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Trichoderma Spp.: A Biocontrol Agent for Sustainable Management of Plant Diseases

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ABSTRACT

Traditional methods for controlling plant diseases and increasing yields, such as chemical pesticides, herbicides or fertilizers are not environmentally friendly because they often contain aromatic groups or methylated and ethylated substances that have significant negative effects on the environment. Long-term usage of chemical pesticides can poison water, pollute the atmosphere and occasionally leave dangerous residues that can encourage the growth of particular resistant organisms. Trichoderma spp. are mostly asexual fungi found in rotting wood and all types of agricultural soils. Its hostile behavior demonstrates that they parasitize a variety of soil-borne and foliar diseases. Recent research demonstrates that the fungus functions as a biocontrol agent. These reactions are a crucial component of its biocontrol strategy. It is currently employed in sustainable disease management methods to control plant diseases. In addition to controlling diseases, Trichoderma species also promote plant growth and root development (biofertilizer) and activate the defense mechanisms of plants. Some strains have been demonstrated to colonize root surfaces with vigorous and long-lasting colonization after penetrating the epidermis. Biological control plays a very important role in plant disease management.

Keywords: *Trichoderma, mycoparasitism, development, biocontrol, systemic*

Introduction

Traditional methods for controlling plant diseases and increasing yields, such as chemical pesticides, herbicides or fertilizers are not environmentally friendly because they often contain aromatic groups or methylated and ethylated substances that have significant negative effects on the environment. Long-term usage of chemical pesticides can poison water, pollute the atmosphere and occasionally leave dangerous residues that can encourage the growth of particular resistant organisms. Researchers are searching for alternatives to these issues, such as using bicontrol agents (BCA) alone or in combination with other chemicals to control illness in an environmentally benign and long-lasting manner. *Pseudomonas*, *Bacillus* and *Agrobacterium* are examples of bacteria-based biocontrol agents that are now in use. Fungal biocontrol agents include *Aspergillus*, *Gliocladium*, *Trichoderma*, *Ampelomyces* and *Coniothyrium* (1, 2, 3, 4,5). *Trichoderma* spp. is one of the most adaptable biocontrol agent among them and has been used for a long time to control plant pathogenic fungus. An earlier investigation discovered that when plants were treated with conidial suspensions of *Trichoderma* spp., the diseases of seed rot, damping off, and root rot of sunflower and mungbean caused by *Sclerotium rolfsii* were averted as well as the plant growth was promoted (6). *T. virens* and *T. harzianum* prevented the noxious fungi from growing on *Ganoderma* (7). These are widespread facultative anaerobic fungi that can be found in agricultural soils and other substrates like decaying wood in large numbers (8, 9). Since most of their strains are evolved to an asexual life cycle and they are *Deuteromycetes* members, none of them have or display a stable sexual state (10). In addition to reducing the growth of dangerous bacteria, it can also be used to promote rhizosphere colonisation, plant and root growth and plant defense responses (11). The role of *Trichoderma* is not only to control growth of pathogenic microbes, but there are various other uses for *Trichoderma* such as, stimulate colonization of rhizosphere, enhance plant defense responses (12, 10). In the early 1930s *Trichoderma* was introduced as possessing biocontrol ability (13). It is an opportunistic, avirulent plant symbiont fungus which acts as an antagonistic and parasitic fungus against many plant pathogenic fungi and offers protection from phytopathogenic plant diseases. Numerous researches have demonstrated the efficiency of *Trichoderma* spp. as biocontrol agents for controlling plant diseases, and at the moment, commercial products of *Trichoderma* are offered as biopesticides, soil amendments or stimulants for plant growth (1, 14, 10, 12). *Trichoderma lingnorum* (*viride*) was shown by (13) to have biocontrollable effects on the soil-borne fungus *Rhizoctonia solani*. Later, the same species of *Trichoderma* was found to have mycoparsitic effects on *Phytophthora*, *Pythium*, *Rhizopus* and *Sclerotium rolfsii* (15). *Trichoderma* spp. is the basis for modern fungal biocontrol observation and foundation, and as a result, it has received considerable attention as a biocontrol model (14).

