Trichoderma* species also play a key role in mycoparasitism of fungal pathogens. Contreras-Cornejo *et al*. (2016) reported T. atroviride produced 6-pentyl-α-pyrone and T. virens produced mono- and sesquiterpenes with antimicrobial functions. According to Karlsson *et al*. (2017) lectins from the fungus cell wall and release of secondary metabolites play important roles in recognition and signaling pathways such as MAPK and cAMP pathway in *Trichoderma*. After recognition of hosts, expression of molecular weapons involved in host lysis and parasitization occur. During mycoparasitism genes families such as ech42 and prb1 are upregulated in *Trichoderma* (Köhl *et al*., 2019). Nature of antagonism by *Trichoderma* species also dependent upon target pathogen. Against R. solani, parasitism is more common mode of antagonism while, against Fusarium, antibiosis is the predominant one.

3.1.3 Antibiosis

The antagonistic organisms release low molecular weight diffusible secondary metabolites and antifungal antibiotics that are detrimental for the pathogen and inhibit their growth. Majority of *Trichoderma* species produce different types of volatile and nonvolatile toxic such as harzianic acid, alamethicins, tricholin, peptaibols, antibiotics, 6-penthyl-α-pyrone, massoilactone, viridin, gliovirin, glisoprenins and heptelidic acid (Benítez *et al*., 2004). In general, antibiotic production is directly correlated with biocontrol ability of *Trichoderma* strains. According to Shi *et al*. (2012) *T. pseudokoningii* SMF2, exhibited antibiotic activities by producing TrichokoninsVI, a type of peptaibol causing extensive programmed cell death in fungal pathogens. Siddiquee (2017) found *T. harzianum* synthesized trichorzins, harzianins, trichotoxin, and trichokindins. Several *Trichoderma* species are also capable of producing polyketides, tetracyclines, macrolides and mycotoxins (Zeilinger *et al*., 2015) terpenoids, pyrones and anthraquinones (Siddiquee, 2014). However, a particular antibiotic may play important role in antibiosis of one strain and another strain may not even produce it.

3.1.4 Sclerotial parasitization

The soil borne pathogens R. solani, S. rolfsii and S. sclerotiorum, have the ability to survive in soil for prolonged duration due to formation of sclerotia, a resting structure. These sclerotia play important role in disease cycle of the pathogen. *Trichoderma* species have ability to parasitize the mycelium and sclerotia of these soil borne plant pathogens. Papavizas and Lewis (1989); Bhagat and Pan (2011); Sarrocco *et al*. (2006); Adhikari *et al* (2022) reported that the different strains of *Trichoderma* spp. varied in their ability to colonize the sclerotia of S. rolfsii. According to Sarrocco *et al*. (2006); Köhl *et al*. (2019), some *Trichoderma* species are able to penetrate the rind and colonize the inner cell layers of sclerotia, leading to destroying and leaving them not viable. Rawat and Tewari (2010) reported *T. harzianum* parasitization on sclerotia of S. rolfsii caused deformation, lysis and degradation and disappearance of cytoplasmic granules of cell wall causing loss of cellular integrity in sclerotia. Sarrocco *et al*. (2006) reported the uniformly distribution of T. virens mycelium beneath the rind of sclerotia but not in cortex and medulla. *Trichoderma* entered the sclerotia without any preferential point and caused infection. *Trichoderma* can induce enzymatic degradation of rind walls and degrade melanin of the sclerotia (Sarrocco *et al*., 2006). Liu *et al*. (2009) found the uniformly distribution of T. virens mycelium in inner and outer layer of sclerotia as intercellular fungal growth. Tsahouridou and Thanassoulopoulos (2001) observed the presence of hyphae, conidia and chlamydospores of T. koningii in the medullar tissues of the sclerotia. Ibarra-Medina *et al*. (2010) reported deformations, collapsing, cracking and increment or diminishing sclerotia size of sclerotia by different strains of *Trichoderma*. According to Butler *et al*. (2005) among different mechanism of action in biocontrol, destruction of the melanin or inhibition of its synthesis is an important one.

3.2 Indirect action of biocontrol agents

3.2.1 Induction of resistance in plants

Plants have ability to protect themselves from range of deleterious microorganisms. They are enable to recognize the invaders and produce an arsenal of antimicrobial compounds and thereby reduce the impact of pathogens invasion (Djonović *et al*., 2007). Induction of defense response is one of the most effective resistance mechanisms and are activated only upon pathogen invasion. The induction of plant resistance to pathogens are the consequences of the action of various elicitors released from the microorganisms cells (Tyśkiewicz *et al*., 2022). *Trichoderma* strains have ability to induce plant defense response and systemic resistance in plant. During plant - *Trichoderma* interaction, *Trichoderma* release numerous elicitors which induce salicylic acid (SA), jasmonic acid (JA) or reactive oxygen species (ROS) mediated signals in plant triggering defense proteins expression (Nawrocka & Małolepsza, 2013). After gene activation, the plant produces different enzymes that suppress the pathogen and enhance biochemical and structural barriers against the intruders (Nawrocka & Małolepsza, 2013). Perazzolli *et al*. (2011) showed that *Trichoderma* strain, T39 reduced downy mildew severity on susceptible grapevines by a direct modulation of defense-related genes and enhanced their expression after pathogen inoculation. They suggested that jasmonic acid and ethylene signals were induced by T39. Vinale *et al*. (2008) reported plant defence mechanisms were activated and plant growth in pea, tomato and canola were regulated when harzianolide, 6-pentyl-a-pyrone, and harzianopyridone were applied. Alizadeh *et al*. (2013) reported *T. harzianum* Tr6, elicit induced resistance in cucumber against F. oxysporum f.sp. radicis cucumerinum and in A. thaliana against B. cinerea. Plants immune system are trigger via microbe-associated molecular patterns (MAMPs) when *Trichoderma* colonize root of plants (Hermosa *et al*., 2012). According to Guo *et al*. (2021) T. asperellum ACCC30536 secreted xylanase that stimulated the systemic resistance in Populus davidiana and P. alba var. pyramidalis Louche seedlings against Alternaria alternata, R. solani, and F. oxysporum.

