

ENHANCING ABIOTIC STRESS TOLERANCE IN PLANTS: THE MULTIFACETED ROLE OF TRICHODERMA

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Abstract:

Fungi, such as *Trichoderma* spp., have emerged as beneficial bio-control agents with remarkable capabilities to mitigate various abiotic stresses and combat plant pathogens in modern agriculture. This review highlights the interaction between *Trichoderma* and plants, focusing on its role in enhancing tolerance to abiotic stresses. *Trichoderma* establishes a symbiotic relationship with plant roots, secreting enzymes and antibiotics that break down pathogenic fungi and activate induced systemic resistance (ISR). Notably, *Trichoderma* treated plants exhibit increased resistance to drought, salinity, heat, and heavy metals due to altered hormone levels and enhanced antioxidant defense mechanisms. The production of bioactive compounds, including auxins, phytoalexins, and siderophores, by *Trichoderma* further contributes to enhanced plant growth and development. The colonization process and molecular signaling pathways involved in *Trichoderma* -plant interactions are also discussed. Understanding the potential of *Trichoderma* in promoting abiotic stress tolerance in plants will pave the way for sustainable agricultural practices and crop improvement. In conclusion, *Trichoderma*-plant interactions significantly enhance plant tolerance to abiotic stresses. The multifaceted mechanisms employed by *Trichoderma* lead to better growth, nutrient absorption, and stress resilience. Unraveling precise molecular and physiological mechanisms is crucial for devising effective strategies in stress-prone environments.

Keywords: *Trichoderma*, Biological control, Abiotic stresses, induced systemic resistance (ISR), *Trichoderma* -plant interactions.

1. Introduction:

Fungi that act as bio-control agents have become useful tools in the modern and sustainable agricultural system. They have the capacity to mitigate abiotic stresses like drought, salinity, extremely high or low temperatures, and heavy metal stresses, as well as the adverse impacts of plant pathogens. Due to their high capacity for reproduction, ability to endure harsh environments, prolific production of secondary metabolites, and resistance to plant pathogenic fungus, *Trichoderma* spp. have attracted significant interest among beneficial fungi (Benítez, Rincón et al. 2004, Harman 2006, Contreras-Cornejo, Macías-Rodríguez et al. 2016). Additionally, they have been used in biotechnological applications and offer significant agricultural endeavours like their capacity to reduce biotic and abiotic stressors and improve plant growth and output. (Lorito, Woo et al. 2010, Hermosa, Viterbo et al. 2012).

The first step in a successful plant and *Trichoderma* interaction results in the exchange of signals and the development of elicitors that lead to symbiotic relationship between them, is colonisation with *Trichoderma* and plant roots. Produced enzymes and antibiotics go towards fungal pathogens, successfully breaking down their hyphae to allow entry into the host cell. Both enzymes and antibiotics have antifungal properties and work in concert.(Shoresh, Harman et al. 2010)*Alternaria alternate*, *Botrytis cinerea*, *Rhizoctonia solani*, *Sclerotinia sclerotiorum*, *Pythium* spp., and *Fusarium* spp. are just a few of the diseases that *Trichoderma* are known to be resistant to.(Harman, Howell et al. 2004, Harman, Petzoldt et al. 2004)including that of nematode (Sharon, Bar-Eyal et al. 2001). After successful colonisation, they also cause ISR (systemic induced resistance), which results in the signalling of several hormones and eventually encourages growth.(Shoresh, Harman et al. 2010).

Crop production was impacted globally by abiotic factors like salt, drought, heavy metal buildup, and severe temperatures. Recent research, however, suggests that *Trichoderma* promotes resistance to abiotic stressors and enhances growth in a variety of plant species, including radish, cucumber, pepper, bottle gourd, periwinkle, bitter melon, chrysanthemum, lettuce, and tomato. (De Souza 2008, Bae, Sicher et al. 2009, Brotman, Landau et al. 2013, Contreras-Cornejo, Macías-Rodríguez et al. 2016, Zeilinger, Gruber et al. 2016, Kashyap, Kumar et al. 2017, Yasmeen and Siddiqui 2017) *Trichoderma* colonized plants produce certain compounds (Auxins, ethylene, gibberellins, plant enzymes, antioxidants) and phytoalexins and phenols that provide tolerance to abiotic stresses and enhance the branching capacity of the root system (Brotman, Landau et al. 2013, López-Bucio, Pelagio-Flores et al. 2015).