Biocontrol mechanisms of *Trichoderma* spp.:

Biocontrol agents that are effective against fungal phytopathogens include *Trichoderma* species. They can exert their influence indirectly by vying for resources and space, altering the environment, or fostering plant development, plant defense systems and antibiosis or they can exert their influence directly through mechanisms like mycoparasitism (1, 16, 12). These are some examples of the mechanisms

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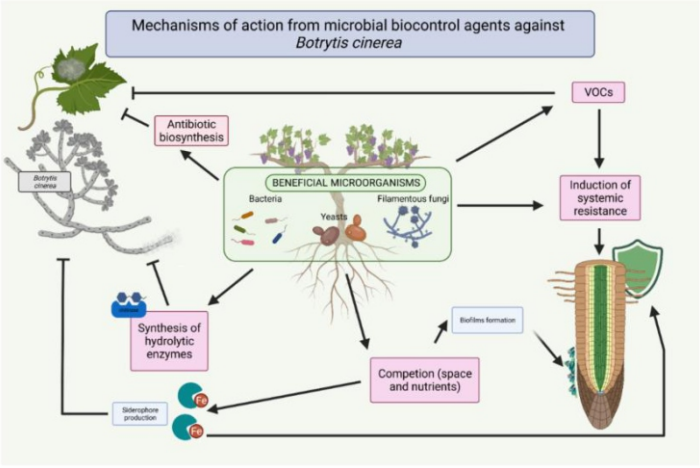
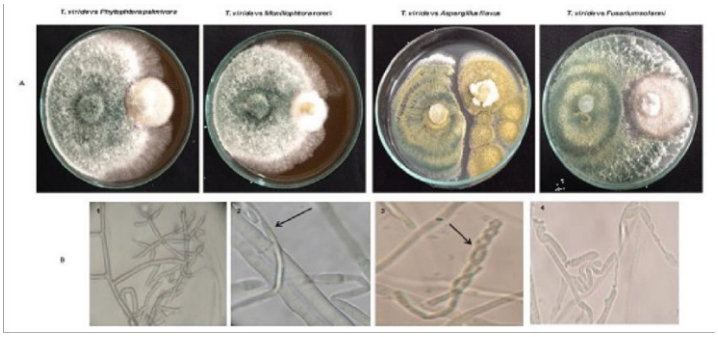
Biocontrol by competition for nutrients and living space:
Trichoderma spp. are quickly expanding fungi with long-lasting conidia and a wide range of substrate preferences. They are fierce rivals in the race for food and dwelling space (17). These species are also inherently resistant to a variety of harmful substances, such as phenolic compounds, fungicides and herbicides. As a result, they have the ability to multiply quickly and have an influence on infections by generating metabolic substances that prevent spore germination (fungistasis), kill cells (antibiosis) or alter the rhizosphere (for example, by making the soil acidic so that the pathogens cannot thrive) (18). The most frequent cause of death for microorganisms is starvation, therefore competition for scarce resources is crucial for the biocontrol of phytopathogens. For filamentous fungus, iron uptake is critical, and in the absence of iron, the fungi release siderophores, low-molecular-weight chelators that are specific to ferric iron. Highly effective siderophores produced by *Trichoderma* species chelate iron and inhibit the growth of other fungus (18). It is therefore a biocontrol agent that is influenced by the properties of the soil.



