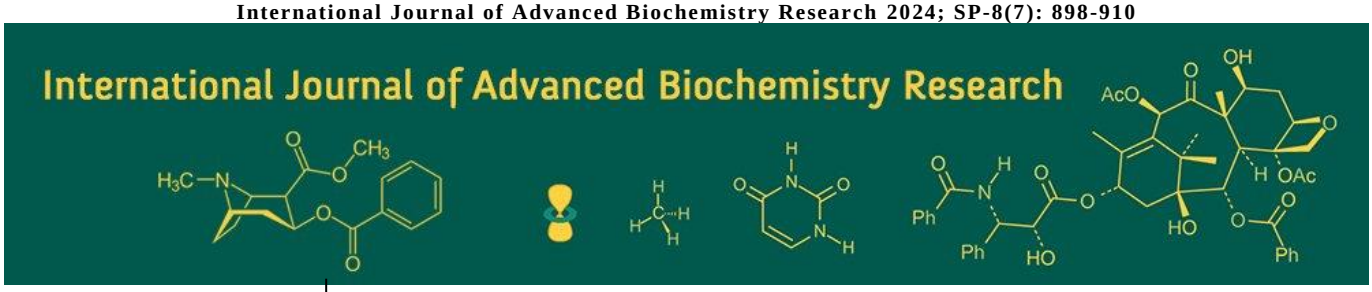

ISSN Print: 2617-4693
ISSN Online: 2617-4707
IJABR 2024; SP-8(7): 898-910
www.biochemjournal.com
Received: 14-05-2024
Accepted: 19-06-2024

Lokenath Dash
Department of Agriculture, Swami Vivekananda University, Barrackpore, West Bengal, India

Amisha Singh
Department of Agriculture, Swami Vivekananda University, Barrackpore, West Bengal, India

Poulomi Sen
Department of Agriculture, Sister Nivedita University, New Town, Kolkata, West Bengal, India

Avishek Chatterjee
Department of Agriculture, Swami Vivekananda University, Barrackpore, West Bengal, India

Corresponding Author:
Avishek Chatterjee
Department of Agriculture, Swami Vivekananda University, Barrackpore, West Bengal, India

Trichoderma as a possible biocontrol agent and its use in agriculture

Lokenath Dash, Amisha Singh, Poulomi Sen and Avishek Chatterjee

DOI: https://doi.org/10.33545/26174693.2024.v8.i7Sl.1670

Abstract
Increased agricultural food production is required to feed the growing global population. However, risk of pest infestation hugely hampers the agricultural production every year. The main factor reducing this loss is the usage of chemical insecticides. Even though these compounds are highly effective, they have a severe impact on both human life and the environment. Therefore, it is crucial to create innovative, secure alternatives that are both effective and safe. *Trichoderma* species are opportunistic, avirulent plant symbionts. Their symbiotic relationship with plants increases plant resilience to diseases, enhances growth and productivity, encourages nutrient uptake and fertilizer use efficiency. Antibiosis, competition, and mycoparasitism are a few of the key ways that *Trichoderma* responds to the presence of other competing pathogenic organisms by inhibiting or blocking their growth, among other biocontrol mechanisms. Indirectly and directly, the use of *Trichoderma* as a biocontrol agent for insect pest has been contemplated recently. *Trichoderma* is capable of directly reducing insect pests through parasitism and the formation of insecticidal secondary metabolites, antifeedant chemicals, and repellent metabolites, according to studies conducted so far. Additionally, indirectly, through the induction of innate plant defence mechanisms, the recruitment of natural enemies, or the parasitism of microorganisms that lives in symbiotic relationship with insects. The existing data on *Trichoderma* spp. and its biocontrol activity in long-term disease management programmes are reviewed in this work.

Keywords: *Trichoderma*, Biocontrol agent, antibiosis, mycoparasitism

Introduction
Biological control, as defined by Cook and Baker 1983, is the process that reduces the number of microbes or pathogens without the assistance of outside humans. Tubef first used the term "biocontrol" in 1914, and Smith first connected it to insects and plant pathogens in 1909. By examining the antagonistic potential of some microorganisms, this methodological scheme uses natural predators that have the capacity to eradicate and control the growth of pests as well as pathogens, making it an environmentally friendly method for controlling crop diseases (Gawai, 2018) [14]. Chemical compounds have been used to control plant diseases (chemical control), but overuse of these compounds has facilitated the evolution of fungicide resistance in pathogens. In contrast, using antagonistic microbes to control plant pathogens (biological control) poses no risk when it strengthens the local antagonist population. Many microbial antagonists have been reported to possess antagonistic activities against plant fungal pathogens, such as *Pseudomonas fluorescens*, *Agrobacterium radiobacter*, *Bacillus subtilis*, *B. cereus*, *B. amyloliquefaciens*, *Trichoderma virens*, *Burkholderia cepacia*, *Saccharomyces* sp., *Gliocadium* sp. etc. The specificity of the biological control agent released in a new ecosystem is one of the major issues with this approach, so the viability of such introductions must be carefully considered.
The genus *Trichoderma* belongs to the Kingdom-Fungi, Phylum-Deuteromycotina, Class-Sodariomycetes, Order-Hypocreales, Family-Hypocreaceae. However, *Trichoderma* fungi, which are common in most ecosystems, can eliminate this significant concern (Brotman *et al*., 2010) [15] of chemical control. In recent years, the use of pesticides in economically significant crops has decreased as a result of integrated pest management strategies, reduced or controlled pesticide use, and increased use of fungal biocontrol agents, particularly *Trichoderma* spp. The most widely and frequently used fungal biocontrol agents against fungi are *Trichoderma* spp.

They are used in different crops as bio control agents which include pulses, grapes, cotton, onions, carrots, peas, plums, maize, and apples. Due to their capacity to produce enzymes that break down polysaccharides, *Trichoderma* spp. can grow on a wide range of substrates and has a very rapid growth rate. In addition, they can withstand a variety of environmental conditions (Papavizas 1985; Elad *et al*., 1993) [97, 38]. Through the use of antagonists, phytopathogenic fungi have been used to control plant diseases, *Trichoderma* has been utilized in 90% of these applications. *Trichoderma* spp. are also used to treat plant diseases brought on by nematodes and insects that rob crops in a variety of settings, including greenhouses, fields, and post-harvest (Ferreira and Musumeci 2021) [40]. Additionally, *Trichoderma* species provide benefits to agriculture such as increased photosynthetic capacity and yields, effective nutrient uptake, and resistance to abiotic stress (Sood *et al*., 2020) [117]. Effectiveness of *Trichoderma* as a biocontrol agent, the mechanisms of its biocontrol, and the variables that affect its biocontrol is discussed in this brief review article.

Morphology and features of *Trichoderma*

Rifai 1969 and Domsch *et al*., 1980 explained that colonies of *Trichoderma* spp. grown in culture appeared floccose, tufted green, rapidly multiplying, and sporulating well under incandescent light or produced spores in bands under normal conditions. The sterile, creeping, septate tufts of conidiophores that rise upright from a small branch are known as phialides in *Trichoderma* spp. When *T. viride* was observed, it was discovered that conidia have double-layered walls made up of an inner layer with a moderate electron density and an outer layer with a coarse outer layer known as an epipore. According to Hashioka *et al*., 1996 [50], the conidia and hyphae have a distinct mucilaginous substance surrounding them. Chlamydospores are formed in the cultural media as well, but they do so later, according to Majumdar 1993 [73] and Sengupta 1995 [113]. These round, double-walled, intercalary or, rarely, terminal chlamydospores serve as resting spores under unfavorable circumstances. In order to see the branching pattern of the fungus that produces cellulolytic enzymes, *T. reesei*'s micromorphology was studied by confocal laser scanning microscopy a few years ago (Novy *et al*., 2016) [95]. According to Kubicek *et al*., 2009 [63] and Jaklitsch 2009 [57], *Trichoderma* spp. are typically found in areas with decomposing plant materials, primarily cellulosic materials. The presence of branched conidiophores with bright green conidia is the distinguishing characteristic of *Trichoderma* spp. The strain's phialides and phialospores are found in the conidiophores. *T. viride* bears globose conidia, while *T. harzianum* has light green conidia that are globose to sub-globose, according to Shah *et al*., 2012 [16], *T. pseudokoningii* showed small, light green conidia.