The purpose of this review is to examine the current understanding of the interaction between *Trichoderma* and plants, specifically their role in enhancing tolerance to abiotic stresses.

2. Bioactive Compounds produced by *Trichoderma* and Their Role in Inducing Plant Responses and Enhancing Disease Resistance:

Trichoderma species release specific classes of compounds into the interaction zone, triggering resistance in plants. One such class includes proteins that exhibit enzymatic and other activities. Xylanases, cellulases, and swollenin are among the proteins secreted by *Trichoderma*. (Fuchs, Saxena et al. 1989, Lotan and Fluhr 1990, Anderson, Bailey et al. 1993, Martinez, Blanc et al. 2001). *Trichoderma* fungi have the ability to produce plant growth-promoting compounds that can enhance photosynthesis, increase biomass production, and trigger developmental programs by regulating gene expression. These compounds play a significant role in promoting plant growth and development. (Chacón, Rodríguez-Galán et al. 2007, Shores and Harman 2008, Vargas, Mandawe et al. 2009, Harman 2011, Studholme, Harris et al. 2013, Martínez-Medina, Del Mar Alguacil et al. 2014, Pereira, Queiroz et al. 2014, Rubio, Quijada et al. 2014). *Trichoderma virens* and *Trichoderma atroviride* are

capable of producing auxins such as indole-3-acetic acid (IAA), indole-3-ethanol (IET), indole-3-acetaldehyde (IALD), and indole-3-carboxaldehyde (ICALD). These auxins play a significant role in stimulating cell division, elongation, and differentiation processes in plants. As a result, the growth and yield of the plant host are increased, leading to enhanced overall plant development and productivity.(Contreras-Cornejo, Macías-Rodríguez et al. 2009, Contreras-Cornejo, Macías-Rodríguez et al. 2011, Rubio, Quijada et al. 2014). This study is consistent with the experiment conducted on cherry rootstock, which observed elevated levels of indole-3-acetic acid (IAA) in both the leaves and roots. The findings suggest that the production of IAA by *Trichoderma* or other factors influenced the increased accumulation of IAA in various parts of the cherry rootstock, indicating its potential role in regulating plant growth and development (Sofa, Scopa et al. 2011). The phytostimulant properties of *Trichoderma* are also reliant on the accumulation of auxins in tomato plants. Auxin accumulation, possibly facilitated by *Trichoderma* or its activities, plays a crucial role in promoting plant growth and development in tomatoes. This suggests that *Trichoderma*-induced auxin accumulation contributes to the positive effects observed in terms of plant stimulation and enhancement in tomato cultivation (Chowdappa, Kumar et al. 2013, Martínez-Medina, Del Mar Alguacil et al. 2014). *Trichoderma* species produce a range of secondary metabolites, including both volatile and non-volatile substances. Some of the notable secondary metabolites produced by *Trichoderma* spp. include 6-n-pentyl-6H-pyran-2-one (6PP), gliotoxin, viridian, harzianopyridone, harziandione, and peptaibols. These compounds contribute to the bioactive properties and beneficial effects exhibited by *Trichoderma*, such as their antifungal activity, plant growth promotion, and mycoparasitic capabilities. (Reino, Guerrero et al. 2008, Vinale, Sivasithamparam et al. 2008, Vinale, Sivasithamparam et al. 2008). Exposure of *Arabidopsis thaliana* seedlings to volatile organic compounds (VOCs) released by *Trichoderma* results in enhanced root branching, increased