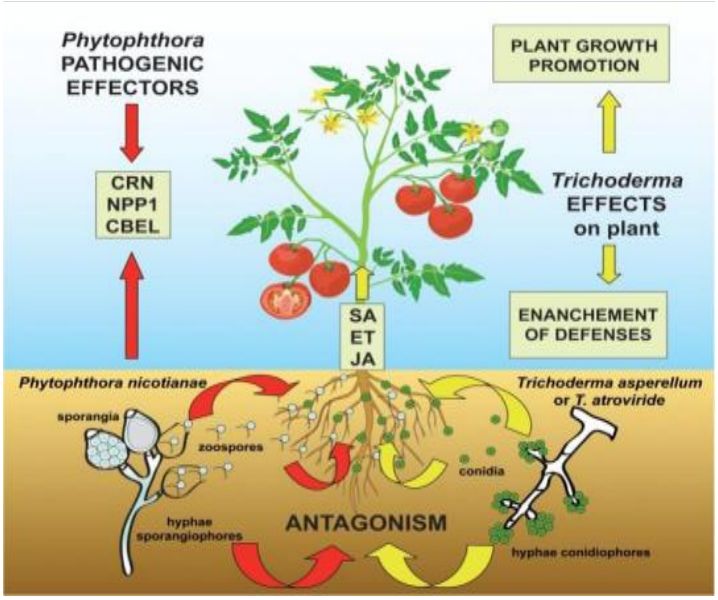
Mechanism of action of biocontrol agents against Botrytis cinerea

Biocontrol by mycoparasitism:
Mycoparasitism refers to the direct connection between *Trichoderma* and the pathogen. As previously indicated, *Trichoderma* spp. was first identified as a biocontrol agent by (13) who also observed the mycoparasitism of *T. lignorum* (*viride*) hypae coiling and killing *R. solani* (15). A complex mechanism known as mycoparasitism typically involves the creation of a cell wall lytic enzyme. The four sequential steps of the mycoparasitism process, according to (19), are chemotropism and identification, attachment and coiling, cell wall penetration, and host cell digesting. *Trichoderma* strains are able to recognize other fungi, move directly in their direction and produce hydrolytic cell wall-degrading enzymes in sequence. It adheres to the host, forms appressoria on the surface of the host, enters the host cell, and collapses the host hyphae (20). First described in 1994 (21), the molecular level induction of mycoparasitism was based on the research of regulation of an endochitinase-encoding gene (ech42). During the mycoparasitic interaction between *T. harzianum* and *Rhizoctonia solani*, was expressed. In a different investigation, it was discovered that treatments comprising pure colloidal chitin from fungus cell walls were insufficient to cause mycoparasitic in the P1 mutant strain of *T. atroviride*. Instead, exochitinase nagI or endochitinase ech42 gene expression was required (12). *Trichoderma* species also play important roles in the mycoparasitism/biocontrol process by producing and controlling lytic enzymes such as chitinases, glucanases and proteases (22).



Antagonistic action of Trichoderma spp.

Plant growth enhancement
In addition to controlling diseases, *Trichoderma* species also promote plant growth and root development (biofertilizer) and activate the defense mechanisms of plants (10). Some strains have been demonstrated to colonize root surfaces with vigorous and long-lasting colonization after penetrating the epidermis (10). It has been demonstrated that *Trichoderma* spp. enhances the growth of lettuce, tomato and pepper plants (11). In a study on maize plants, the plant roots were almost twice as long as untreated plants several months following treatment with *Trichoderma harzianum* strain T-22 (10). *Trichoderma harzianum* (6-pentyl-alpha pryone) and *Trichoderma koningii* (*koninging A*) create secondary metabolites that have the ability to control plant growth (23, 24). Additionally, *Trichoderma* spp. generated gluconic and citric acids, reduced the pH of the soil, and improved the solubilization of phosphates, micronutrients, and mineral components like iron, magnesium, and manganese (18, 25, 12).



(Frontiers)
Plant growth promotion and plant defense induction by Trichoderma

Induction of plant defense
It is well known that *Trichoderma* spp. stimulate plant gene expression for defense against bacteria, including chitinase, glucanase and peroxidase (26, 27, 25). Additionally, it has been demonstrated that pre-treating plants with *Trichoderma* species boosted their resistance to pathogen invasion (10). These species are rapid growth, spore producers and opportunistic invaders. They generate antibiotics and have enzymes that break down cell walls, such as celluloses,