***Trichoderma* as a biocontrol agent**

Early in the 1930s, researchers began to notice *Trichoderma*'s efficacy as a biocontrol agent. *Trichoderma* is thought to have a biocontrol mechanism that involves mycoparasitism, competition, antibiosis, or a combination of all of these (Elad 1996) [36]. In 1933, Weindling claimed that a *T. lignorum* strain produced a "Lethal principle" that was secreted in the environment and caused the biocontrol agent to engage in parasitic activity. Lumsden *et al*., 1992 [71] found that *T. virens* can suppress the damping-off of zinnias brought on by *R. solani* and *Pythium ultimum*. Utilizing microorganisms as biocontrol agents to combat plant pathogens is very environmentally friendly. About 20 different species of *Trichoderma* have the potential to function as biocontrol agents for soil-borne and foliar plant pathogens. They include species with significant antagonistic characteristics such as *T. harzianum*, *T. viride*, *T. atroviride*, *T. pseudokoningii*, *T. longibrachiatum*, *T. hamatum*, *T. polysporum*, and *T. reesei* (Monaco *et al*., 1991) [82]. Mukherjee and Raghu 1997 observed Glicocladium virens and *Trichoderma* sp. suppressing S. rolsfii on ginger rhizomes. Through the production of specific volatile compounds, four *Trichoderma* species were able to inhibit the growth of *Fusarium oxysporum* (Li *et al*., 2018) [67].

Bicontrol Mechanisms of *Trichoderma*

The biocontrol action of *Trichoderma* is through various mechanisms. The major mechanisms include antibiosis, competition and mycoparasitism. These mechanisms are described below.

Antibiosis action of *Trichoderma*

One of the primary elements determining the fungus' saprophytic capacity is antibiosis. A group of researchers (Manibhusanrao *et al*., 1989) [74] revealed that antibiotics produced by *T. harzianum* such as trichodermin, suzukacillin, and alamethicin impact the morphological or physiological sequences that lead to its effective penetration. Volatile and non-volatile toxic metabolites that inhibit colonization by antagonized microorganisms are produced by most of the *Trichoderma* strains; among all these metabolites, Vey *et al*., 2001 described the production of harzianic acid, alamethicins, tricholin, peptaibols, antibiotics, 6-penthyl-α-pyrone, massoilactone, viridin, gliovirin, glisoprenins, heptelidic acid and others. Antibiotic studies on both volatile and non-volatile antibiotics revealed that *T. harzianum* and *T. viride* were particularly effective in reducing the radial growth of *S. rolfsii* (Rao and Kulkarni, 2003) [102]. *Trichoderma* spp. has been shown to produce volatile and nonvolatile antibiotics that are antagonistic to a variety of pathogenic fungi (Mukhopadhyay and Kaur, 1990) [92]. *T. harzianum*, *T. viride*, *T. aureoviride*, and *G. virens* were utilized to isolate their five local isolates from ginger rhizosphere, and their method of antagonism against *R. solani*, harming Capsicum annuum and C. frutescens, was evaluated *in vitro*. Non-volatile antibiotics were found to be more efficiently effective than volatile antibiotics (Bunker and Mathur, 2001) [17]. There have also been reports of overproduction of antibiotics by strains, such as *T. virens* mutants producing too much gliovirinwhich offer similar biocontrol to the wildtype, and gliovirin deficient mutants that did not safeguard cotton seedlings from Phytium ultimum, while the parental strain did (Chet *et al*., 1997) [22]. *T. virens* strains that are most effective as biocontrol agents may generally produce gliovirin (Howell 1998) [53]. Furthermore, the most successful *T. harzianum* strains generate pyrone antibiotics against *Gaeumannomyces graminis* var. tritici, which clearly contributed to its success. Bhagat and Pan, 2010 [11] used dual culture tests and antibiotic production (volatile and nonvolatile) to test 12 strains of *Trichoderma* spp. *in vitro* against *R. solani* Kuhn., which causes root and collar rot of French bean (*Phaseolus*

vulgaris L.), and found that all isolates significantlyreduced *R. solani* mycelial growth. When antibiotics and various types of hydrolytic enzymes were combined and applied to *B. cinerea* and *F. oxysporum*, synergism occurred, but it waslesser when the antibiotics were incorporated first, indicating that cellwall deterioration was required to establish the relationship (Howell 2003) [54]. The synergistic effects of a *T. harzianum* endochitinase and the antibiotic gliotoxin, as well as hydrolytic enzymes and peptaibols, on *B. cinerea* conidial germination are well known (Howell 2003) [54].

Mycoparasitic action of *Trichoderma*

Through activation of plant defense systems

Trichoderma settles only the root's external layers, acting as a root endophyte as a result of a salicylic acidmediated plant reaction that prevents the fungus from becoming a systemic pathogen by preventing it from reaching vascular bundles (Alonso Ramirez *et al*., 2014; Poveda *et al*., 2020a) [1, 97]. *Trichoderma* is thus capable of activating systemic plant resistances against pests and/or pathogens (Poveda *et al*., 2020b) [98]. *Trichoderma* species have been shown to parasitize not only fungus, but additionally eggs and larvae of early stages of nematodes (Zhang *et al*., 2014; Ibrahim *et al*., 2020) [129] and insects (Hatvani *et al*., 2019) [51]. *T. longibrachiatum* and *T. harzianum* parasitize mature hemipteran insects of the silverleaf whitefly (Bemisia tabaci) and the tropical bedbug (*Cimex hemipterus*), resulting in 40% death for the whitefly in 5 days and 90% death for the bedbug in 14 days (Anwar *et al*., 2016) [15]. When sprayed to wheat grains, T. album destroys 94% of the lesser grain borer (*Rhyzopertha dominica*) in 7 days (Mohamed and Taha, 2017) [2]. Inoculating the leaves of *Circium arvense* and *Arabodopsis thaliana* with *T. viride* and *T. gamsii*, respectively, activates plant systemic defenses and reduces eating of the thristle tortoise beetle (*Cassida rubiginosa*) (Gange *et al*., 2012) [43] and cabbage looper (Trichoplusia ni) (Zhou *et al*., 2018) [129]. *T. harzianum*, *T. longibrachiatum*, and T. atrovirdae may stimulate S Amediated systemic defense against the potato aphid (*Macrosiphum euphorbiae*) by settling in tomato plant roots, resulting in 100% aphid mortality in 25 days. This occurs as a result of plant synthesis of VOCs such as methyl salicylate, which draws the parasitoid wasp (*Aphidus ervi*) (Coppola *et al*., 2017, 2019a, 2019b) [25, 26, 27] as well as the predatory aphid (*Macrolopholus pygmaeus*) (Battaglia *et al*., 2013) [8]. When *T. harzianum*, *T. asperellum*, and *T. atroviride* spores are inoculated directly with hazelnut branches, they greatly diminish the beetle number by simply mycoparasiting the beetle-symbiotic fungus. (Kushiyev *et al*., 2020) [64].

Through cell wall degrading lytic enzymes

Chitinases derived from bacteria and fungi are thought to behaving greater potential antifungal agents than plant chitinases. Chitinases are classified as 1, 4 acetylglucosaminidases (GlcNAcases), endochitinases, and exochitinases. *T. harzianum* TM and *T. asperellum* strains both had the glcNAcases CHIT73 and CHIT102 (Haran *et al*., 1996) [47]. Fungal chitinases have an antifungal impact due to their chitinolytic activity, particularly in *Trichoderma*, with an ED50 value equivalent to several commercial fungicides (Lorito *et al*., 1993) [69]. *Trichoderma* derived chitinase enzymes have the ability to cause distortions in ascomycetes and basidiomycetes' cell walls (Monte 2001) [83]. Chit42 is an endochitinase secreted by *T. harzianum* that may hydrolyze the cell walls of Botrytiscineraand inhibit spore germination and pollen tube elongation in a variety of fungi (Marcovich and Konova, 2002) [77]. Two *T. harzianum*-derived chitinases with a similar molecular weight but separate PI values may be employed to inhibit spore germination and germ tube development in fungi from various genera such as *Fusarium*, Gliocladium, *Trichoderma*, Rhizoctonia, Ustilago, Botrytis, Sclerotium, and Alternaria (Marcovich and Konova 2002) [77]. *Trichoderma longibrachiatum*'s chitinase action may be useful in controlling Aphis gossypi infestations in cotton plants (Anwar *et al*., 2023) [15]. The antifungal efficacy of *Trichoderma asperellum*, as well as its involvement in inducing a defensive reaction against leaf spot disease in lettuce via chitinase action, has already been established (Baiyee *et al*., 2019) [7]. Just a few of the many identified 1, 3 glucanases have been successfully cloned, including bgn 13.1. l am 1.3 (Cohen Kupiec 1999) [23] from *T. harzianum*, glu 78 (Donzelli *et al*., 2001) [33] from *T. atroviride*, and Tv-bgn1 and Tv-bgn2 from *T. virens* (Kim *et al*., 2002) [58]. Glucanases appear to be responsible for *Trichoderma's* antagonism of plantpathogenic oomycetes such as *Pythium*.When chitinase and glucanase were expressed together in a transgenic tobacco plant, immunity towards bacterial infection was increased (Jach *et al*., 1995) [56]. Several *Trichoderma* spp. 1, 6glucanases have exhibited antagonistic action, either alone or in conjunction with chitinases (da Silva Aires *et al*., 2012) [29]. Prb1, an alkaline protease isolated from *T. harzianum* IMI 206040, has been shown to have an important role in biological regulation. *T. harzianum* protease Pra1 has been shown to exhibit attraction for fungus cell walls, which could be effective in biocontrol (Elad *et al*., 2000) [35]. When the *T. virens* extracellular serine protease gene (tvsp1) was cloned, it was discovered that overexpression significantly increased cotton seedling protection against *R. solani* (Pozo *et al*., 2004) [99].