3.2.2 Growth promotion

Trichoderma spp. are hyperparasite of other fungi as well as avirulent plant symbionts (Saba *et al*., 2012). Some strains of *Trichoderma* colonize root surfaces of plants and penetrate into the epidermal cells. Root colonization by *Trichoderma* suppress deleterious root microflora, produce growth stimulating factors and increase nutrient uptake. Mastouri, (2010) reported increase in vigour and emergence of tomato by *T. afroharzianum*. Mayo-Prieto *et al*. (2020) observed *Trichoderma* isolated from soil increased hypocotyl diameter and length of root system of bean plants. Degani *et al*. (2021)caused by Magnaporthiopsis maydis, is considered a major threat to commercial fields in Israel, Egypt, Spain, and India. Today's control methods include chemical and agronomical intervention but rely almost solely on resistant maize cultivars. In recent years, LWD research focused on eco-friendly biological approaches to restrain the pathogen. The current study conducted during two growing seasons explores the potential of three *Trichoderma* species as bioprotective treatments against LWD. These species excelled in preliminary assays performed previously under controlled conditions and were applied here in the field by directly adding them to each seed with the sowing. In the first field experiment, *Trichoderma* longibrachiatum successfully rescued the plants' growth indices (weight and height also reported reduction in incidence of *Magnaporthiopsis maydis* in maize and improved growth and yield by application of *T. longibrachiatum*. Nieto-Jacobo *et al*. (2017) reported increase in *Arabidopsis* fresh biomass by 72% and the number of secondary roots by 64 by *Trichoderma atroviride*. However, they found that *T. asperellum* significantly inhibited *Arabidopsis* growth up to 74% than in non-inoculated soil. They stated that not all *Trichoderma* strains promote plant growth. Baazeem *et al*. (2021) revealed that inoculation of *T. hamatum* on maize, cowpea, small millet, green gram, and black gram resulted in improved seedlings growth. They also reported that the enzyme activity of rhizosphere soil improved by 12-69%. *T. hamatum* soil treatment promote enzyme mediated nutrient recycling activity.

Bader *et al*. (2020) found that *Trichoderma* strains were able to produce IAA and solubilize inorganic phosphorous resulting in improved growth of tomato plant. They also found increased photosynthesis, and dry roots weight indicating profound effect of *Trichoderma* inoculation on root development and modification of root architecture. According to Contreras-Cornejo *et al*. (2009) *Trichoderma* spp. can induce growth promotion in *A. thaliana* by synthesizing IAA.

3.2.3 Germination stimulation

Seed treatment with *Trichoderma* spp. trigger seed to produce enzymes and phytohormones required for seed germination and also enhance seed germination and seedling vigor. Several researchers have observed enhanced germination percent in tomato, pea beans, chickpea, etc. (Mastouri, 2010; Singh *et al*., 2015; Mayo-Prieto *et al*., 2020). Bezuidenhout *et al*. (2012) observed that seeds treated with *Trichoderma* had early germination indicating the effect similar to gibberellic acid. Upon evaluation of secondary metabolites secreted by *T. harzianum*, gliotoxin was found to be mimicking the plant growth hormone. According to Howell (2002) germinating seeds release nutrients and addition of *Trichoderma*, metabolizes these nutrients rendering them unavailable to the pathogens.

3.2.4 Responses of Trichoderma under drought stress

Generally, plants face several abiotic stresses that affect seed germination, seedling vigor, plant establishment, growth and development, and ultimately seed yield. Several *Trichoderma* species are competent to alleviate abiotic stress and improve plant growth and vigor (Hermosa *et al*., 2012). Bae *et al*. (2009) reported that *T. hamatum* increasing root growth of cocoa plants resulting in tolerance towards water stress condition. Mastouri *et al*. (2010) reported that *Trichoderma* strains are known to offer plant tolerance against physiological stress such as seed aging. The researcher found that peroxide levels were reduced when physiologically stressed seed of tomato treated with *T. harzianum*. Under continuous stress, Reactive oxygen species (ROS) production is increased (Schafer & Buettner, 2001). Production of ROS is important as they play a crucial role in signaling during stress condition. In response to produced ROS, plants activate the antioxidant defense systems and increased activities of ascorbate and glutathione-recycling enzymes. Mastouri *et al*. (2010) demonstrated that *T. harzianum* increases seedling vigor and ameliorates stress by inducing physiological protection in plants against oxidative damage. Navazio *et al*. (2007) observed that when soybean cell culture was treated with culture filtrate of *T. atroviride,* intracellular ROS accumulation was detected. Such signals can induce plant ROS scavenging mechanisms which results in protection against the oxidative damage (Mastouri *et al*., 2010). Along with the previously mentioned mechanism, *Trichoderma* can ameliorate plant growth by lowering deleterious elevated ethylene levels under abiotic stress conditions (Brotman *et al*., 2013). In recent studies, it has been observed that *Trichoderma* spp. can reprogram plant gene expression which is a primary method of pathogen control. As a result, induced systemic resistance (ISR) occurs (Shoresh *et al*., 2010). According to Mishra *et al*. (2020) *Trichoderma* has the ability to produce high level of phenols and proline in drought stressed rice plants leading to accumulation of chlorophyll in the plant. Ma *et al*. (2020)whereas the underlying mechanisms of *Trichoderma*-induced drought resistance of host plants remain largely elusive. Herein, the effects of a *Trichderoma harzianum* isolate on maize's responses to drought stress were investigated. Inoculation with *T. harzianum* significantly promoted the growth and enhanced drought tolerance of maize plants. The whole genome expression profiles of the *Trichoderma*-inoculated plants were examined by RNA-sequencing, showing that several differentially expressed genes were positively associated with the process of ethanol-acetic acid metabolism. Compared with non-inoculated (control reported increment in ABA level with drought stress, however, the levels of ABA was remarkably high in *T. harzianum* inoculated maize plants than the controls. Increased levels of ABA responsive gene transcripts were observed in transgenic Arabidopsis plants when exposed to abiotic and biotic stresses (Shi *et al*., 2017).