chitinases and glucanases (12). Additionally, *Trichoderma* spp. induces the development of systemic acquired resistance (SAR), induced systemic resistance (ISR) and the hypersensitive response in plants (18, 12). For instance, *T. hamatum* actively generated systemic alterations in plant physiology and disease resistance in tomato plants (28). In a cucumber plant investigation, *T. asperellum* generated a systemic response of two defense genes that encode phenylalanine and hydroperoxidase lyase as well as a systemic buildup of phytoalexins against *Pseudomonas syringae* pv. *lachrymans* (26). Compared to *G. boninense* alone treated plants, oil palm plants treated with *T. harzianum* and *Ganoderma boninense* expressed more of the defense gene chitinase (29). These species may indirectly contribute to systemic resistance, according to a number of studies (30,31). They are effective in controlling plant diseases by inducing localized or systemic resistance (10). Thus, the host plant, the pathogen, the biocontrol agent, and a number of environmental parameters interact intricately in the disease control by root-colonizing *Trichoderma* spp. (10, 32, 28).

Plant root colonization

Studies of the early-invading fungi *Trichoderma* spp. demonstrated that root colonisation induced plant defence responses such as induction of peroxidases, chitinases, -1, 3 glucanase, phenylalanine, and hydroperoxide lyase; activated signalling of biosynthetic pathways; and caused accumulation of low-molecular weight phytoalexins (33, 26, 10) Under the electron microscope, the physical interaction between *T. harzianum* T-203 and a cucumber plant (34). They discovered that the fungus pierced the root and spread across the epidermis and outer cortex, which prompted peroxidase and chitinase levels to rise. Therefore, the interaction appears to be a symbiotic relationship in which *Trichoderma* lives in the nutritional niche provided by the plant, and the plant was protected from disease.

Production of antibiotics and secondary compounds

Trichoderma spp. generate secondary chemicals and antibiotics that are essential for antagonistic biocontrol activities (12, 35). They developed a variety of secondary chemicals, including terpenes, polyketides and pyrones, which had antibacterial and antifungal properties, according to Sivasithamparam and Secondary metabolites, such as antibiotics, that are chemically distinct from natural compounds and do not directly participate in natural growth, development or reproduction may be crucial for the defence response, symbiosis, metal transport, differentiation, and promoting or inhibiting spore formation and germination (36, 12). Antibiotic use is frequently linked to biocontrol action. As an illustration, the creation of an antibiotic similar to pyrone from *T. harzianum* shown biocontrol action against *Ganumannomyces graminis*. The first secondary metabolite identified in *Trichoderma* spp. was the peptide antibiotic paracelsin (37,38). According to Sivasithamparam, the secondary metabolites produced by *Trichoderma* spp. can be divided into three categories:

i) volatile compounds (such as 6-pentyl-alpha-pyrone) (ii) water-soluble compounds (such as heptelidic acid) (iii) peptaibol compounds, which are linear oligopeptides made up of 12–22 amino acids that are rich in alpha-aminoisobutyrate, N-acetylated at the Nterminus and have an amino alcohol group at the C-terminus.

Biocontrol genes and their functions

Due of its viability in combating diseases, the genus *Trichoderma* functions as a biocontrol agent. Protease, chitinase, glucanase, tubulins, proteinase, xylanase, monooxygenase, galacturonase, cell adhesion proteins, and stress tolerant genes are a few common types of biocontrol genes that are simple to isolate, clone, and characterise. These genes each have a special role to play in the biocontrol system, such as the breakdown of cell walls, hyphal development, stress resistance, and parasitic activity. Microtubule-based structural proteins known as tubulins aid in understanding how infections' cell walls are constructed (39). The breaking of the glycosidic linkages is aided by chitinase. D-glucose is converted to D-glucono-1,5-lactone by the enzyme glucose oxidase, and hydrogen peroxide is known to have antifungal properties (40). Hemicellulose, a crucial component of plant cell walls, is broken down by xylanase. Antibiosis is the antagonism of *pathogen* caused by the toxicity of secondary metabolites generated by *Trichoderma* spp. In *Trichoderma* spp. several genes involved in secondary metabolite synthesis have been discovered. These genes encode secondary metabolites, such as pyrones, polyketides, peptaibols, gliotoxin, gliovirin, terpenoids, and other chemicals. Depending on the chemical and the target location, varying amounts of these compounds are poisonous to pathogen.