Competition mechanism of Biocontrol

Trichoderma strains, like any other beneficial antagonist, can withstand the fungistatic effects of soil caused by the presence of plant metabolites and can grow quickly in soil while being resilient to toxic substances such as herbicides, fungicides, phenolic compounds, and pesticides such as DDT (Chet *et al*. 1997) [22]. *Trichoderma* strains are very effective in managing multiple phytopathogens such as *R. solani*, P. ultimum, or *S. rolfsii* as an alternative to chemicals such as capatan, benomyl, and others because they can recover very quickly after the addition of sublethal doses of some of these toxic compounds (Vyas and Vyas 1995) [122]. Starvation is the most prevalent cause of mortality in microorganisms. As a result, Chet *et al*., 1997 [22] argued that competing for nutrition availability might result in fungal pathogen biological control. Iron absorption, for example, is required for most filamentous fungus to survive (Eisendle *et al*., 2004) [34]. A variety of *Trichoderma* BCAs can produce siderophores (low-molecular-weight ferric-ironspecific chelators) that are highly effective at chelating ambient iron and thereby inhibiting the growth of other fungus (Chet and Inbar 1994) [21]. As a result, the soil composition influences the efficiency of *Pythium* biocontrol by *Trichoderma* in relation to iron availability.

T. harzianum T35 management of *Fusarium oxysporum* through competition for both Rhizosphere colonization and nutrients is becoming increasingly useful when nutrient concentrations decline progressively (Tjamos 1992) [199]. Competition has become extremely significant in the biocontrol of phytopathogens such as *B. cinerea*, which is the most important pre- and post-harvest pathogenic agent in numerous countries (Latorre *et al*., 2001) [65]. The main advantage of using *Trichoderma* to control *B. cinerea* is that *Trichoderma* uses an array of biocontrol mechanisms, making it nearly impossible for *B. cinerea* to generate a resistant strain, despite the fact that *B. cinerea* has outstanding genetic variability (Latorre *et al*. 2001) [65]. Among all methods of competition, nutritional competition is the most important because *B. cinerea* is especially vulnerable to nutrient deficit. *Trichoderma* spp. and *R. solani* may compete for nutrition, rhizosphere, and root colonization (Yu *et al*., 2022) [127] and for seed exudates, which stimulate the growth of *R. solani* propagules in soil (Nawrocka *et al*., 2018) [93]. *Trichoderma* genes can be used to make transgenic plants resistant to fungal pathogens.

Factors influencing biocontrol potential of *Trichoderma* species

Environmental factors

The optimal growth temperature in *Trichoderma* species varies, however the majority of them are mesophilic (Samuels 1996) [110]. Several researchers determined that water conditions have a substantial impact on *Trichoderma* activities such as spore germination and germ tube growth (Magan, 1998) [7], contact with other fungus (Badham 1991) [5], and the generation of enzymes (Grajek and Gervais 1987) [45]. Cellobiohydrolase and NAGase enzyme secretion was found to be optimal at higher water potentials, whereas secreted glucosidase, xylosidase, and chymotrypsin like enzyme activities were found to be optimal at lower water potentials (Mukhopadhyay and Kumar 2020) [92]. A group of scientists namely, Zehra *et al*., 2017 [128] investigated the biocontrol ability of several *Trichoderma* species against *Alternaria alternata* and *Fusarium oxysporum* under various environmental circumstances such as salt, pH, and temperature, and discovered that *T. harzianum* was particularly most effective.

Practical factors influencing fungicide characters of *Trichoderma*

Preventive treatments are found effective when *Trichoderma* species are inoculated before the pathogen or when the time gap between antagonist and pathogen inoculation is concised. This was demonstrated by Diaz-Gutiérrez *et al*., 2021 [30] through their experiment. They assessed the obstructive and curative capabilities of *T. asperellum* UDEAGIEM-H01 against *Fusarium oxysporum* in stevia plants. The *Fusarium* wilt infestation was only 10% when the antagonist was inoculated 6 days before the pathogen whereas the infestation was about 70% when the inoculation was done 6 days after the pathogen attack. This indicated the greater effectiveness of biocontrol in early inoculation of antagonist. However, protective effect was seen in a therapeutic treatment against Phytopthora cactorum in graft wound of pear plant when the application of *Trichoderma* strains was done 24 h after pathogen inoculation (Sánchez *et al*., 2019) [111]. Advanced symptoms of diseases on infected plants and tissues have not been yet reported that have shown curative effects on application of *Trichoderma* spp. In another proposition Harman, 2000 stated that *Trichoderma* spp. should be used as a integrated management strategy along with the application of systemic fungicides when the disease pressure is high as because some *Trichoderma* spp. resist amalgamation with fungicides. Another group of scientists demonstrated that the mutual application of difenoconazole-propiconazole and *T. harzianum* was observed to control 60% of the Southern corn leaf blight in maize under natural field conditions. The singular treatment of the fungicides was seen to give no better results (Wang *et al*., 2019) [123].

The frequency of application too affects the biocontrol efficiency of *Trichoderma* spp. It was seen by Harman, 2011 that in orderly applications, 500 mg/Ha of commercial preparation 1 × 1010 cfu/g is recommendable for treatments with seed of tested crops; whereas 1 × 104-1 × 105 cfu/mL are applied for potting soils in greenhouse. However, upon heavy disease infestation situations, more frequent inoculations and higher concentrations of *Trichoderma* spp. are essential to reduce any more spread of the pathogens (Hanada *et al*., 2009) [46].

The application procedure of *Trichoderma* spp. to the ecosystem effects the biocontrol efficacy (Rojo *et al*., 2007) [104]. Application of *T. harzianum* spores by pollinators like honey bees (Apis mellifera) and bumblebees (*Bombus terrestris*) were seen to be more effective than spray applications to control *B. cinerea* in strawberry (Kovach *et al*., 2000) [62]. The method of application also depends on the nature of the pathogen to be controlled, the site where it attacks and the tissues where the disease occurs. Applications in soil are useful to suppress sclerotia and other survival structures of soil borne pathogens that decreases the levels of primary inoculum of pathogens (Amira *et al*., 2017) [2]. However, control of foliar phases of diseases caused by polycyclic pathogens would not be effectively controlled by soil application of inoculum (Elad 2000) [35].