4. MODE OF APPLICATION

There are several methods for application of *Trichoderma* for the successful control of plant diseases. Mode of application of *Trichoderma* play a vital role in establishment and site of action of the antagonist.

4.1 Seed treatment

Seed treatment is one of the effective method for application of biocontrol agents. In this method seed is coated with conidia of *Trichoderma* before sowing. The ability of the antagonist to proliferate and colonize the rhizosphere determine the efficacy of seed treatment

(Nakkeeran *et al*., 2016). Juliatti *et al*. (2019) suggested that soon after treatment, seeds should be sown to avoid drying of spore and to enhance spore germination. Seed microbiolization not only promote seed germination, seedling emergence and disease control but also protect them from other fungi during storage (Juliatti *et al*., 2019). Biswas and Sen (2000) reported seed treatment with conidial suspension of *Trichoderma* was effective in reducing collar rot of groundnut caused by S. rolfsii. Under saline condition, tomato seeds treated with *Trichoderma* spp. germinated faster than control (Contreras-Cornejo *et al*., 2016; Mastouri, 2010). Juliatti *et al*. (2019) stated that seed microbiolization as an important method of application of biocontrol agents since it requires a small amount of biological material compared to the quantity needed for soil application.

4.2 Soil treatment

For the biocontrol of soil borne plant pathogens, soil application of *Trichoderma* are also recommended. But for their effective management, high population of the antagonist is required (Nakkeeran *et al*., 2016). Jegathambigai *et al*. (2010) reported that soil amendment with *Trichoderma* spp. provided control of Pigeonpea wilt caused by *Fusarium udum* and collar rot of Zamioculcas caused by *S. rolfsii* by 22-30.9% whereas seed treatment was ineffective at high level of pathogen and disease control was less than 7%. As *Trichoderma* sp. is a soil inhabitant, it has an opportunity to establish and multiply more quickly in soil than on seed surface. Although soil application of bio agents is effective against plant pathogens, their feasibility for field application is low because of the cost of production and higher volume requirements.

4.3 Foliar application

It is difficult for biocontrol agents to establish and proliferate in phyllosphere as the foliar environment is frequently fluctuating and harsh (Sawant, 2014). However, the success of antagonists on foliage depends on its ability to colonize the surfaces (Lo *et al*., 1997) brown patch, and dollar spot of creeping bentgrass was investigated. Spray applications of conidial suspensions (SA. Panwar *et al*. (2014) reported that the foliar spray of antagonist reduced the fusarium head blight of wheat caused by *F. graminearum* under greenhouse condition. Oros and Naar (2017) also reported that the liquid formulations of *T. harzianum* were efficient against rose black spot disease caused by *Diplocarpon rosae*. According to Sawant (2014), *Trichoderma* have been successfully utilized to control foliar diseases such as *B. cinerea* in strawberry*, C. gloeosporioides* and *Plasmopara viticola* in grape, *Cladosporium fulvum* in tomato and *S. sclerotiorum* in cucumber. Foliar application of bio agents is preferred during evening hours as there is least environmental effect on colonization and efficacy (Avila & Gutierrez, 1992).

5. CONCLUSION

Trichoderma is an important component in integrated disease management strategies. It does not lead to development of resistance in plant pathogens, do not enter into the food chain and do not create any pollution problems in the environment. Along with controlling plant pathogens, *Trichoderma* strains also stimulate growth and resistance in plants. *Trichoderma* is a soil resident, thus it may quickly colonize new soil, which has a positive impact on the health of the soil as well. It can be used in a variety of ways to effectively control plant diseases. *Trichoderma* application method is crucial for the establishment and location of the antagonist's site of action.

REFERENCES

Adhikari, P., Shrestha, S. M., Manandhar, H. K. & Marahatta, S. (2022). Effect of *Trichoderma* isolates on *Sclerotium rolfsii* Sacc. *Journal of Agriculture and Forestry University, 5,* 299–310.

Alizadeh, H., Behboudi, K., Ahmadzadeh, M., Javan-Nikkhah, M., Zamioudis, C., Pieterse, C. M. J., & Bakker, P. A. H. M. (2013). Induced systemic resistance in cucumber and *Arabidopsis thaliana* by the combination of *Trichoderma harzianum* Tr6 and *Pseudomonas* sp. Ps14. *Biological Control*, *65*(1), 14–23.

Amin, F., Razdan, V. K., Mohiddin, F. A., Bhat, K. A., & Banday, S. (2010). Potential of *Trichoderma* species ss bio-control agents of soil borne fungal propagules. *Journal of Phytology*, *2010*(10), 38–41.