biomass production, and expedited flowering.(Contreras-Cornejo, Macías-Rodríguez et al. 2011, Hidangmayum and Dwivedi 2018). Recent studies have uncovered that *T. atroviride* produces a volatile compound called 6-PP. This compound has been found to promote plant growth and play a role in regulating root architecture. Specifically, it inhibits primary root growth while inducing the formation of lateral roots. This indicates that 6-PP emitted by *T. atroviride* has the ability to influence and shape the root development of plants.(Garnica - Vergara, Barrera - Ortiz et al. 2016). Strains of *T. virens* have been found to produce a hydrophobin-like protein called Sm1. This protein exhibits properties similar to hydrophobins and has been shown to induce the biosynthesis of terpenoid phytoalexins and enhance peroxidase activity in cotton plants. The presence of Sm1 in *T. virens* strains suggests its role in stimulating the plant's defense mechanisms and enhancing its ability to respond to pathogen attacks.(Hanson and Howell 2004, Djonovi , Pozo et al. 2006, Djonovic, Vargas et al. 2007). The growth-promoting effects of *Trichoderma harzianum* are attributed to the production of harzianic acid (HA), a nitrogen heterocyclic compound. HA has been demonstrated to enhance plant growth and development by facilitating nutrient uptake, regulating hormones, and influencing various physiological processes. The presence of HA in *Trichoderma harzianum* underscores its potential as a bioactive compound that promotes plant growth. HA acts as a natural defense mechanism, counteracting the growth and activity of fungal pathogens specifically in canola plants.(Vinale, Flematti et al. 2009). *Trichoderma* species promote nutrient uptake and plant growth through their ability to produce siderophores. These secondary metabolites have the capability to bind essential metal ions, particularly iron. By producing siderophores, *Trichoderma* enhances the availability and uptake of iron and other essential metals by plants, leading to improved nutrient acquisition and enhanced plant growth.(Vinale, Nigro et al. 2013). Siderophores produced by beneficial microorganisms play a crucial role in facilitating plant iron uptake,

especially in calcareous soil conditions. In calcareous soil, iron availability to plants is often limited due to high pH and the formation of insoluble iron compounds. However, beneficial microorganisms, such as *Trichoderma*, produce siderophores that can solubilize and chelate iron, making it more accessible for plant uptake. This ability of siderophores to enhance iron availability in calcareous soil is of significant importance for promoting optimal iron uptake by plants and maintaining their healthy growth and development.(Sharma, Johri et al. 2003, Vinale, Nigro et al. 2013).

3. Induced systemic tolerance

When foreign interactions or penetration occur in plant roots, the plant's immune system is triggered. However, *Trichoderma* spp. have the ability to modify the plant's immune system and are recognized as non-pathogenic.(Pieterse, Van der Does et al. 2012). Several well-known strains of *Trichoderma* have the capability to stimulate the synthesis of jasmonic acid (JA) and ethylene (ET), both of which play a role in the development of induced systemic resistance (ISR). (Contreras-Cornejo, Macías-Rodríguez et al. 2011, Salas-Marina, Silva-Flores et al. 2011, Hermosa, Viterbo et al. 2012, Nawrocka and Małolepsza 2013). A study conducted on maize implemented specific inhibitors targeting the synthesis of jasmonic acid (JA) and ethylene (ET). The results of this study demonstrated that these signaling pathways mediated the protective response against *C. graminicola*(Djonovi , Pozo et al. 2006). Likewise, the induction of systemic resistance (ISR) against *Botrytis cinerea* in *Arabidopsis thaliana* was observed through the use of *Trichodermaasperellum* or *Trichodermaharzianum* T39.(Korolev, Rav David et al. 2008, Segarra, Casanova et al. 2010, Velázquez-Robledo, Contreras-Cornejo et al. 2011, Nawrocka and Małolepsza 2013). *Trichoderma* spp. plays a crucial role in effectively suppressing plant diseases and inhibiting the growth of pathogens in both greenhouse and field conditions.(Harman 2000). Considering the fact that *Trichoderma* produces various elicitors that interact with plant receptors, leading to the