Development of transgenics

T. virens genes encoding hydrolytic enzymes have been extracted to investigate their function in mycoparasitism and antifungal activity (Baek *et al*., 1999; Kim *et al*., 2002) [6, 58]. Emani *et al*., 2003 [39] conducted research on the efficiency of the 42 kDa endochitinase genes from *T. virens* against fungal infections in cotton. Cotton plants altered with one of the 42 kDa endochitinase genes obtained from *T. virens* demonstrated a high level of resistance to *R. solani* and A. alternata infestation. Though previous research had shown that overexpression of plant chitinase genes in transgenics had increased disease resistance (Brogue *et al*., 1991) [14], it was verified when *Trichoderma* chitinase (chit42) expression in tobacco and potato raised resistance to both foliar (*B. cinerea* and *Alternaria alternata*) and soilborne (*Rhizoctonia solani*) pathogens (Lorito *et al*., 1998) [70]. Transgenic apple plants that overexpressed *T. atroviride* CHIT42 exhibited increased resistance to Venturia inaequalis (Bolar *et al*., 2000) [12]. The same research group (Brants *et al*., 2001) [13] discovered that cell cultures of transgenic tobacco expressing the chit 42 gene together with a *T. atroviride* secretion signal peptide might prevent the germination of Penicillium digitatum conidia. Chit42 expression in broccoli by (Mora *et al*., 2001) [85] resulted in a considerable reduction in the severity of disease caused by

A. brassicicola in leaves, which was shown to be comparable to the efficiency of fungicides on non-transgenic plants.

When the Gluc78 gene, which encodes the exo1,3glucanase a from *T. atroviride*, was inserted into the pearl millet genome, varied levels of resistance to the downy mildew disease (*Sclerospora graminicola*) were seen in different transgenic types (O'kennedy *et al*., 2011) [95]. The expression of the endochitinase chit 36 gene obtained from *T. asperelloides* T203 inhibited the growth of Alternaria radicina and *B. cinerea* on carrot leaves (Baranski *et al*., 2008) [100]. When investigated by Shah *et al*. 2010 [15], the same chit42 of another strain of *T. virens* was shown to have higher endo chitinase activity in tobacco and tomato leaf and stem tissue compared to root tissue. The first glucanase of this genus to be expressed in plants, the alpha-1, s3-glucanase gene agn 13.1 isolated from *T. harzianum*, showed antifungal and antioomycete activity, and the expression of this enzyme in *Arabidopsis trichomes* resulted in significant resistance to infection by *B. cinerea* (Calo *et al*., 2006) [18]. *T. virens* endochitinase gene (cht 42) identified and inserted in transgenic rice shown increased resistance to sheath blight (Shah *et al*., 2009) [14]. The heat shock protein (HSP) hsp70 gene was isolated from *T. harzianum* and introduced to Arabidopsis to induce stress tolerance (Montero-Barrientos *et al*., 2010) [85]. When *T. harzianum* strain genes encoding a 42 kDa endochitinase (harchit) and a chitosanase (harcho) were inserted in sorghum plants, seedling toleranct to the anthracnose disease was reported (Kosambo-Ayoo *et al*., 2011) [59]. A list of genes used as bio control agents isolated from *Trichoderma* enlisted in table no 1.

Conclusion

Trichoderma can play an important part in integrated pest management which is becoming popular day by day. The combination of *Trichoderma* with GRAS drugs, cultural practices, physical techniques, and other antagonists in an integrated treatment system can be used to increase food producer output and income in a sustainable manner. Different *Trichoderma* have been isolated and studied for their biocontrol mechanisms. The principal activity noticed was the infections' development and proliferation being limited by parasitism, competition, and antibiosis. The mechanisms of biocontrol exerted by *Trichoderma* strains on various phytopathogens and pests under study have provided us with a better understanding of those mechanisms, as well as the signaling pathways and associated components involved in procedures such as host acknowledgment by *Trichoderma* spp. These approaches will aid in the efficient isolation of better enhanced strains, allowing for the development of more effective formulations for disease management before and after harvest periods. Despite the fact that *Trichoderma* has demonstrated similar or even greater efficacy than fungicides and pesticides in specific conditions (Ferreira and Musumeci 2021) [40], complete replacement of fungicides with *Trichoderma* isstill far from practical, as much work remains to be done to make this possibility a reality.

Table 1: List of some biocontrol genes isolated from *Trichoderma* strains

Sl. No.	Name of the strain	Isolated gene	Function	Reference
1.	*T. harzianum* strain IMI206040)	proteinase prb1 and endochitinase (ech42 genes	This gene expression helps to regulate hydrolytic enzymes.	Cortes *et al*. 1998 [28]
2.	*T. harzianum* strain P1 74058	ech 42 gene.	Disruption of this gene affects the biocontrol activity	Woo *et al*. 1999 [127]
3.	*Trichoderma* strain SY	Xylanase gene Xyl	Assists to breakdown hemicellulose.	Min *et al*. 2002 [80]
4.	*T. longibrachiatum* wild type strain CECT2606	B-1,4-endoglucanase gene, egl1	Shows better biocontrol activity against *Pythium ultimum* on cucumber	Migheli *et al*. 1998 [79]
5.	*T. atroviride* strain P1 (ATCC 74058)	1,3-βglucosidase gene, gluc78	Helps to degrade cell wall of *Pythium* and Phytophthora pathogens.	Donzelli *et al*. 2001 [33]
6.	*T. harzianum* strain ATCC 90237	trichodiene synthase tri5 gene	Enhances the virulence against *Fusarium* spp.	Gallo *et al*. 2004 [41]
7.	*T. virens* strain IMI 304061	TgaA, TgaB genes	Enhances virulence against the plant pathogenic interactions.	Mukherjee *et al*. 2004 [87]
8.	*T. hamatum* strain LU593	chitinase chit42 and proteinase prb1 gene	Exhibits moderate biocontrol activity against Sclerotinia sclerotiorum.	Steyaert *et al*. 2004
9.	*T. virens* strain IMI 304061	TmkA Mitogen Activated Protein kinase gene	This gene inhibits the formation of conidia in *R. solani*.	Mukherjee *et al*. 2003 [90]
10.	*T. virens* wildtype strain Gv298 and an arginine auxotrophic strain, Tv10.4	tvsp1 serine protease encoding gene	Involved in pathogenesis or biocontrol process of *R. solani*.	Pozo *et al*. 2004 [99]
11.	*T. harzianum* T88	beta tubulin gene	Expresses biocontrol mechanisms like mycoparasitism, and antifungal activity	Li *et al*. 2007 [66]
12.	*T. hamatum* LU593	monooxygenase gene	Shows enhanced antagonist activity against *S. sclerotiorum*, *S. minor* and *S. cepivorum*.	Carpenter *et al*. 2008 [20]
13.	*T. virens* Gv298	TvBgn2 and TvBgn3 genes	These genes help to encode cell wall degrading enzymes.	Dzonovic *et al*. 2007 [31]
14.	*T. harzianum* CECT 2413	erg1 gene	erg1 gene silencing increases resistance towards terbinafine that shows antifungal activity.	Cardoza *et al*. 2006 [19]
15.	*T. harzianum Rifai* CECT 2413	qid74 gene	This gene is involved in protection of cell and adherence to hydrophobic surfaces that aids in antagonism against *R. solani*.	Rosado *et al*. 2007 [106]
16.	*T. viride* IFO31137	endo β-1,6-glactanase gene	Expression of this gene influences the production of proteins.	Kotake *et al*. 2004 [60]

17.	*T. atroviride* strain P1ATCC 74058	tga1 gene	Enhances the antifungal activity through formation of chitinase and production of antifungal metabolites.	Reithner *et al*. 2005 [103]
18.	*T. harzianum* CECT 2413	ThPTR2 gene	Induces locomotion of peptide that increases mycoparasistism	Vizcaino *et al*. 2006 [19]
19.	*T. virens* IMI 304061	tac1, adenylate cyclase gene	This gene expression leads to Mycoparasitism against *R. solani*, *S. rolfsii*, *Pythium* Spp. and production of secondary metabolites.	Mukherjee *et al*. 2007 [87]
20.	*T. harzianum*	ThChit gene	This gene shows antifungal activity in transgenic tobacco.	Saiprasad *et al*. 2009 [110]
21.	*T. harzianum* CECT 2413	T34 hsp70	Enhancement of fungal resistance to heat and abiotic stresses.	MonteroBarrientos *et al*. 2008 [75]
22.	*T. harzianum*	serine protease gene SL41	This gene expresses biocontrol activity against pathogens.	Liu *et al*. 2009 [68]
23.	*T. atroviride* P1 (ATCC 74058)	Taabc2 gene	Plays important role in antagonistic role against *R. solani*, *P. ultimum*, and *B. cinerea*.	Ruocco *et al*. 2009 [108]
24.	*T. harzianum* CECT 2413	Thctf1transcription factor gene	This gene shows antifungal action against *R. solani*, *Fusarium oxysporum* and *B. cinerea*	Rubio *et al*. 2009 [107]
25.	*T. harzianum* T34 CECT 2413	endopolygalacturonase ThPG1 gene	This gene expression helps in secretion of plant cell wall degrading enzymes against *R. solani* and *P. ultimum*.	MoranDiez *et al*. 2009 [86]
26.	*T. asperellum* (Enzymology Group collection, UFGICB	tag 3 gene	Induces production of cell wall degrading enzyme glucanase.	Marcello *et al*. 2010 [76]
27.	*T. virens* strain TvSMOE38	Sm1 gene, cysteinerich protein	This gene codes for a small cysteine rich protein that induces defense responses in dicot and monocot plants and in protection of crop diseases.	Buensanteai *et al*. 2010 [16]
28.	*T. harzianum* E58	CRE1 gene	This gene helps to produce cellulase and hemicellulase enzymes. Accession number not available Shows enhanced biocontrol activity.	Saadia *et al*. 2008 [109]
29.	*T. brevicompactum* IBT40841	tri5 gene	Production of trichodermin and antifungal activity against *C. albicans*, *C. glabrata* and *A. fumigatus*.	Tijerino *et al*. 2011 [119]
30.	*T. harzianum* CECT 2413	Thke11 gene	This gene expression modulates glucosidase activity, and increases salt and osmotic stress tolerance in *A. thaliana*	Hermosa *et al*. 2011 [52]