Amir-Ahmadi, N., Moosavi, M. R., & Moafpourian, G. (2017). Effect of soil texture and its organic content on the efficacy of *Trichoderma harzianum* (MIAU 145 C) in controlling *Meloidogyne javanica* and stimulating the growth of kidney beans. *Bio-control Science and Technology*, *27*(1), 115–127.

Askew, D. J., & Laing, M. D. (1993). An adapted selective medium for the quantitative isolation of *Trichoderma* species. *Plant Pathology*, *42*, 686–690.

Avila, de M. C., & Gutierrez, de G. A. (1992). Biological control of *Sclerotinia sclerotiorum* (Lib.) de Bary on lettuce *(Lactuca sativa* L.). *Fitopatologia Colombiana*, *16*(1–2), 172–179.

Baazeem, A., Almanea, A., Manikandan, P., Alorabi, M., Vijayaraghavan, P., & Abdel-Hadi, A. (2021). *In vitro* antibacterial, antifungal, nematocidal and growth promoting activities of *Trichoderma hamatum* fb10 and its secondary metabolites. *Journal of Fungi*, *7*(5), 1–13.

Bader, A. N., Salerno, G. L., Covacevich, F., & Consolo, V. F. (2020). Native *Trichoderma harzianum* strains from Argentina produce indole-3 acetic acid and phosphorus solubilization, promote growth and control wilt disease on tomato (*Solanum lycopersicum* L.). *Journal of King Saud University - Science*, *32*(1), 867–873.

Bae,H., Sicher, R. C., Kim, M. S., Kim, S. H., Strem, M. D., Melnick, R. L., & Bailey, B. A. (2009). The beneficial endophyte *Trichoderma hamatum* isolate DIS 219b promotes growth and delays the onset of the drought response in Theobroma cacao. *Journal of Experimental Botany, 60(*11), 3279–3295.

Barman, S., Gorai, S., P., & Mandaloma, N. C. (2021). *Trichoderma* spp. Application and future prospects in agricultural industry. In Surajit De Manda & A. K. Passari (Eds.), *Recent Advancement in Microbial Biotechnology* (pp. 49–70). Academic Press.

Basim, H., Ozturk, S.B. & Yegen, O. (1999). Efficacy of a biological fungicide (Planter Box *Trichoderma harzianum* Rifai T-22) against seedling root rot pathogens (*Rhizoctonia solani, Fusarum* sp) of cotton. GAP-Environmental Symposium. Sanliurfa. Turkey, 137-144

Benítez, T., Rincón, A. M., Limón, M. C., & Codón, A. C. (2004). Bio-control mechanisms of *Trichoderma* strains. *International Microbiology*, *7*(4), 249–260.

Bezuidenhout, J., Rensburg, L. Van, & Jansen Van Rensburg, P. (2012). Molecular similarity between gibberellic acid and gliotoxin: unravelling the mechanism of action for plant growth promotion by *Trichoderma harzianum* . *Journal of Agricultural Science and Technology B*, *2*(June), 703–712.

Bhagat, S., & Pan, S. (2011). Parasitic ability of *Trichoderma* isolates against sclerotia of *Sclerotium rolfsii* and management of collar rot of brinjal. *Biopesticide International, 7*(1), 52-59.

Biswas, K. K., & Sen, C. (2000). Management of stem rot of groundnut caused by *Sclerotium rolfsii* through *Trichoderma harzianum*. *Indian Phytopathology*, *53*(3), 290–295.

Blaszczyk, L., Siwulski, M., Sobieralski, K., Lisiecka, J., & Jędryczka, M. (2014). *Trichoderma* spp. - Application and prospects for use in organic farming and industry. *Journal of Plant Protection Research*, *54*(4), 309–317.

Brotman, Y., Gupta, J., & Viterbo, A. (2010). *Trichoderma*. *Current Biology*, *20*(9), 390–391.

Butler, M. J., Gardiner, R. B., & Day, A. W. (2005). Degradation of melanin or inhibition of its synthesis: Are these a significant approach as a biological control of phytopathogenic fungi? *Biological Control*, *32*(2), 326–336.

Carro-Huerga, G., Mayo-Prieto, S., Rodríguez-González, Á., Álvarez-García, S., Gutiérrez, S., & Casquero, P. A. (2021). The influence of temperature on the growth, sporulation, colonization, and survival of *Trichoderma* spp. in grapevine pruning wounds. *Agronomy*, *11*, 1771.

Chet, I., & Inbar, J. (1994). Biological control of fungal pathogens. *Applied Biochemistry and Biotechnology*, *48*(1), 37–43.

Chet, I., 1987, *Trichoderma*-application, mode of action and potential as a biocontrol agent of soilborne plant pathogenic fungi. In Chet, I.(ed) Innovative approaches to plant disease control (pp 137–160). John Wiley and Sons, New York.

Chovanec, P., Kaliňák, M., Liptaj, T., Pronayová, N., Jakubík, T., Hudecová, D., & Varečka, Ľ. (2005). Study of *Trichoderma* viride metabolism under conditions of the restriction of oxidative processes. *Canadian Journal of Microbiology*, *51*(10), 853–862..

Contreras-Cornejo, H. A., Macías-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 Physiology*, *149*(3), 1579–1592.