Table 1. Different types of biocontrol genes and their activities

Gene	Function	Reference
Chitinases	Degrade chitin polymers by breaking β-1,4 glycosidic linkages, Endochitinases break chitin into chitotetraose, chitotriose, and diacetylchitobiose	41,42
Glucanases	Reduce spore germination or pathogen growth, provide stiffness of the cell wall	43
Proteases	Help in the lysis of cell walls, accelerate the peptide bond breakage, function as proteolytic inactivators of pathogen enzymes	44, 45, 46
Pyrones	Secondary metabolites produced by *Trichoderma* spp. that have strong biocontrol activity	47
Polyketides	Including iron uptake, antibacterial, and antifungal activity	48
Peptaibols	Make holes in lipid membranes, and proclivity to establish systemic resistance in plants against plant diseases	49
Gliotoxins	Contain sulfur having antimicrobial, antiviral, and immunomodulatory activities	49
Terpenes	Antifungal activity	50
Oxidases	Encode ABC transporters and detoxifying enzymes.	51
Xylanases	Breakdown the plant cell wall and trigger the defensive signaling system	

Competition for Nutrients

Microorganisms require nutrients to survive, so competition for nutrient constraints and the colonization of plant tissues results in pathogens control. When resources are few, microorganisms with the same ecological niche and physiological requirements struggle for nourishment (52). *Trichoderma* spp., compete with *R. solani* for nutrients, mainly carbon. Comparatively to other fungi, they are better at mobilizing and absorbing soil nutrients (53). Moreover, in comparison to other fungi, they have a remarkable ability for ATP through the sugars metabolism including cellulose, hemicelluloses, glucans, and chitin (54). Biomass components, mainly cellulose and hemicelluloses, are thought to be significant determinants of biocontrol fungi's antagonistic activity. They are intended to be part of the saprophytic lifestyle and plant pathogen competition. *Trichoderma* spp., undoubtedly the most investigated fungal biocontrol agent, contain bulk of the genes encoding biomass-degrading hydrolytic enzymes found so far. Proteases, cellulases, hemicelluloses and amylases, are biological substrates degrading hydrolytic enzymes. As a result, *Trichoderma* spp. aid in carbon recycling. *Trichoderma* spp. and *R. solani*'s competitive capacity for cellulose utilization on wheat straw was assessed in a prior research (55). So far, only Gtt1, a high-affinity glucose transporter discovered in *T. harzianum*, has been examined, and its mRNA level rose in response to *R. solani* (56). Competition for micronutrients can also arise in the soil. The most well-known example is competition for iron, which is essential for fungal pathogen development and pathogenicity. *Trichoderma* spp. secrete a number of siderophores that chelate iron and alter its availability to other bacteria. *T. harzianum* produced the most siderophores and had potent antifungal properties. A paucity of iron in the environment causes siderophore development and iron competition. *Trichoderma* spp. biocontrol ability against *R. solani* is influenced by iron competition. As compared to *R. solani* and *Trichoderma* spp. can more effectively access the limited amounts of iron available. A peptide synthetase gene, *Psy1*, has been discovered. *Psy1* disruptants generated normal levels of gliotoxin but struggled to grow in low-iron environments, indicating that *Psy1* is involved in siderophore synthesis (57) Harzianic acid is a siderophore released by *T. harzianum* that promotes plant development while also acting as an antifungal against *R. solani.*