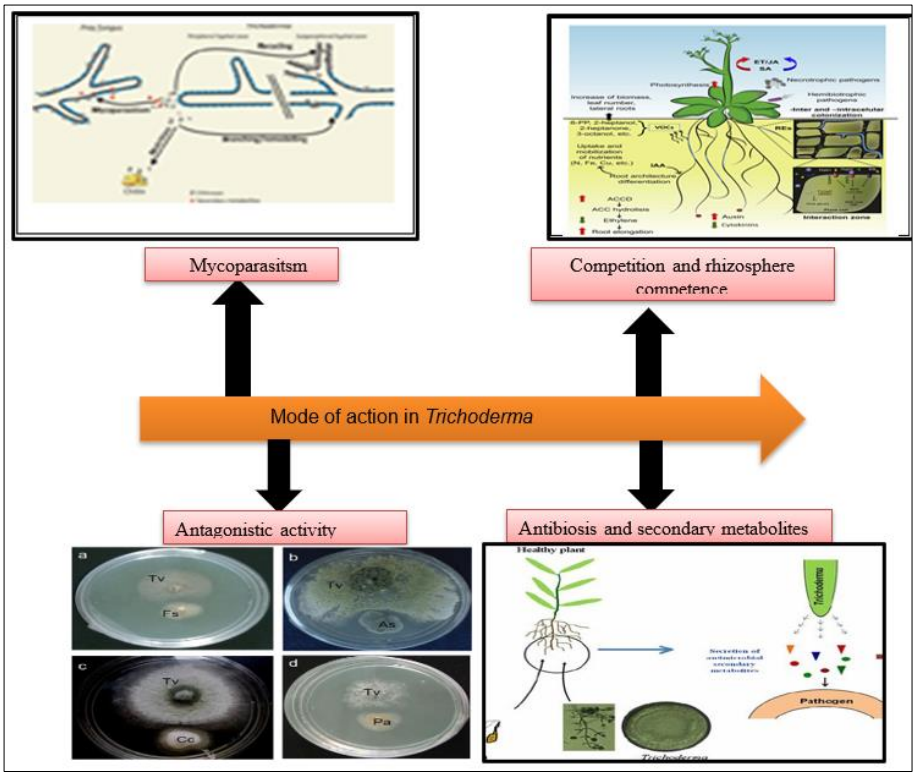

Fig 1: Different biocontrol mechanism of *Trichoderma*

References

1. Alonso-Ramírez A, Poveda J, Martín I, Hermosa R, Monte E, Nicolás C, *et al*. Salicylic acid prevents *Trichoderma harzianum* from entering the vascular system of roots. Molecular Plant Pathology. 2014;15:823-831.
2. Amira MB, Lopez D, Mohamed AT, Khouaja A, Chaar H, Fumanal B, *et al*. Beneficial effect of *Trichoderma harzianum* strain Ths97 in biocontrolling *Fusarium*

solani causal agent of root rot disease in olive trees. Biological Control. 2017;110:70-78.
3. Anwar W, Amin H, Khan HAA, Akhter A, Bashir U, Anjum T, *et al*. Chitinase of *Trichoderma longibrachiatum* for control of Aphis gossypii in cotton plants. Scientific Reports. 2023;13(1):13181.
4. Anwar W, Subhani MN, Haider MS, Shahi AA, Mushtaq H, Rehman MZ, *et al*. First record of *Trichoderma longibrachiatum* as entomopathogenic fungi against Bemisia tabaci in Pakistan. Phytopathologia Mediterranea. 2016;28:287-294.
5. Badham ER. Growth and competition between Lentinus edodes and *Trichoderma harzianum* on sawdust substrates. Mycologia. 1991;83:455-463.
6. Baek JM, Howell CR, Kenerley CM. The role of extracellular chitinase from *Trichoderma virens* Gv29-8 in the biocontrol of *Rhizoctonia solani*. Current Genetics. 1999;35:41-50.
7. Baiyee B, Ito SI, Sunpapao A. *Trichoderma asperellum* T1 mediated antifungal activity and induced defense response against leaf spot fungi in lettuce (*Lactuca sativa* L.). Physiology and Molecular Plant Pathology. 2019;106:96-101.
8. Battaglia D, Bossi S, Cascone P, Digilio MC, Prieto JD, Fanti P, *et al*. Tomato below ground-above ground interactions: *Trichoderma longibrachiatum* affects the performance of *Macrosiphum euphorbiae* and its natural antagonists. Molecular Plant-Microbe Interactions. 2013;26:1249-1256.
9. Benítez T. Biofungicides: *Trichoderma* as a biocontrol agent against phytopathogenic fungi. Recent Research Developments in Microbiology. 1998;2:129-150.
10. Benítez T, Rincón AM, Limón MC, Codon AC. Biocontrol mechanisms of *Trichoderma* strains. International Microbiology. 2004;7(4):249-260.
11. Bhagat S, Pan S. Biological management of root and collar rot (*Rhizoctonia solani*) of French bean (*Phaseolus vulgaris*). Indian Journal of Agricultural Sciences. 2010;80(1):42-50.
12. Bolar JP, Norelli JL, Wong KW, Hayes CK, Harman GE, Aldwinckle HS, *et al*. Expression of endochitinase from *Trichoderma harzianum* in transgenic apple increases resistance to apple scab and reduces vigour. Phytopathology. 2000;90:72-77.
13. Brants A, Earle ED. Transgenic tobacco cell cultures expressing a *Trichoderma harzianum* endochitinase gene release the enzyme into the medium. Plant Cell Reports. 2001;20:73-78.
14. Brogue K, Chet I, Holliday M, Cressman R, Biddle P, Knowlton S, *et al*. Transgenic plants with enhanced resistance to the fungal pathogen *Rhizoctonia solani*. Science. 1991;254:1194-1197.
15. Brotman Y, Kapuganti JG, Viterbo A. *Trichoderma*. Current Biology. 2010;20(9):390-391.
16. Buensanteai N, Mukherjee PM, Horwitz BA, Cheng C. Expression and purification of biologically active *Trichoderma virens* proteinaceous elicitor Sm1 in Pichia pastoris. Protein Expression and Purification. 2010;72:131-138.
17. Bunker RN, Mathur K. Antagonism of local biocontrol agents to *Rhizoctonia solani* inciting dry root rot of chilli. Journal of Mycology and Plant Pathology. 2001;31:337-353.
18. Calo L, García I, Gotor C, Romero LC. Leaf hairs influence phytopathogenic fungus infection and conferred an increased resistance when expressing a *Trichoderma*-1, 3-glucanase. Experimental Botany. 2006;56:3911-3020.
19. Cardoza RE, Vizcaino JA, Hermosa MR, Gonzalez FJ, Llobell A, Monte M, *et al*. Cloning and characterization of the erg1 gene of *Trichoderma harzianum*: Effect of the erg1 silencing on ergosterol biosynthesis and resistance to terbinafine. Fungal Genetics and Biology. 2006;43:164-178.
20. Carpenter MA, Ridgway HJ, Stringer AM, Hay AJ, Stewart A. Characterization of a *Trichoderma hamatum* monooxygenase gene involved in antagonistic activity against fungal plant pathogens. Current Genetics. 2008;53:193-205.
21. Chet I, Inbar J. Biological control of fungal pathogens. Applied Biochemistry and Biotechnology. 1994;48:37-43.
22. Chet I, Inbar J, Hadar I. Fungal antagonists and mycoparasites. In: Wicklow DT, Söderström B, editors. The Mycota IV: Environmental and Microbial Relationships. Springer-Verlag; c1997. p. 165-184.
23. Cohen-Kupiec R, Broglie KE, Friesem D, Broglie RM, Chet I. Molecular characterization of a novel β-1,3-exoglucanase related to mycoparasitism of *Trichoderma harzianum*. Gene. 1999;226:147-154.
24. Cook RJ, Baker KF. The nature and practice of biological control of plant pathogens. Phytopathology; c1983.
25. Coppola M, Cascone P, Chiusano ML, Colantuono C, Lorito M, Pennacchio F, *et al*. *Trichoderma harzianum* enhances tomato indirect defense against aphids. Insect Science. 2017;24:1025-1033.
26. Coppola M, Cascone P, Lelio ID, Woo SL, Lorito M, Rao R, *et al*. *Trichoderma atroviride* P1 colonization of tomato plants enhances both direct and indirect defence barriers against insects. Physiological and Molecular Plant Pathology. 2019;10:813.
27. Coppola M, Diretto G, Digilio MC, Woo SL, Giuliano G, Molisso D, *et al*. Transcriptome and metabolome reprogramming in tomato plants by *Trichoderma harzianum* strain T22 primes and enhances defense responses against aphids. Physiological and Molecular Plant Pathology. 2019;10:745.
28. Cortes C, Gutierrez A, Olmedo V, Inbar J, Chet I, Herrera Estrella A, *et al*. The expression of genes involved in parasitism by *Trichoderma harzianum* is triggered by a diffusible factor. Molecular and General Genetics. 1998;260:218-225.
29. da Silva Aires R, Steindorff AS, Ramada MHS, de Siqueira SJL, Ulhoa CJ. Biochemical characterization of a 27kDa 1,3-β-d-glucanase from *Trichoderma asperellum* induced by cell wall of *Rhizoctonia solani*. Carbohydrate Polymers. 2012;87:1219-1223.
30. Díaz-Gutiérrez C, Arroyave C, Llugany M, Poschenrieder C, Martos S, Peláez C, *et al*. *Trichoderma asperellum* as a preventive and curative agent to control *Fusarium* wilt in Stevia rebaudiana. Biological Control. 2021;155:104-537.
31. Djonovic S, Vittone G, Mendoza-Herrera A, Kenerley CM. Enhanced biocontrol activity of *Trichoderma virens* transformants constitutively coexpressing β-1,3-