Contreras-Cornejo, H. A., Macías-Rodríguez, L., Beltrán-Peña, E., Herrera-Estrella, A., & López-Bucio, J. (2011). *Trichoderma*-induced plant immunity likely involves both hormonal-and camalexin-dependent mechanisms in *Arabidopsis thaliana* and confers resistance against necrotrophic fungi *Botrytis cinerea*. *Plant Signaling & Behavior, 6*(10), 1554-1563.

Contreras-Cornejo, H. A., Macías-Rodríguez, L., del-Val, E., & Larsen, J. (2016). Ecological functions of *Trichoderma* spp. and their secondary metabolites in the rhizosphere: interactions with plants. *FEMS Microbiology Ecology*, *92*(4), fiw036.

Daryaei, A., Jones, E. E., Alizadeh, H., Glare, T. R., & Falloon, R. E. (2016). Biochemical characteristics of *Trichoderma* atroviride associated with conidium fitness for biological control. *Bio-control Science and Technology*, *26*(2), 189–205.

Degani, O., Rabinovitz, O., Becher, P., Gordani, A., & Chen, A. (2021). *Trichoderma longibrachiatum* and *Trichoderma asperellum* confer growth promotion and protection against late wilt disease in the field. *Journal of Fungi*, *7*(6).

Deng, Y., Dai, B., Xu, J., Liu, X., & Xu, J. (2018). Anaerobic co-digestion of rice straw and soybean straw to increase biogas production by pretreatment with *Trichoderma reesei* RUT C30. *Environmental Progress and Sustainable Energy*, *37*(3), 1050–1057.

Dhanya, M. K., Anjumol, K. B., Murugan, M., & Deepthy, K. B. (2016). With plant protection chemicals and fertilizers in cardamom. Journal of Tropical Agriculture, 54(2), 129–135.

Di Lelio, I., Coppola, M., Comite, E., Molisso, D., Lorito, M., Woo, S. L., Pennacchio, F., Rao, R., & Digilio, M. C. (2021). Temperature differentially influences the capacity of *Trichoderma* species to induce plant defense responses in tomato against insect pests. *Frontiers in Plant Science*, *12*(June), 1–15.

Djonović, S., Vargas, W. A., Kolomiets, M. V., Horndeski, M., Wiest, A., & Kenerley, C. M. (2007). A proteinaceous elicitor Sm1 from the beneficial fungus *Trichoderma virens* is required for induced systemic resistance in maize. *Plant Physiology*, *145*(3), 875–889.

Domingues, M. V. P. F., de Moura, K. E., Salomão, D., Elias, L. M., & Patricio, F. R. A. (2016). Effect of temperature on mycelial growth of *Trichoderma*, *Sclerotinia minor* and *S. sclerotiorum*, as well as on mycoparasitism. *Summa Phytopathologica*, *42*(3), 222–227.

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*(10), 749–759.

Eisendle, M., Oberegger, H., Buttinger, R., Illmer, P., & Haas, H. (2004). Biosynthesis and uptake of siderophores is controlled by the PacC-mediated ambient-pH regulatory system in *Aspergillus nidulans*. *Eukaryotic Cell*, *3*(2), 561–563.

Elad, Y., & Chet, I. (1983). Improved selective media for isolation of *Trichoderma* spp. or *Fusarium* spp. *Phytoparasitica*, *11*(1), 55–58.

Elad, Y., Chet, I., & Henis, Y. (1981). A selective medium for improving quantative isolation of *Trichoderma* spp. from soil. *Phytoparasitica*, *9*(1), 59–67.

Esposito, E., & Da Silva, M. (1998). Systematics and environmental application of the genus *Trichoderma*. *Critical Reviews in Microbiology*, *24*(2), 89–98.

Freeman, S., Minz, D., Kolesnik, I., Barbul, O., Zveibil, A., Maymon, M., Nitzani, Y., Benny, K., Dalia, R., Alon, B., Arnon, D., Sharoni, S., & Elad, Y. (2004). *Trichoderma* bio-control of *Colletotrichum acutatum* and *Botrytis cinerea* and survival in strawberry. *European Journal of Plant Pathology*, *110*(4), 361–370.

Gal-Hemed, I., Atanasova, L., Komon-Zelazowska, M., Druzhinina, I. S., Viterbo, A., & Yarden, O. (2011). Marine isolates of *Trichoderma* spp. as potential halotolerant agents of biological control for arid-zone agriculture. *Applied and Environmental Microbiology*, *77*(15), 5100–5109.

Ghorbanpour, M., Omidvari, M., Abbaszadeh-Dahaji, P., Omidvar, R., & Kariman, K. (2018). Mechanisms underlying the protective effects of beneficial fungi against plant diseases. *Biological Control*, *117*, 147–157.

Guo, J. H., Qi, H. Y., Guo, Y. H., Ge, H. L., Gong, L. Y., Zhang, L. X., & Sun, P. H. (2004). Biocontrol of tomato wilt by plant growth-promoting rhizobacteria. Biological control, 29(1), 66-72.

Guo, R., Ji, S., Wang, Z., Zhang, H., Wang, Y., & Liu, Z. (2021). *Trichoderma asperellum* xylanases promote growth and induce resistance in poplar. *Microbiological Research*, *248*(April), 126767.

Harman, G. E. (2006). Overview of mechanisms and uses of *Trichoderma* spp. *Phytopathology*, *96*(2), 190–194.

Harman, G. E., Howell, C. R., Viterbo, A., Chet, I., & Lorito, M. (2004). *Trichoderma* species - Opportunistic, avirulent plant symbionts. *Nature Reviews Microbiology*, *2*(1), 43–56.

Hermosa, R., Viterbo, A., Chet, I., & Monte, E. (2012). Plant-beneficial effects of *Trichoderma* and of its genes. *Microbiology*, *158*(1), 17–25.