Trichoderma spp. Induced Resistance in Different Plants

***Trichoderma*-Induced Systemic Resistance**

Depending on the pathosystem, plant defense responses are usually triggered by activation of a complex signal transduction network that includes salicylic acid (SA), jasmonic acid (JA), either with or without ethylene (ET), and abscisic acid (ABA) as important plant immunity regulators. SA-mediated signaling pathways in plants result in systemic acquired resistance (SAR) against biotrophic and hemibiotrophic diseases (58). JA/ET-mediated signaling pathways, on the other hand, result in induced systemic resistance (ISR) in plants against necrotrophic diseases (59). According to a recent research, *Trichoderma* spp. induce a hybrid ISR/SAR type of resistance in plants against fungal pathogens including *R. solani* known as *Trichoderma*-induced systemic resistance (TISR; 60). Hence, resistance in plants is increased by *Trichoderma* spp. against *R. solani*, which can be activated through signaling pathways that involve both SA and JA/ET-mediated signal transduction. Even still, scientists disagree on the method by which *Trichoderma* spp. activate defensive responses and the sort of resistance they induce in plants. Furthermore, there are significant gaps and differences when it comes to explaining the crosstalk of signaling molecules involved in *Trichoderma*-induced defense responses in plants. Other chemicals that may reduce or increase the synthesis and activity of signaling molecules must also be considered in order to better comprehend the crucial interactions between JA, SA, ET, and their derivatives in the intricate signaling network

Role of MAMP's, Reaction Oxygen and Nitrogen Species, Transcription Facrtors, Defense Related Genes and Enzymes

Trichoderma spp. release MAMPs for molecular recognition by receptors of plants**.** PRRs recognize MAMPs released by *Trichoderma* spp. By signaling molecules within the plants, these MAMPs contribute to the signal cascade. *Trichoderma* MAMPs transiently promote Ca^{2+} and H^{+} influx and K^{+} and Cl^{-} ejection in response to suitable plant receptors. Variations in the plasma membrane potential (Vm) occur often because of ion imbalances and changes in the channel activity (61). Plant cells undergo fast ROS, RNS and pH changes during depolarization. In addition to changes in ion absorption, *Trichoderma* spp. releases organic acids (gluconic or citric acid) into the soil, which lowers the soil pH. ROS and RNS are released during cell wall expansion and lignification. Furthermore, cell wall peroxidases and calcium channels become active. Many secondary metabolites and signaling molecules, including as H_2O_2 and NO, as well as SA and its derivatives, and JA/ET are generated and accumulated in response to *Trichoderma* spp. (62). *Trichoderma* spp. MAMPS and other effector molecules bind to PRRs and intracellular receptors in plants, triggering MTI (MAMPS-triggered) and ETI (effector-triggered) immunity. This interaction between *Trichoderma* spp. and plants produces ROS and RNS, which act as signaling molecules and initiate a defensive response in plants by synthesizing antifungal molecules, such as phytoalexins, VOCs (volatile organic compounds), PRs proteins, such as CWDEs, and so on.

Reactive Oxygen and Nitrogen Species

In oxidative signaling, reactive oxygen (RO) and reactive nitrogen (RN) species interact with multiple hormonal signaling pathways. When plants were challenged with necrotrophic fungi, such as *R. solani*, among all RO and RN species, H_2O_2 and nitric oxide (NO) were shown to be quickly produced and were considered primary defensive activators. The processes by which NO may influence defensive signaling cascades were well investigated. S-nitrosylation and tyrosine-rich group nitration have emerged as significant NO-dependent protein regulatory mechanisms. Protein cysteine-rich thiol groups react with NO to create S-nitrosothiols so-called "reversible S-nitrosylation of proteins." S-nitrosylation plays an important role in defensive responses, as shown by its effects on the SA signaling protein NPR1 and the ROS-generating NADPH oxidase complex AtRBOHD. NO has been shown to work with ROS and SA to establish SAR in plants (Sami *et al*., 2018). NO is also linked to other resistance-inducing signaling pathways, such as JA and ET. NO *via* S-nitrosylation has been shown in recent research to be one of the key regulators of SA-dependent systemic defensive responses in *T. atroviride*-treated plants.

Transcription Factors, Defense-Related Genes, and Enzymes

Transcription Factors and Pathogenesis-Related Genes

Transcription factors modulate the expression of certain genes required for many key physiological activities and stress responses, acting as regulators of gene transcription.

The *WRKY* transcription factor family has been connected to abiotic stress, growth, and development in addition to plant–microbe interactions. As discussed before, SAR often results in increased levels of SA and coordinated activation of PR genes, such as *PR5*, *PR2*, and *PR1* involving one or more signaling molecules, that transmit an elevated immune response against *R. solani*.