and β-1,6-glucanase genes. Molecular Plant Pathology. 2007;8(4):469-480.
32. Domsch KH, Gams W, Anderson TH. *Trichoderma* pero. Ex Fries, 1821. In: Compendium of Soil Fungi. 1980;1:368-377, 794-809.
33. Donzelli BG, Lorito M, Scala F, Harman GE. Cloning, sequence and structure of a gene encoding an antifungal glucan 1,3-β-glucosidase from *Trichoderma atroviride* (*T. harzianum*). Gene. 2001;277:199-208.
34. Eisendle M, Oberegger H, Buttinger R, Illmer P, Haas H. Biosynthesis and uptake of siderophores is controlled by the PacC mediated ambient-pH regulatory system in Aspergillus nidulans. Eukaryotic Cell. 2004;3:561-563.
35. Elad Y. Biological control of foliar pathogens by means of *Trichoderma harzianum* and potential modes of action. Crop Protection. 2000;19:709-714.
36. Elad Y. Mechanisms involved in the biological control of Botrytis cinerea incited diseases. Plant Pathology. 1996;102:719-732.
37. Elad Y, Freeman S, Monte E (eds). Biocontrol agents: Mode of action and interaction with other means of control. IOBC wprs Bulletin, vol 24. Sevilla, España.
38. Elad Y, Zimand G, Zaqs Y, Zuriel S, Chet I. Use of *Trichoderma harzianum* in combination or alternation with fungicides to control cucumber grey mould (Botrytis cinerea) under commercial greenhouse conditions. Plant Pathology. 1993;42:324-332.
39. Emani C, Garcia JM, Lopata-Finch E, Pozo MJ, Uribe P, Kim DJ, *et al*. Enhanced fungal resistance in transgenic cotton expressing an endochitinase gene from *Trichoderma virens*. Plant Biotechnology. 2003;1(5):321-336.
40. Ferreira FV, Musumeci MA. *Trichoderma* as biological control agent: Scope and prospects to improve efficacy. Microbiology and Biotechnology. 2021;37(5):90.
41. Gallo A, Mule G, Favilla M, Altomare C. Isolation and characterization of a trichodiene synthase homologous gene in *Trichoderma harzianum*. Physiological and Molecular Plant Pathology. 2004;65:11-20.
42. Gams W, Bissett J. Morphology and identification of *Trichoderma* and Gliocladium; c2002. p. 3-31.
43. Gange AC, Eschen R, Wearn JA, Thawer A, Sutton BC. Differential effects of foliar endophytic fungi on insect herbivores attacking a herbaceous plant. Oecologia. 2012;168:1023-1031.
44. Gawai DU. Role of fungi as biocontrol agents for the control of plant diseases in sustainable agriculture. Fungi and their role in sustainable development: Current viewpoints; c2018. p. 283-291.
45. Grajek W, Gervais P. Influence of water activity on the enzyme biosynthesis and enzyme activities produced by *Trichoderma* viride TS in solid-state fermentation. Enzyme and Microbial Technology. 1987;9:658-662.
46. Hanada RE, Pomella AW, Soberanis W, Loguercio LL, Pereira JO. Biocontrol potential of *Trichoderma* martiale against the black-pod disease (*Phytophthora palmivora*) of cacao. Biological Control. 2009;50:143-149.
47. Haran S, Schickler H, Oppenheim A, Chet I. Differential expression of *Trichoderma harzianum* chitinases during mycoparasitism. Phytopathology. 1996;86:980-985.
48. Harman GE. Myths and dogmas of biocontrol changes in perceptions derived from research on *Trichoderma harzianum* T-22. Plant Disease. 2000;84:377-393.
49. Harman GE. *Trichoderma*-not just for biocontrol anymore. Phytoparasitica. 2011;39:103-108.
50. Hashioka Y, Horino O, Kamei T. Electron micrographs of *Trichoderma* and *Pachybasidia*. Reports of Tottori Mycological Institute. 1996;5:18-24.
51. Hatvani L, Homa M, Chenthamara K, Cai F, Kocsubé S, Atanasova L, *et al*. Agricultural systems as potential sources of emerging human mycoses caused by *Trichoderma*: a successful, common phylotype of *Trichoderma longibrachiatum* in the frontline. FEMS Microbiology. 2019:246-366.
52. Hermosa R, Botella L, Keck M, Jimenez JA, Montero-Barrientos M, Arbona V, *et al*. The overexpression in Arabidopsis thaliana of a *Trichoderma harzianum* gene that modulates glucosidase activity, and enhances tolerance to salt and osmotic stresses. Journal of Plant Physiology. 2011;168:1295-1302.
53. Howell CR. The role of antibiosis in biocontrol. In: Harman GE, Kubicek CP (eds). *Trichoderma* & Gliocladium, vol. 2. Taylor & Francis; c1998. p. 173-184.
54. Howell CR. Mechanisms employed by *Trichoderma* species in the biological control of plant diseases: the history and evolution of current concepts. Plant Disease. 2003;87:4-10.
55. Ibrahim DS, Elderiny MM, Ansari RA, Rizvi R, Sumbul A, Mahmood I, *et al*. Role of *Trichoderma* spp. in the management of plant-parasitic nematodes infesting important crop. In: Ansari RA, Rizvi R, Mahmood I. (Eds.), Management of Phytonematodes: Recent Advances and Future Challenges; c2020. p. 259-278.
56. Jach G, Gorngardt B, Mundy J, Logemann J, Pinsdorf E, Leah R, *et al*. Enhanced quantitative resistance against fungal disease by combinational expression of different barley antifungal proteins in transgenic tobacco. The Plant Journal. 1995;8:97-109.
57. Jaklitsch WM. European species of Hypocrea. Part I. The green-spored species. Studies in Mycology. 2009;63:1-91.
58. Kim DJ, Baek JM, Uribe P, Kenerley CM, Cook DR. Cloning and characterization of multiple glycosyl hydrolase genes from *Trichoderma virens*. Current Genetics. 2002;40:374-384.
59. Kosambo-Ayoo LM, Bader M, Loerz H, Becker D. Transgenic sorghum (*Sorghum bicolor* L. Moench) developed by transformation with chitinase and chitosanase genes from *Trichoderma harzianum* expresses tolerance to anthracnose. Biotechnology. 2011;10:3659-3670.
60. Kotake T, Kaneko S, Kubomoto A, Haque MA, Kobayashi H, Tsumuraya Y, *et al*. Molecular cloning and expression in Escherichia coli of a *Trichoderma* viride endo-β-(1→6)-galactanase gene. Biochemical. 2004;377:749-755.
62. Kovach J, Petzoldt R, Harman GE. Use of honey bees and bumble bees to disseminate *Trichoderma harzianum* 1295-22 to strawberries for Botrytis control. Biological Control. 2000;18:235-242.
63. Kubicek CP, Mikus M, Schuster A, Schmoll M, Seiboth B. Metabolic engineering strategies for the