Howell, C. R. (2002). Cotton seedling preemergence damping-off incited by *Rhizopus oryzae* and *Pythium* spp. and its biological control with *Trichoderma* spp. *Phytopathology*, *92*(2), 177–180.

Huang, X. Q., Wen, T., Zhang, J. B., Meng, L., Zhu, T. B., Liu, L. L., & Cai, Z. C. (2015). Control of soil-borne pathogen *Fusarium oxysporum* by biological soil disinfestation with incorporation of various organic matters. *European journal of plant pathology, 143*(2), 223-235.

Ibarra-Medina, V. A., Ferrera-Cerrato, R., Alarcón, A., Lara-Hernández, M. E., & Valdez-CarrascoJorge, M. (2010). Isolation and screening of *Trichoderma* strains antagonistic to *Sclerotinia sclerotiorum* and *Sclerotinia minor*. *Revista Mexicana de Micología*, *31*, 53–63.

Jegathambigai, V., Wijeratnam, R. S. W., & Wijesundera, R. L. C. (2010). Effect of *Trichoderma* sp. on *Sclerotium rolfsii* , the causative agent of collar rot on *Zamioculcas zamiifolia* and an on farm method to mass produce *Trichoderma* species. *Plant Pathology Journal*, *9*(2), 47–55.

Juliatti, F. C., Rezende, A. A., Juliatti, B. C. M., & Tâmara, M. P. (2019). *Trichoderma* as a bio-control agent against *Sclerotinia* stem rot or white mold on soybeans in Brazil: usage and technology. In *Trichoderma - The Most Widely Used Fungicide* (pp. 1–23). https://doi.org/10.5772/intechopen.84544

Junaid, J. M., Dar, N. A., Bhat, T. A., Bhat, A. H., & Bhat, M. A. (2013). Commercial biocontrol agents and their mechanism of action in the management of plant pathogens. *International Journal of Modern Plant & Animal Sciences, 1*(2), 39-57.

Karlsson, M., Atanasova, L., Jensen, D. F., & Zeilinger, S. (2017). Necrotrophic mycoparasites and their genomes. *Microbiology Spectrum*, *5*(2), 10.1128.

Kim, S. I., Shim, J. O., Shin, H. S., Choi, H. J., & Lee, M. W. (1992). Suppressive mechanism of soil-borne disease development and its practical application-isolation and identification of species of *Trichoderma* antagonistic to soil diseases and its activities in the rhizosphere. *The Korean Journal of Mycology, 20*(4), 337-346.

Klein, D., & Eveleigh, D. E. (2002). *Trichoderma* and *Gliocladium* (Christian P. Kubicek & G. E. Harman (eds.); 1st ed.). Taylor & Francis Ltd. London.

Köhl, J., Kolnaar, R., & Ravensberg, W. J. (2019). Mode of action of microbial biological control agents against plant diseases: Relevance beyond efficacy. *Frontiers in Plant Science*, *10*(July), 1–19. https://doi.org/10.3389/fpls.2019.00845

Lewis, J. A., & Papavizas, G. C. (1984). A new approach to stimulate population proliferation of *Trichoderma* species and other potential bio-control fungi introduced into natural soils. *Phytopathology*, 74, 1240–1244.

Liu, L. N., Zhang, J. Z., & Xu, T. (2009). Histopathological studies of sclerotia of *Rhizoctonia solani* parasitized by the EGFP transformant of *Trichoderma* virens. *Letters in Applied Microbiology*, *49*(6), 745–750.

Lo, C. T., Nelson, E. B., & Harman, G. E. (1997). Improved bio-control efficacy of *Trichoderma harzianum* 1295-22 for foliar phases of turf diseases by use of spray applications. *Plant Disease*, *81*(10), 1132–1138.

Ma, Z., Ge, L., Zhou, C., & Lu, X. (2020). *Trichoderma harzianum* improves drought resistance in maize by mediating acetic acid-ethanol metabolic pathways. *Pakistan Journal of Botany*, *52*(3), 1045–1054Mastouri, F. (2010). Use of *Trichoderma* spp. to improve plant performance under abiotic stresses. (PhD thesis, Cornell University, USA).

Mayo-Prieto, S., Campelo, M. P., Lorenzana, A., Rodríguez-González, A., Reinoso, B., Gutiérrez, S., & Casquero, P. A. (2020). Antifungal activity and bean growth promotion of *Trichoderma* strains isolated from seed vs soil. *European Journal of Plant Pathology*, *158*(4), 817–828.

Mishra, D., Rajput, R. S., Zaidi, N. W., & Singh, H. B. (2020). Sheath blight and drought stress management in rice (*Oryza sativa*) through *Trichoderma* spp. *Indian Phytopathology*, *73*, 71–77.

Moosavi, M. R., & Zare, R. (2015). Factors affecting commercial success of bio-control agents of phytonematodes. In T. H. Askary & P. R. P. Martinelli (Eds.), *Bio-control Agents of Phytonematodes* (pp. 423–445). CABI.

Moreno-Ruiz, D., Lichius, A., Turra, D., Di Pietro, A., & Zeilinger, S. (2020). Chemotropism assays for plant symbiosis and mycoparasitism related compound screening in *Trichoderma atroviride*. *Frontiers in Microbiology*, *11*, 601251.

Mukherjee, M., Mukherjee, P. K., Horwitz, B. A., Zachow, C., Berg, G., & Zeilinger, S. (2012). *Trichoderma*-plant-pathogen interactions: Advances in genetics of biological control. *Indian Journal of Microbiology*, *53*(4), 522–529.