Defense-Related Genes and Enzymes

Many studies have shown that plants treated with *Trichoderma* spp. boosted the activity of defense-related enzymes, such as peroxidase, chitinase, peroxidase, -1, 3-glucanase, phenylpropanoids, polyphenol oxidase, superoxide dismutase, chitinase, and phenylalanine ammonia-lyase (PAL). When cotton seeds were treated with *T. virens*, for example, peroxidase activity was increased in the roots of treated cotton plants (33). Furthermore, by boosting ROS scavenging enzymes, *Trichoderma* spp. contribute to plant resistance to *R. solani*. *Trichoderma harzianum*, for example, increases the activities of ascorbate peroxidase (APX), guaiacol peroxidase (GPX), superoxide dismutase (SOD), and catalase (CAT) in tomato plants against *R. solani*. *Trichoderma* spp. also produce lytic enzymes, such as chitinase and β-1,3-glucanase, which break down *R. solani* chitin and β-1,3-glucan components.

Functions of biocontrol genes

A gene called tvsp1 that codes for serine protease was successfully cloned from *Trichoderma virens*, and its function was investigated. Serine protease has a significant role in the pathogenesis or biocontrol of *Rhizoctonia solani*, a fungus that harms cotton seedlings. *Escherichia coli* was used to produce the tvsp1 gene and clone it using the pET-30 vector. Serine protease thus aids in the destruction of the fungal cell wall (46) Trichodiene synthase gene tri5 was identified and described from *T. harzianum*. Trichothecene, an enzyme that prevents the synthesis of proteins and DNA in pathogen cells and slows their growth, is produced by the tri5 gene. Trichothecene exhibits phytotoxic properties toward *Fusarium* species. It was possible to isolate the gene tri5 by creating certain primers. The sequence was cloned after being introduced into the pGEMT vector. By screening with other *Trichoderma* isolates, the presence of the tri5 gene was verified (63) Exo-1,3-glucanase, an enzyme that breaks down cell walls, is encoded by the gene tag83, which was identified and described from *Trichoderma asperellum*. Reverse transcription-polymerase chain reaction was used to analyse the gene expression in real time (RT-PCR). By contrasting the enzyme activity of glucanase with diverse carbon sources, including starch, cellulose, chitin, chitosan, and the *R. solani* cell walls, the enzyme activity of glucanase was examined. With *R. solani*, the tag83 gene was expressed, demonstrating that the glucanase enzyme has parasitic activity against infections (64).

Transformants of *T. virens*, TvBgn2 and TvBgn3, expressed two distinct types of 1,3 and 1,6 glucanase genes. These genes produce an enzyme that breaks down cell walls and aids in biocontrol activities. To measure the enzyme activity against pathogens including *R. solani*, *Pythium ultimum* and *Rhizopus oryzae*, *T. virens* GV29.8 wild type and double over expression (DOE) transformant strains were utilised (65). From *Trichoderma atroviride*, gluc78, a gene that produces an antifungal glucan 1, 3-glucosidase, was identified, cloned, and sequenced. This gene is important for the pathogens' cell wall breakdown. Pathogens including *R. solani* and *P. ultimum* were used in the expression investigation of the gluc78 gene that was cloned in the pGEM-T vector (66).