improvement of cellulose production by Hypocrea jecorina. Biotechnology for Biofuels. 2009;2:19.
64. Kushiyev R, Tuncer C, Erper I, Özer G. The utility of *Trichoderma* spp. isolates to control of *Xylosandrus germanus* Blandford (Coleoptera: Curculionidae: Scolytinae). Plant Diseases and Protection. 2020;128:153-160.
65. Latorre BA, Lillo C, Rioja ME. Eficacia de los tratamientos fungicidas para el control de Botrytis cinerea de la viden función de la época de aplicación. Cien Inv Agr. 2001;28:61-66.
66. Li M, Yang Q. Isolation and characterization of a β-tubulin gene from *Trichoderma harzianum*. Biochemical Genetics. 2007;45:529-534.
67. Li N, Alfiky A, Wang W, Islam M, Nourollahi K, Liu X, *et al*. Volatile compound-mediated recognition and inhibition between *Trichoderma* biocontrol agents and *Fusarium oxysporum*. Frontiers in Microbiology. 2018;9:2614.
68. Liu Y, Yang Q, Song J. A new serine protease gene from *Trichoderma harzianum* is expressed in *Saccharomyces cerevisiae*. Applied Biochemistry and Microbiology. 2009;45(1):22-26.
69. Lorito M, Haynes CK, Broadway RM, Harman GE. Endochitinase from Gliocladium virens: Isolation, characterization and synergistic antifungal activity in combination with gliotoxin. Phytopathology. 1993;83:308-313.
70. Lorito M, Woo SL, Fernández IG, Colucci G, Harman GE, Pintor-Toro JA, *et al*. Genes from mycoparasitic fungi as a source for improving plant resistance to fungal pathogens. Proceedings of the National Academy of Sciences. 1998;95:7860-7865.
71. Lumsden RD, Locke JC, Adkins ST, Walter JF, Ridout CJ. Isolation and localization of the antibiotic gliotoxin produced by Gliocladium virens from alginate pril in soil and soilless media. Phytopathology. 1992;82:230-235.
72. Magan N. Effects of water potential and temperature on spore germination and germ-tube growth *in vitro* and on straw leaf sheaths. Transactions of the British Mycological Society. 1988;90:97-107.
73. Majumdar D. Hyperparasitic potential of a few biotypes of *Trichoderma harzianum* and Gliocladium virens against two pathogens of Betel vine (Piper betel). M.Sc. Dissertation; c1993. p. 54-82.
74. Manibhusanrao K, Sreenivasaprasad S, Baby UF, Joe Y. Susceptibility of rice sheath pathogen to mycoparasites. Current Science. 1989;58(9):515-518.
75. Montero-Barrientos M, Hermosa R, Nicolas C, Cardoza RE, Gutierrez S, Monte E, *et al*. Overexpression of a *Trichoderma* HSP70 gene increases fungal resistance to heat and other abiotic stresses. Fungal Genetics and Biology. 2008;45:1506-1513.
76. Marcello CM, Steindorff AS, Silva SP, Silva RN, Bataus LAM. Expression analysis of the exo-β-1, 3-glucanase from the mycoparasitic fungus *Trichoderma asperellum*. Microbiological Research. 2010;165:75-81.
77. Marcovich NA, Konovoa GL. Lytic Enzymes of *Trichoderma* and Their Role in Plant Defense from Fungal Diseases. Applied Biochemistry and Microbiology. 2002;39(4):341-345.
78. Mercado JA, Martín-Pizarro C, Pascual L, Quesada MA, Pliego-Alfaro F, de los Santos B, *et al*. Evaluation of tolerance to *Colletotrichum acutatum* in strawberry plants transformed with *Trichoderma* derived-genes. Acta Horticulturae. 2007;738:383-388.
79. Migheli Q, GonzalezCandelas L, Dealessi L, Camponogara A, RamonVidal D. Transformants of *Trichoderma longibrachiatum* overexpressing the β-1,4-endoglucanase gene egl1 show enhanced biocontrol of *Pythium ultimum* on cucumber. Biological Control. 1998;88(7):673-677.
80. Min YS, Kim BG, Lee C, Ho Gil H, Joong Hoon AHN. Purification, Characterization, and cDNA cloning of Xylanase from fungus *Trichoderma* strain SY. Microbiology and Biotechnology. 2002;12(6):1-5.
81. Mohamed GS, Taha E. Potency of entomopathogenic fungi, *Trichoderma album* Preuss in controlling *Rhizopertha dominica* F. (Coleoptera: Bostrichidae) under laboratory conditions. Plant Protection and Pathology. 2017;8:571-576.
82. Monaco C, Perello A, Alippi HE, Pasquare AO. *Trichoderma* spp.: Biocontrol agent of *Fusarium* spp. and Sclerotium rolfsii by seed treatment. Advances in Horticultural Science. 1991;5(3):92-95.
83. Monte E. Understanding *Trichoderma*: between biotechnology and microbial ecology. International Microbiology. 2001;4:1-4.
84. Montero-Barrientos M, Hermosa MR, Cardoza RE, Gutiérrez S, Nicolás C, Monte E, *et al*. Transgenic expression of the *Trichoderma harzianum* hsp70 gene increases Arabidopsis resistance to heat and other abiotic stresses. Plant Physiology. 2010;167:659-665.
85. Mora AA, Earle ED. Resistance to Alternaria brassicicola in transgenic broccoli expressing a *Trichoderma harzianum* endochitinase gene. Molecular Breeding. 2001;8:1-9.
86. MoranDiez E, Hermosa R, Ambrosino P, Cadoza RE, Gutierrez S. The ThPG1 endopolygalacturonase is Required for the *Trichoderma harzianum*-Plant beneficial interaction. American Phytopathological Society. 2009;22(8):1021-1031.
87. Mukherjee M, Mukherjee PK, Kale PS. cAMP signalling is involved in growth, germination, mycoparasitism and secondary metabolism in *Trichoderma virens*. Microbiology. 2007;153:1734-1742.
88. Mukherjee PK, Raghu K. Effect of temperature on antagonistic and biocontrol potential of *Trichoderma* spp., on Sclerotium rolfsii. Mycopathologia. 1997;139:151-155.
89. Mukherjee PM, Latha J, Hadar R, Horwitz BA. Role of two G protein alpha subunits, TgaA and TgaB, in the antagonism of plant pathogens by *Trichoderma virens*. Applied and Environmental Microbiology. 2004;70(1):542-549.
90. Mukherjee PM, Latha J, Hardar R, Horwitz BA. TmkA, Mitogen activated Protein Kinase of *Trichoderma virens* is involved in biocontrol properties and repression of conidiation in the dark. Eukaryotic Cell. 2003;2:446-455.
91. Mukhopadhyay AN, Kaur NP. Biological control of chickpea wilt complex by *Trichoderma harzianum*. Plant Protection in the Tropics; c1990. p. 20-23.
92. Mukhopadhyay R, Kumar D. *Trichoderma*: A beneficial antifungal agent and insights into its