Nakkeeran, S., Perumal, R., & Aiyanathan, K. E. A. (2016). Exploring the potential of *Trichoderma* for the management of seed and soil-borne diseases of crops. In R. Muniappan & E. Heinrichs (Eds.), *Integrated Pest Management of Tropical Vegetable Crops* (pp. 77–130). Springer.

Navazio, L., Moscatiello, R., Genre, A., Novero, M., Baldan, B., Bonfante, P., & Mariani, P. (2007). A diffusible signal from arbuscular mycorrhizal fungi elicits a transient cytosolic calcium elevation in host plant cells. *Plant physiology, 144*(2), 673-681.

Nawrocka, J., & Małolepsza, U. (2013). Diversity in plant systemic resistance induced by *Trichoderma*. *Biological Control*, *67*(2), 149–156.

Nieto-Jacobo, M. F., Steyaert, J. M., Salazar-Badillo, F. B., Vi Nguyen, D., Rostás, M., Braithwaite, M., De Souza, J. T., Jimenez-Bremont, J. F., Ohkura, M., Stewart, A., & Mendoza-Mendoza, A. (2017). Environmental growth conditions of *Trichoderma* spp. affects indole acetic acid derivatives, volatile organic compounds, and plant growth promotion. *Frontiers in Plant Science*, *8*(February), 1–18. https://doi.org/10.3389/fpls.2017.00102

O'Brien, P. (2017). Biological control of plant diseases. *Australasian Plant Pathology*, *46*(4), 293–304.

Oros, G., & Naar, Z. (2017). Mycofungicide: *Trichoderma* based preparation for foliar applications. *American Journal of Plant Sciences*, *8*, 113–125.

Oszust, K., Cybulska, J., & Frąc, M. (2020). How do *Trichoderma* genus fungi win a nutritional competition battle against soft fruit pathogens? A report on niche overlap nutritional potentiates. *International Journal of Molecular Science*, *21*(12), 423.

Panwar, V., Aggarwal, A., Singh, G., Saharan, M. S., Verma, A., Sharma, I., & Singh Saharan, M. (2014). Efficacy of foliar spray of *Trichoderma* isolates against *Fusarium graminearum* causing head blight of wheat. *Journal of Wheat Research*, *6*(1), 59–63.

Papavizas, G. C. (1982). Survival of *Trichoderma harzianum* in soil and in pea and bean rhizospheres. *Phytopathology*, *72*(1), 121.

Papavizas, G. C. (1985). *Trichoderma* and *Gliocladium*: biology, ecology, and potential for bio-control. *Annual Reviews of Phytopathology*, *23*, 23–54.

Papavizas, G. C., & Lewis, J. A. (1989). Effect of *Gliocladium* and *Trichoderma* on damping-off and blight of snapbean caused by *Sclerotium rolfsii* in the greenhouse. *Plant Pathology*, *38*(2), 277–286.

Papavizas, G. C., & Lumsden, R. D. (1982). Improved medium for isolation of *Trichoderma* spp. from soil. *Plant Disease*, *66*, 1019–1020.

Pastrana, A. M., Basallote-Ureba, M. J., Aguado, A., Akdi, K., & Capote, N. (2016). Biological control of strawberry soil-borne pathogens *Macrophomina phaseolina* and *Fusarium solani*, using *Trichoderma asperellum* and *Bacillus* spp. *Phytopathologia Mediterranea*, *55*(1), 109–120.

Perazzolli, M., Roatti, B., Bozza, E., & Pertot, Il. (2011). *Trichoderma harzianum* T39 induces resistance against downy mildew by priming for defense without costs for grapevine. *Biological Control*, *58*(1), 74–82.

Poosapati, S., Ravulapalli, P. D., Tippirishetty, N., Vishwanathaswamy, D. K., & Chunduri, S. (2014). Selection of high temperature and salinity tolerant *Trichoderma* isolates with antagonistic activity against *Sclerotium rolfsii*. *SpringerPlus*, *3*(1), 1–11.

Rawat, R., & Tewari, L. (2010). Transmission electron microscopic study of the cytological changes in *Sclerotium rolfsii* parasitized by a bio-control fungus *Trichoderma* sp. *Mycology*, *1*(4), 237–241.

Saba, H., Vibhash, D., Manisha, M., Prashant, K. S., Farhan, H., & Tauseef, A. (2012). *Trichoderma* – a promising plant growth stimulator and bio-control agent. *Mycosphere*, *3*(4), 524–531. https://doi.org/10.5943/mycosphere/3/4/14

Samuels, G. J., & Hebbar, P. K. (2015). *Trichoderma: Identification and agricultural applications*. APS Press.

Sarrocco, S., Guidi, L., Fambrini, S., Degl'Innocenti, E., & Vannacci, G. (2009). Competition for cellulose exploitation between *Rhizoctonia solani* and two *Trichoderma* isolates in the decomposition of wheat straw. *Journal of Plant Pathology*, *91*(2), 331–338.

Sarrocco, S., Mikkelsen, L., Vergara, M., Jensen, D. F., Lübeck, M., & Vannacci, G. (2006). Histopathological studies of sclerotia of phytopathogenic fungi parasitized by a GFP transformed *Trichoderma virens* antagonistic strain. *Mycological Research*, *110*(2), 179–187

Sawant, I. S. (2014). *Trichoderma*- foliar pathogen interactions. *The Open Mycology Journal*, *8*(1), 58–70.