recognition of *Trichoderma* and the induction of resistance in plants.(Djonovi , Pozo et al. 2006, Shoresh, Harman et al. 2010, Salas-Marina, Silva-Flores et al. 2011). Furthermore, it has been observed that different strains of *Trichoderma* produce small secondary metabolites, which have the ability to induce the production of pathogenesis-related (PR) proteins and systematically reduce disease symptoms.(Vinale, Sivasithamparam et al. 2008, Vinale, Sivasithamparam et al. 2008). Mycoparasitism is widely recognized as a crucial phenomenon in various systems, as it possesses the potential to attack and lyse plant pathogenic fungi such as *Alternaria alternate*, *Botrytis cinerea*, *Rhizoctoniasolani*, *Sclerotiniasclerotiorum*, *Pythium*spp., and *Fusarium* spp.(Harman, Howell et al. 2004). *Trichoderma* utilizes a range of enzymes such as chitinases, glucanases, and proteases to parasitize and derive nutrients from both active and non-active resting spores of the pathogen. These enzymes play vital roles in breaking down the host pathogen, facilitating nutrient uptake by the mycoparasite, and degrading the pathogen's cell wall components. By producing chitinases, glucanases, and proteases, *Trichoderma* effectively promotes the flow of nutrients into its own cells while dismantling and utilizing the resources of the host pathogen. (Mukherjee, Mukhopadhyay et al. 2008, Inch and Gilbert 2011).

4. Colonization and interaction

Numerous *Trichoderma* strains have been identified to colonize the roots of both monocot and dicot plants(Harman and Shoresh 2007). The interactions between *Trichoderma* and plant roots include various stages, such as recognition, attachment, penetration, colonization, and nutrient transfer from the root(Mukherjee, Mukherjee et al. 2012). Initially, their hyphae wrap around the roots, creating aspersoria-like structures, and ultimately, they penetrate the root cortex.(Yedidia, Benhamou et al. 1999). Appressoria-like structures enable *Trichoderma* to attach to the host plant roots, and this attachment process is facilitated by two hydrophobin-like proteins: TasHyd1 from *T. asperelloides* and *qid74* from *T. harzianum*. The

qid74 gene is responsible for encoding a cysteine-rich cell wall protein, while the TasHyd1 protein possesses an expansin-like characteristic along with a cellulose-binding domain. This cellulose-binding domain allows TasHyd1 to recognize cellulose and modify the architecture of the plant cell wall by secreting cellulolytic and proteolytic enzymes (Viterbo and Chet 2006, Brotman, Briff et al. 2008, Samolski, Rincon et al. 2012). These hydrophobin-like proteins, TasHyd1 and *qid74*, play a crucial role in facilitating root colonization. They promote fungal-host recognition and adhesion, essential for establishing symbiotic associations between *Trichoderma* and the host plant (Viterbo and Chet 2006). It has been reported that *T. harzianum* produces plant cell wall degrading enzymes, such as endopolygalacturonase, which play a crucial role in facilitating active root colonization (Morán-Diez, Hermosa et al. 2009). Studies have demonstrated that *T. virens* produces auxins and other related compounds that potentially aid in root colonization by promoting root growth. These compounds have the ability to enhance the development of plant roots, thereby facilitating a more effective and beneficial interaction between *T. virens* and the host plant (Contreras-Cornejo, Macías-Rodríguez et al. 2009). Both symbiotic and non-symbiotic beneficial microbes are initially perceived by the plant as potential pathogens, leading to the activation of plant immunity. This recognition process is triggered by the detection of microbes-associated molecular patterns (MAMPs) by specific receptors present in the plant (Jones and Dangl 2006, Boller and Felix 2009, Pieterse, Van der Does et al. 2012). *Trichoderma* is capable of reshaping or manipulating the plant's immune response by reprogramming its transcriptome and proteome. Through this process, *Trichoderma* can modify how the plant reacts to its presence, leading to more favorable interactions, such as establishing symbiotic relationships or inducing systemic resistance against pathogens. Ultimately, this ability contributes to improved plant health and growth (Marra, Ambrosino et al. 2006, Alfano, Ivey et al. 2007, Segarra, Casanova et al. 2007, Shores and Harman 2008).

The general mechanism of root colonization and interaction involves exchanges of molecular signals and the deposition of fungal elicitors in the root apoplast. For instance, when colonized by *T. harzianum*, maize seedlings exhibit significant changes in their shoot proteomes, despite T22 primarily interacting with the roots. This suggests that intricate signaling and communication pathways play a crucial role in the overall effects of root colonization by *Trichoderma* species on the entire plant (Shoresh and Harman 2008, Contreras-Cornejo, Macías-Rodríguez et al. 2016). While *Trichoderma* species are renowned for their rhizosphere colonization and limited root penetration, some of these species also act as typical endophytes within plants. They achieve this by entering through trichomes, where they produce appressoria-like structures to facilitate their entry and establish a beneficial relationship with the host plant (Bae, Sicher et al. 2009). Consequently, their interaction results in mutual benefits, as *Trichoderma* can thrive in the soil while serving as valuable plant symbionts. They establish a harmonious relationship with plants, promoting their growth and well-being.