mechanism of biocontrol potential. Biological Pest Control. 2020;30(1):1-8.
93. Nawrocka J, Małolepsza U, Szymczak K, Szczech M. Involvement of metabolic components, volatile compounds, PR proteins, and mechanical strengthening in multilayer protection of cucumber plants against *Rhizoctonia solani* activated by *Trichoderma atroviride* TRS25. Protoplasma. 2018;255:359-373.
94. Novy V, Schmid M, Eibinger M, Petrasek Z, Nidetzky B. The micromorphology of *Trichoderma* reesei analyzed in cultivations on lactose and solid lignocellulosic substrate, and its relationship with cellulase production. Biotechnology for Biofuels. 2016;9(1):1-11.
95. O'Kennedy MM, Crampton BG, Lorito M, Chakauya E, Breese WA, Burger JT, Botha FC, *et al*. Expression of a -1,3-glucanase from a biocontrol fungus in transgenic pearl millet. South African Journal of Botany. 2011;77:335-345.
96. Papavizas GC. *Trichoderma* and Gliocladium: Biology, ecology, and potential for biocontrol. Annual Review of Phytopathology. 1985;23:23-54.
97. Poveda J. Cyanobacteria in plant health: biological strategy against abiotic and biotic stresses. Crop Protection. 2020;10:54-50.
98. Poveda J. *Trichoderma parareesei* favours the tolerance of rapeseed (*Brassica napus* L.) to salinity and drought due to a chorismate mutase. Agronomy. 2020;10(1):118.
99. Pozo MJ, JongMin B, Garcia JM, Kenerley CM. Functional analysis of tvsp1, a serine protease-encoding gene in the biocontrol agent *Trichoderma virens*. Fungal Genetics and Biology. 2004;41:336-348.
100. Baranski R, E Klocke. Chitinase CHIT36 from *Trichoderma harzianum* enhances resistance of transgenic carrot to fungal pathogens. Phytopathology. 2008;156:513-521.
101. Rao SN, Kulkarni S. Effect of *Trichoderma* Spp. on the Growth of Sclerotium rolfsii Sacc. Biological Control; c2003. p. 181-184.
102. Reithner B, Brunner K, Schuhmacher R, Peissl I, Seidl V, Krska R, *et al*. The G protein α subunit Tga1 of *Trichoderma atroviride* is involved in chitinase formation and differential production of antifungal metabolites. Fungal Genetics and Biology. 2005;42:749-760.
103. Rifai MA. A revision of the genus *Trichoderma*. Mycological Papers. 1969;116:1-56.
104. Rojo FG, Reynoso MM, Ferez M, Chulze SN, Torres AM. Biological control by *Trichoderma* species of *Fusarium* solani causing peanut brown root rot under field conditions. Crop Protection. 2007;26:549-555.
105. Rosado IV, Rey M, Codon AC, Govantes J, MorenoMateos MA, Benitez T, *et al*. QID74 Cell wall protein of *Trichoderma harzianum* is involved in cell protection and adherence to hydrophobic surfaces. Fungal Genetics and Biology. 2007;44:950-964.
106. Rubio MB, Hermosa R, Reino JL, Collado IG, Monte E. Thctf1 transcription factor of *Trichoderma harzianum* is involved in 6-pentyl 2H-pyran-2-one production and antifungal activity. Fungal Genetics and Biology. 2009;46:17-27.
107. Ruocco M, Lanzuise S, Vinale F, Marra R, Turra D, LoisWoo S, *et al*. Identification of a New Biocontrol Gene in *Trichoderma atroviride*: The Role of an ABC Transporter Membrane Pump in the interaction with different plant-pathogenic fungi. American Phytopathological Society. 2009;22(3):291-301.
108. Saadia M, Ahmed S, Jamil A. Isolation and cloning of cre1 gene from a filamentous fungus *Trichoderma harzianum*. Pakistan Journal of Botany. 2008;40(1):421-426.
109. Saiprasad GVS, Mythili JB, Anand L, Suneetha C, Rashmi HJ, Naveena C, *et al*. Development of *Trichoderma harzianum* gene construct conferring antifungal activity in transgenic tobacco. Indian Journal of Biotechnology. 2009;8:199-206.
110. Samuels GJ. *Trichoderma*: A review of biology and systematics of the genus. Mycological Research. 1996;100:923-935.
111. Sánchez-Montesinos B, Diánez F, Moreno-Gavira A, Gea FJ, Santos M. Plant growth promotion and biocontrol of *Pythium ultimum* by saline tolerant *Trichoderma* isolates under salinity stress. International Journal of Environmental Research and Public Health. 2019;16:2053.
112. Sengupta J. Physico-chemical response of four different isolates of *Trichoderma harzianum*. M.Sc. Dissertation; c1995. p. 42-98.
113. Shah JM, Raghupathy V, Veluthambi K. Enhanced sheath blight resistance in transgenic rice expressing an endochitinase gene from *Trichoderma virens*. Biotechnology Letters. 2009;31:239-244.
114. Shah MR, Mukherjee PK, Eapen S. Expression of a fungal endochitinase gene in transgenic tomato and tobacco results in enhanced tolerance to fungal pathogens. Physiology and Molecular Biology of Plants. 2010;16:39-51.
115. Shah S, Nasreen S, Sheikh PA. Cultural and morphological characterization of *Trichoderma* spp. associated with green mold disease of Pleurotus spp. in Kashmir. Research Journal of Microbiology. 2012;7:139-144.
116. Sood M, Kapoor D, Kumar V, Sheteiwy MS, Ramakrishnan M, Landi M, *et al*. *Trichoderma*: The secrets of a multitalented biocontrol agent. Plants. 2020;9:762.
117. Steyaert JM, Stewart A, Jaspers MV, Carpenter M, Ridgway HJ. Co-expression of two genes, a chitinase (chit42) and proteinase (prb1), implicated in mycoparasitism by *Trichoderma hamatum*. Mycologia. 2004;96(6):1245-1252.
118. Tijerino A, Cardoza RE, Moraga J, Malmierca MG, Vicente F, Aleu J, *et al*. Overexpression of the trichodiene synthase gene tri5 increases trichodermin production and antimicrobial activity in *Trichoderma* brevicompactum. Fungal Genetics and Biology. 2011;48:285-296.
119. Tjamos EC. Selective elimination of soilborne plant pathogens and enhancement of antagonists by steaming, sublethal fumigation and soil solarization. In: Biol. Control of Plant Diseases: Progress and Challenges for the Future; c1992. p. 1-15.
120. Vey A, Hoagland RE, Butt TM. Toxic metabolites of fungal biocontrol agents. In: Butt TM, Jackson C, Magan N (eds) Fungi as biol. control agents: Progress, problems and potential; c2001. p. 311-346.

121. Vizcaino JA, Cardoza RA, Hauser M, Hermosa R, Rey M, Lobell A, *et al*. ThPTR2, a di/tri-peptide transporter gene from *Trichoderma harzianum*. Fungal Genetics and Biology. 2006;43:234-246.
122. Vyas SC, Vyas S. Integrated control of dry root of soybean. In: Lyr H, Russell PE and Sisler HD (eds) Modern fungicides and antifungal compounds; c1995. p. 565-572.
123. Wang S-Q, Jia M, Meng W, Wang X-H, Li Y-Q, Jie C, *et al*. Combined application of *Trichoderma harzianum* SH2303 and difenocona zole-propiconazolein controlling Southern corn leaf blight disease caused by Cochliobolus heterostrophus in maize. Journal of Integrative Agriculture. 2019;18:2063-2071.
124. Weindling R. *Trichoderma lignorum* as a parasite of other soil fungi. Phytopathology. 1931;22:837-845.
125. Weindling R. Studies on a lethal principle effective in the parasite action of *Trichoderma lignorum* on *Rhizoctonia solani* and other soil fungi. Phytopathology. 1933;24:1153-1179.
126. Woo S, Donzelli B, Scala F, Mach R, Harman GE, Kubicek CP, *et al*. Disruption of the ech42 (endochitinase encoding) gene affects biocontrol activity in *Trichoderma harzianum* P1. American Phytopathological Society. 1999;12(5):219-229.
127. Yu Y, Gui Y, Li Z, Jiang C, Guo J, Niu D, *et al*. Induced systemic resistance for improving plant immunity by beneficial microbes. Annual Review of Phytopathology. 2022;11:1-19.
128. Zehra A, Dubey MK, Meena M, Upadhyay RS. Effect of different environmental conditions on growth and sporulation of some *Trichoderma* species. Journal of Environmental Biology. 2017;38:197-203.
129. Zhang S, Gan Y, Xu B, Xue Y. The parasitic and lethal effects of *Trichoderma longibrachiatum* against Heterodera avenae. Biological Control. 2014;72:1-8.
130. Zhou D, Huang XF, Guo J, dos-Santos ML, Vivanco JM. *Trichoderma gamsii* affected herbivore feeding behaviour on Arabidopsis thaliana by modifying the leaf metabolome and phytohormones. Microbial Biotechnology. 2018;11:1195-1206.