Schafer, F. Q., & Buettner, G. R. (2001). Redox environment of the cell as viewed through the redox state of the glutathione disulfide/glutathione couple. *Free radical biology and medicine, 30*(11), 1191-1212.

Seema, M., & Devaki, N. S. (2012). *In vitro* evaluation of biological control agents against *Rhizoctonia solani*. *Journal of Agricultural Technology*, *8*(1), 233–240.

Sharma, R. L., Singh, B. P., Thakur, M. P., & Thapak, S. K. (2005). Effect of media, temperature, ph and light on the growth and sporulation of *Fusarium oxysporum* f. sp. *lini* (Bolley) Snyder and Hensan. *Annals of Plant Protection Sciences*, *13*, 172-174.

Shi, H., Liu, W., Yaoa, Y., Weia, Y., & Chan, Z. (2017). Alcohol dehydrogenase 1 (ADH1) confers both abiotic and biotic stress resistance in *Arabidopsis*. *Plant Science*, *262*, 24–31.

Shi, M., Chen, L., Wang, X. W., Zhang, T., Zhao, P. B., Song, X. Y., Sun, C. Y., Chen, X. L., Zhou, B. C., & Zhang, Y. Z. (2012). Antimicrobial peptaibols from *Trichoderma pseudokoningii* induce programmed cell death in plant fungal pathogens. *Microbiology*, *158*(1), 166–175.

Shoresh, M., Harman, G. E., & Mastouri, F. (2010). Induced systemic resistance and plant responses to fungal biocontrol agents. *Annual review of Phytopathology, 48*(1), 21-43.

Siddiquee, S. (2014). Recent advancements on the role and analysis of volatile compounds (VOCs) from *Trichoderma*. In V. K. Gupta, M. Schmoll, A. Herrera-Estrella, R. S. Upadhyay, I. Druzhinina, & M. G. Tuohy (Eds.), *Biotechnology and Biology of Trichoderma* (pp. 139–175). Elsevier.

Siddiquee, S. (2017). Fungal volatile organic compounds: emphasis on their plant growth-promoting. In D. Choudhary, A. Sharma, P. Agarwal, A. Varma, & N. Tuteja (Eds.), *Volatiles and Food Security: Role of Volatiles in Agro-Ecosystems* (pp. 313–333). Springer.

Singh, R.S., Singh, J., Singh, H.V., Dhaliwal, G.S., Arora, R., Randhawa, N.S. & Dhawan, A.K. (1998). Effect of irrigation and pH on efficacy of *Trichoderma* in biocontrol of black scurf of potato. In Ecological agriculture and sustainable development, Proceedings of International Conference on Ecological Agriculture: Towards Sustainable Development 1998 (pp. 375-381). Chandigarh, India.

Singh, B. N., Singh, A., Singh, G. S., & Dwivedi, P. (2015). Potential role of *Trichoderma asperellum* T42 strain in growth of pea plant for sustainable agriculture. *Journal of Pure and Applied Microbiology*, *9*(2), 1069–1074.

Subedi, S., Shrestha, S. M., Kc, G. B., Thapa, R. B., Ghımıre, S. K., Gharti, D. B., & Neupane, S. (2014). Integrated approach for the management of new threat *Stemphylium botryosum* walr causing blight of lentil (*Lens culinaris* Medik). *Türk Tarım ve Doğa Bilimleri Dergisi*, *6*, 1209-1220.

Timila, R. D., Manandhar, S., Manandhar, C., & Mahto, B. N. (2015). The *Trichoderma* spp .: A biological control agents from nepalese soil. In K. B. Karki (Ed.), *Proceedings of the Second National Soil Fertility Research Workshop* (Issues 24-25 March, pp. 294–300). Soil Science Division, Nepal Agricultural Research Council, Nepal.

Tsahouridou, P. C., & Thanassoulopoulos, C. C. (2001). *Trichoderma koningii* as a potential parasite of sclerotia of *Sclerotium rolfsii*. *Cryptogamie Mycologie*, *22*(4), 289–295.

Tyśkiewicz, R., Nowak, A., Ozimek, E., & Jaroszuk-ściseł, J. (2022). *Trichoderma*: The current status of its application in agriculture for the bio-control of fungal phytopathogens and stimulation of plant growth. *International Journal of Molecular Sciences*, *23*(4).

Vinale, F., Sivasithamparam, K., Ghisalberti, E. L., Marra, R., Woo, S. L., & Lorito, M. (2008). *Trichoderma* – plant – pathogen interactions. *Soil Biology & Biochemistry*, *40*, 1–10.

Watanabe, N. (1984): Anugonism by various kinds of *Trichoderma* fungi to soil-borne plant pathogens.*Bulletin Faculty of Agriculture, Meiji University, 66*, 45—50.

Williams, J., Clarkson, J. M., Mills, P. R., & Cooper, R. M. (2003). A selective medium for quantitative reisolation of *Trichoderma harzianum* from *Agaricus bisporus* compost. *Applied and Environmental Microbiology*, *69*(7), 4190–4191.

Wong, P. T. W., Mead, J. A., & Croft, M. C. (2002). Effect of temperature, moisture, soil type and *Trichoderma* species on the survival of *Fusarium pseudograminearum* in wheat straw. *Australasian Plant Pathology*, *31*(3), 253–257.

Zeilinger, S., García-Estrada, C., & Martín, J.-F. (2015). Fungal secondary metabolites in the "OMICS" era. In S. Zeilinger, J. F. Martín, & C. García-Estrada (Eds.), *Biosynthesis and Molecular Genetics of Fungal Secondary Metabolites* (2nd ed., pp. 1–12). Springer.