5. *Trichoderma* provides tolerance to abiotic stresses:

Crop plants can suffer cellular damages due to major abiotic factors such as heat, drought, cold, and salinity. However, certain fungal symbionts are commonly found in association with plant communities that naturally resist these various stresses (Marasco, Rolli et al. 2012). *Trichoderma* strains are recognized for their capacity to enhance plant tolerance to abiotic stress, such as drought and salinity. This is achieved through multiple mechanisms, including the promotion of increased root growth, improved nutritional uptake, and the induction of protective responses against oxidative stress. Consequently, these beneficial effects of *Trichoderma* symbiosis enable plants to better cope with challenging environmental conditions and ultimately thrive despite adverse factors (Mastouri, Björkman et al. 2010, Shoresh, Harman et al. 2010). Plants treated with *Trichoderma* exhibit

significantly increased resistance to water stress. A study conducted on tomatoes demonstrated that T22-inoculated tomato seedlings, under water deficit conditions and in the presence of methyl viologen (MV), which enhances ROS production, experienced reduced oxidative inhibition of seed germination and showed improved seedling growth. These findings highlight the positive impact of *Trichoderma* treatment in mitigating water stress effects on plant growth and development (Mastouri, Björkman et al. 2010, Shores, Harman et al. 2010, Mastouri, Björkman et al. 2012). These effects could be attributed to the stimulation of antioxidant responses and the heightened activities of enzymes involved in ascorbate and glutathione recycling.(Mastouri, Björkman et al. 2012).Under drought conditions, there is typically an increase in the total amino acid content in cacao seedlings. However, when cacao seedlings are inoculated with *T. Hamatum* DIS2196, it mitigates the negative effects of drought and delays the drought-induced changes. This means that the presence of *T. Hamatum* DIS2196 allows the plant to continue its growth despite facing water stress (Bae, Sicher et al. 2009). Furthermore, when maize plants are treated with *T. harzianum*, they exhibit improved resistance to water deficit and enhanced deep rooting. Research findings have revealed that maize plants inoculated with *Trichoderma* demonstrate higher starch content in their leaves. This characteristic could be advantageous in drought conditions, where prolonged stomatal conductance can lead to carbon starvation. The increased starch content helps provide a potential source of carbon for the plant during periods of water scarcity, thus supporting its survival and growth under drought stress (Harman 2000, Shores and Harman 2008, Shukla, Awasthi et al. 2012). The application of *Trichoderma* leads to increased root growth in rice, even under conditions of water deficit. This effect results in a delay in drought responses. Additionally, *Trichoderma* treatment was found to reduce proline, malondialdehyde (MDA), and hydrogen peroxide content, while enhancing the concentration of phenolic compounds in the rice plants. These findings

highlight the positive impact of *Trichoderma* on rice plants, helping them cope with water deficit and mitigate oxidative stress during drought conditions (Shukla, Awasthi et al. 2012). Salinity exerts its influence on the majority of plants by altering water relations within the tissues, disrupting ion balances, and inducing oxidative stress.(Munns 1993, Shoresh, Harman et al. 2010). A study conducted on Indian mustard revealed that higher concentrations of NaCl (200mM) negatively impacted growth and various physio-biochemical attributes. Plant height decreased by 33.7%, root length by 29.7%, and plant dry weight by 34.5%. However, when treated with *Trichodermaharzianum*, the negative effects of NaCl (200mM) were mitigated. The plants treated with *Trichoderma* showed an increase of 13.8%, 11.8%, and 16.7% in shoot length, root length, and plant dry weight, respectively, compared to those treated with NaCl (200mM) alone (Ahmad, Hashem et al. 2015). Therefore, the application of *T. harzianum* mitigates the adverse effects of NaCl stress. Similar findings were observed in tomato plants as well. (Mastouri, Björkman et al. 2012). Furthermore, salinity caused a reduction in the oil content of Indian mustard, potentially attributable to the restricted transport of cytokinin from roots to shoots, leading to alterations in the cytokinin: ABA (abscisic acid) ratio in the leaves.(El-Keltawi and Croteau 1987, Ahmad, Hashem et al. 2015). Beneficial microbes have been shown to reduce ABA accumulation during NaCl stress and improve the transport of cytokinins from roots to shoots.(Aroca, Ruiz-Lozano et al. 2013, Ahmad, Hashem et al. 2015, Hashem, Abd_Allah et al. 2015).