A glucose repressor gene called creI was identified and described from *T. harzianum*. Cellulase and xylanase-coding genes are repressed by this gene. The two main types of enzymes involved in the pathogens' destruction of their cell walls are cellulase and xylanase. The pTZ57R/T plasmid vector was used to clone the gene, which was then transformed into E. coli DH 10B to study the function of the creI gene in the expression of cellulase and xylanase (67). The majority of cells contain tubulins, which interact with benzimidazole fungicides and are crucial to the biocontrol process. From *T. harzianum*, this -tubulin gene was extracted and studied. By employing PCR to amplify the tubulin gene, inverted and nested PCR were used to identify the coding regions and flanking sequences. The presence of motifs for the gene's expression was examined in the sequences. Swiss-model automated comparative protein modelling service created the three-dimensional model of the -tubulin gene (68). Sm1, a cysteine-rich protein, was identified and produced from a gene in *T. virens*. It demonstrates disease defence action in both dicot and monocot plants (69). Serine proteases are essential to the biology of fungi and participate in biocontrol processes. A new serine protease gene called SL41 has been successfully cloned from *T. harzianum* and expressed in *Saccharomyces cerevisiae*. Sequencing the SL41 gene's cDNA led to its cloning in the pMD18-T vector, and the resulting products were then introduced into E. coli DH5-. As a result, serine proteases were cloned and studied (70). Endopolygalacturonase-encoding gene ThPG1 was identified and described from *T. harzianum*. This enzyme assists in the advantageous interactions between plants and pathogens like *R. solani* and *P. ultimum* by degrading their cell walls. By contrasting the wild type and mutant type strains, the expression study of this gene was examined. The polymerase chain reaction was used to acquire the full length cDNA clone of the ThPG1 gene, which was then cloned in the pSIL-pG1 vector. The evolutionary link was discovered using the NJ tree method (neighbor-joining). An endo-(1-6)-galactanase-coding gene, Tv6Gal, was identified from *T. viride*, cloned, and expressed in E. coli. The family of arabinogalactan proteins that are involved in cell-cell adhesion, cell growth, and cell death includes enzymes called galactanases. By using RT-PCR, the gene Tv6Gal's cDNA was cloned into a pGEM-T vector and expressed in E. coli (71). Trichoderma strain SY that produces xylanase was found in the soil. By using RT-PCR, the xylanase gene, Xyl, was cloned. When cultivated on cellulose as the only source of carbon, Xyl was substantially expressed. Amplification of Xyl's full-length cDNA by PCR was followed by cloning in the pGEM-T vector. In order to evaluate the proteins, sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) was used to express the cloned gene in E. coli (72). The g-protein subunit genes TgaA and TgaB were cloned and described from T. virens. According to (48), this gene has antagonistic activity toward *R. solani* and *Sclerotium rolfsii*.

Trichoderma reesei, which isolated, was able to make cellulase, which made it a very significant cellulase or enzyme producer (73). *Trichoderma* spp. produces cellulase that is mostly utilised in the creation of grain alcohol, malt, and baking (74). Numerous cellulases and hemicellulases are produced by the filamentous cellulolytic *Trichoderma* spp. Although it is also utilised in the pulp, paper, and textile sectors, the primary usage of lignocellulosic biomass is the generation of biofuels like ethanol (75, 76, 77). The synthesis of safe industrial enzymes also uses *Trichoderma* species (78). Macerating enzymes are used as a feed supplement for livestock and pet food, as well as to enhance the brewing process for the creation of fruit juice (79).

It is also utilised for seed germination; for instance, a study revealed that sunflower seeds considerably germinated more readily in plants treated with *T*. *viride* or *T*. *resei* than in control plants (80). Numerous *Trichoderma* species are still being used commercially to safeguard and boost the growth of various crops (81). The formulations that are currently on the market arle TrichopelTM, TrichojetTM, TrichodowelsTM, and TrichosealTM (Agimm, New Zealand); RootShieldTM, BioTrek 22TM, T22GTM, and T-22HBTM (Bio-works, USA); SuprevisitTM (Borregaard BioPlant, Denmark); BinabTM (Bio-Innovation Sweden); TriecoTM (Ecosense Labs (Mycology Lab, Malaysia). Even though not all of these items are labelled as biocontrol agents, they are marketed as soil conditioners, plant strengtheners, or promoters of plant development.

Conclusion

Numerous studies have shown that *Trichoderma* is an efficient biocontrol agent for phytopathogenic bacteria since Weindling originally discovered the genus *Trichoderma* spp. in 1930 as a biocontrol agent (82). Only when the biocontrol agent can effectively control the interaction between the host plant and pathogen is a biocontrol program developed. It has long been known that it can successfully control this relationship. It has also been shown that the fungus improves plant defense mechanisms. Therefore, the adoption of *Trichoderma* as a biocontrol agent will undoubtedly ensure sustainable disease management.

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