Salt stress has a negative impact on the photosynthetic pigments in plants. This decrease in pigment content could be attributed to the inhibition of various enzymes involved in chlorophyll biosynthesis, such as -aminolevulinic acid dehydratase and photochlorophyllidreductase. Additionally, the impaired availability of essential elements like Mg²⁺, Fe²⁺, Zn²⁺, and Mn²⁺ required for chlorophyll synthesis may contribute to the

reduced pigment levels under salt stress conditions.(Padmaja, Prasad et al. 1990, Van Assche and Clijsters 1990, Küpper, Küpper et al. 1996, Ahmad, Hashem et al. 2015).

The reduction in carotenoid content under NaCl stress can lead to an increase in reactive oxygen species (ROS) production. As a consequence, this oxidative stress can adversely affect plant growth by causing damage to DNA, RNA, and proteins associated with it.(Misra, Latowski et al. 2006, Ahmad, Jaleel et al. 2010).

Under NaCl stress, the antioxidant defense system, lipid peroxidation, proline-metabolizing enzymes, and various biochemical activities were examined in two *Morusalba* genotypes. This finding aligns with similar observations made by Rawa et al. (2011) in wheat and Zhang et al. (2013) in cucumber. Consequently, the increased pigment concentration in *Trichoderma*-inoculated plants may be attributed to phytohormone production, which potentially plays a role in mitigating the effects of NaCl stress and supporting the plants' response to adverse conditions (Rawat, Singh et al. 2011, Zhang, Yuan et al. 2013, Martínez-Medina, Del Mar Alguacil et al. 2014, Ahmad, Hashem et al. 2015). The rise in photosynthetic pigment levels could be a result of the inhibition of Na uptake.(Iqbal and Ashraf 2013). Indeed, plants inoculated with *Trichoderma* have been observed to exhibit increased potassium content.(Yedidia, Srivastva et al. 2001, Yildirim, Taylor et al. 2006). Enhancing potassium uptake mitigates the adverse impact of salinity.(Shabala and Cuin 2008). Additionally, it induces stomatal closure and helps alleviate salt stress-induced osmotic stress (Shoresh, Harman et al. 2010). Furthermore, salinity decreases the calcium content in plants (Cramer 2002, Neves-Piestun and Bernstein 2005). Nevertheless, *Trichoderma* treatment resulted in a higher calcium content under salt stress compared to the control group.(Yildirim, Taylor et al. 2006).

When exposed to salt stress, mustard plants treated with *Trichoderma* show an increase in proline content. Proline serves as a crucial osmolyte, aiding in the maintenance of cell

osmoregulation during NaCl stress.(Ahmad, Jaleel et al. 2010, Rasool, Ahmad et al. 2013, Ahmad, Hashem et al. 2015). A parallel observation was made in Arabidopsis seedlings inoculated with *Trichoderma* , wherein an augmented accumulation of proline was detected compared to the control group under salt stress conditions (Contreras-Cornejo, Macías-Rodríguez et al. 2014). Proline exhibits strong antioxidative properties, enabling it to effectively scavenge ROS, such as hydrogen peroxide, and safeguard cells from oxidative damage (Ahmad, Jaleel et al. 2010, Jogaiah, Govind et al. 2013). Furthermore, the increased accumulation of proline has been shown to enhance nitrogen fixation in plants.(Ahmad, Hashem et al. 2015). Under severe stress conditions, plants become incapable of efficiently scavenging the accumulated ROS, resulting in damage to cellular components (Mittler 2002). Nonetheless, plants inoculated with *Trichoderma* exhibit enhanced protection through increased ROS scavenging abilities. Proteomics studies have shown that *Trichoderma* - inoculated plants exhibit elevated levels of important antioxidant enzymes, such as SOD (superoxide dismutase), peroxidase, glutathione-reductase, glutathione-S-transferases (GST), and other detoxifying enzymes in their leaves. These findings highlight the potential of *Trichoderma* to bolster the antioxidant defense system of plants, enhancing their ability to counteract oxidative stress (Shoresh and Harman 2008). Inoculation with T22 also resulted in the restoration of vigor in seedlings that had been previously damaged by oxidative stress.(Björkman, Blanchard et al. 1998). A recent study on tomatoes inoculated with *Trichoderma harzianum* AK20G strain demonstrated that it effectively mitigated the adverse effects of chilling stress. This resulted in a reduction in lipid peroxidation rate and electrolyte leakage, ultimately leading to increased leaf water content and proline accumulation (Ghorbanpour, Salimi et al. 2018). Likewise, Arabidopsis plants inoculated with *T. harzianum* exhibited enhanced tolerance to heat stress, with the *Trichoderma* treatment inducing the production of heat shock proteins.(Montero-Barrientos, Hermosa et al. 2008,

Montero-Barrientos, Hermosa et al. 2010). Plants frequently encounter heavy metal accumulation, which can have detrimental effects on their health. This includes the inhibition of photosynthesis, decreased nutrient uptake, reduced cell division, and lower germination percentage.(Sharma and Dubey 2005).

Trichoderma atroviride F6 inoculation on Cd and Ni-contaminated soil leads to significant alleviation of cellular toxicity in mustard plants. Inoculation with *Trichoderma longibrachiatum* (WT2) on sunflower plants subjected to Pb²⁺ effectively mitigated the induced oxidative stress and resulted in increased levels of antioxidant enzymes. However, it is important to note that various strains of *Trichoderma* exhibit different degrees of growth promotion in plants. (Adams, De-Leij et al. 2007, Cao, Jiang et al. 2008, Devi, Sreenivasulu et al. 2017). Plants inoculated with *Trichoderma harzianum* T22 exhibit significant increases in tree growth, although the growth promotion is comparatively lower in metal-contaminated soils than in uncontaminated soils.(Adams, De-Leij et al. 2007). Nonetheless, *Trichoderma atroviride* F6-inoculated plants show increased plant growth in contaminated soils but do not significantly stimulate plant growth in uncontaminated soils. This difference in growth promotion may be attributed to the reduction in damage caused by metal stress in contaminated soils, ultimately leading to enhanced plant growth.(Devi, Sreenivasulu et al. 2017). Similar observations were made in onion plants, where inoculation with *Trichoderma asperellum* resulted in a reduction of the phytotoxic effects caused by copper.(Vargas, Rodríguez-Monroy et al. 2017).

***Trichoderma* Inoculants: Enhancing Plant Growth in Various Crop Species:**

Trichoderma spp. has recently been recognized as a plant growth-promoting fungi (PGPR) attributed to its capability to produce siderophores, phosphates-solubilizing enzymes, and phytohormones.(Doni, Al-Shorgani et al. 2013, Doni, Isahak et al. 2014). Stimulating plant growth is among the advantageous traits of *Trichoderma* (Shukla, Awasthi et al. 2012,

Contreras-Cornejo, Macías-Rodríguez et al. 2016). This can be achieved through various mechanisms, such as mycoparasitism, antibiosis, and toxin degradation, inactivation of pathogenic enzymatic pathways, pathogen resistance, and enhanced nutrient uptake, contributing to overall plant development.(Harman 2006, Lorito, Woo et al. 2010, Doni, Isahak et al. 2014). A significant increase in rice plant height, leaf number, tiller number, and root length was reported.(Doni, Isahak et al. 2014). These enhancements are made possible by the mechanisms involved, such as improved nutrient use efficiency and increased tolerance to abiotic and biotic stress. Notably, the production of phytohormones by *Trichoderma* -treated plants plays a pivotal role in promoting enhanced plant growth.(Chowdappa, Kumar et al. 2013). *Trichoderma* is reported to produce cytokinin-like molecules (e.g., Zeatin) and gibberellins-related molecules (GA3 or GA4), which offer potential benefits for enhancing crop fertility through biological means.(Tucci, Ruocco et al. 2011, Idowu, Oni et al. 2016, Kashyap, Kumar et al. 2017). Rice plants inoculated with *Trichoderma* also exhibited a higher photosynthetic rate.(Doni, Isahak et al. 2014). Rice plants treated with *Trichoderma* exhibited improved nutrient uptake.(Saba, Vibhash et al. 2012, Doni, Isahak et al. 2014). Rice plants treated with *T. harzianum* demonstrated a significant increase in their ability to tolerate drought and water deficit conditions, thereby contributing to better nutrient uptake and overall plant growth (Shukla, Awasthi et al. 2012, Doni, Isahak et al. 2014). Likewise, in maize plants, *Trichoderma* increased growth, enhanced root biomass production, and promoted increased root hair development (Björkman et al., 1998; G. E. Harman, R. Petzoldt, et al., 2004). Research conducted on tomato seeds with *T.harzianum* provides evidence that *Trichoderma* accelerates seed germination and ameliorates the adverse effects of water, osmotic stress, salinity, chilling, and heat stresses by inducing physiological protection against cellular damages (Mastouri, Björkman et al. 2010). *Trichoderma* has also been reported to increase foliar area, promote secondary root

development, and modulate root architecture.(Chacón, Rodríguez-Galán et al. 2007, Mastouri, Björkman et al. 2012). Moreover, there have been reports of increased growth in *Trichoderma* -inoculated plants, including strawberries, tomatoes, soybeans, apples, cotton, and gray mangroves (Porrás, Barrau et al. 2007, Morsy, Abdel-Kawi et al. 2009, Shanmugaiah, Balasubramanian et al. 2009, John, Tyagi et al. 2010, Jayant 2012, Saravanakumar, Arasu et al. 2013, Doni, Isahak et al. 2014).

Conclusion:

In conclusion, *Trichoderma* species have emerged as vital allies in modern agriculture, offering significant benefits in promoting plant growth, enhancing disease resistance, and mitigating the adverse effects of abiotic stresses. The interaction between *Trichoderma* and plants is a complex and multifaceted process involving recognition, colonization, and the exchange of molecular signals that trigger beneficial responses in both partners. Through their mycoparasitic capabilities, *Trichoderma* efficiently suppresses various plant pathogens, including phytopathogenic fungi and nematodes, by producing a diverse array of enzymes and secondary metabolites with antifungal properties.

Moreover, *Trichoderma* is recognized for its ability to induce systemic resistance in plants, leading to enhanced immunity against a wide range of pathogens. By reprogramming plant transcriptomes and proteomes, *Trichoderma* can reshape the plant's immune response, allowing for more favorable interactions and improved plant health.

One of the most significant contributions of *Trichoderma* to modern agriculture lies in its capacity to enhance plant tolerance to abiotic stresses such as drought, salinity, heat, and heavy metal toxicity. The production of growth-promoting compounds, such as auxins and gibberellins, enables *Trichoderma* -inoculated plants to exhibit improved root growth, nutrient uptake, and overall resilience to challenging environmental conditions.

Trichoderma also actively scavenges ROS, mitigating oxidative stress in plants subjected to various abiotic stresses.

The ability of *Trichoderma* to alter plant hormone levels, activate antioxidant defense mechanisms, and enhance nutrient uptake all contribute to its role as a valuable biocontrol agent and plant growth-promoting fungus.

In the context of sustainable agriculture and environmentally friendly practices, *Trichoderma* offers a promising alternative to chemical pesticides and fertilizers. Its potential to stimulate plant growth, induce resistance against pathogens, and improve plant tolerance to abiotic stresses makes it an essential component of integrated pest management and crop protection strategies.

However, while the beneficial effects of *Trichoderma* are well-documented, there is still much to explore and understand about its interactions with different plant species, the mechanisms governing its effects on plant growth, and the factors that influence its effectiveness under diverse environmental conditions.

In conclusion, *Trichoderma* stands as a remarkable example of the potential of beneficial fungi to revolutionize agriculture. Continued research and application of *Trichoderma* and similar biocontrol agents hold great promise in promoting sustainable agricultural practices, increasing crop productivity, and contributing to food security in an ever-changing and challenging world. Embracing the power of *Trichoderma* in agriculture can pave the way for a more resilient and environmentally conscious approach to crop management, benefiting both farmers and consumers alike.

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