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Exploitation of *Trichoderma* spp. for Soil and Crop Health in Sustainable Agriculture

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A B S T R A C T

Trichoderma, a genus of soil fungi, holds considerable economic importance due to its wide distribution across various climates and its ability to thrive in soils subjected to stressors like salinity, alkalinity, nutrient deficiencies, and drought. This review provides an in-depth analysis of the potential applications and role of *Trichoderma* in enhancing sustainable agriculture. It begins by exploring how *Trichoderma* species foster plant growth and development, particularly under biotic and abiotic stress conditions, while offering protection against plant pathogens. The article also examines the agricultural uses of *Trichoderma*, including its role as a biocontrol agent and biofertilizer, which contribute to more sustainable farming practices. However, agricultural chemicals, such as fungicides, can negatively impact *Trichoderma* species. Despite these challenges, the review emphasizes the significant benefits of integrating *Trichoderma* into farming, including improvements in soil quality, enhanced agricultural productivity, and reduced reliance on chemical pesticides. Moreover, *Trichoderma's* ability to interact with plants through root colonization and act as a plant growth enhancer for a wide range of crops further underscores its potential. The safety, affordability, efficacy, and eco-friendly nature of *Trichoderma* spp. make them a promising option for advancing sustainable agriculture.

Introduction

Soil microorganisms, particularly fungi and bacteria, play a pivotal role in nutrient cycling, soil ecosystem protection, and the overall functioning of agroecosystems. They actively participate in the decomposition of soil organic matter and contribute to nutrient cycling based on crop nutrient requirements

(Bardgett and Van Der Putten, 2014; Janati *et al*., 2021). Various fungal and bacterial strains, such as *Trichoderma* spp., *Pseudomonas* spp., *Streptomyces* spp., *Bacillus* spp., *Beauveria bassiana*, *Gliocladium virens*, and *Pythium oligandrum*, have been used as plant growth promoters and biological control agents (Sharma, 2019; Subedi *et al.,* 2020). The utilization and exploitation of these microorganisms offer a sustainable ecological approach to reduce usage of mineral fertilizers, pesticides, and enhance soil health (Zaidi *et al.,* 2017).

Fungal biocontrol agents in Agriculture

Biological control occurs when a biocontrol agent is applied to a host plant to prevent the spread of pathogen-caused plant diseases. It is a viable alternative to chemical control (Awad- Allah *et al.,* 2022). *Trichoderma* spp. are the most widely used biocontrol agents for a variety of root, shoot and postharvest diseases, having antagonistic capabilities based on the activation of several pathways (Abdel-lateif, 2017 and Zin, Badaluddin, 2020). According to Benitez *et al.,* (2004), *Trichoderma* spp. exert biocontrol against fungal phytopathogens either indirectly (by competing for nutrients and space, influencing environmental conditions, stimulating plant development, plant defense mechanisms and antibiosis), or directly (*via* mycoparasitism).

Trichoderma spp. *as* beneficial fungi

Among filamentous fungi, most of the Biological Control Agents (BCAs) belong to the phylum Ascomycota and are mainly representatives of numerous species belonging to the genus *Trichoderma* (Gajera *et al.,* 2013). Numerous studies documented the beneficial properties of avirulent *Trichoderma* strains which allow their use in plant protection, biostimulation, and biofertilization (Ghorbanpour *et al.,* 2018). The multifaceted advantages of *Trichoderma* spp. have garnered significant recognition among researchers and scientists.

Nowadays, more than 340 different species of *Trichoderma* are known in world (Wang, Zhuang, 2019). However, only a few of them are applicable in agriculture, which mainly *include T. harzianum, T. asperellum, T. longibrachiatum, T. guizhouense, and T. viride. Trichoderma* typically produces a variety of secondary metabolites during its growth and reproduction that can weaken the cell walls of pathogenic bacteria and prevent the growth of plant pathogenic bacteria, thereby enhancing plant disease resistance and fostering plant growth (Olowe *et al.,* 2022).

Trichoderma thus plays a crucial role in restoring deteriorated soil and is of great significance in promoting the development of sustainable agriculture. A lot of evidence indicated that the application of *Trichoderma* spp. to plant rhizosphere promoted plant morphological traits such as root-shoot length, biomass, height, number of leaves, tillers and branches (Halifu *et al.,* 2019).

Trichoderma spp. in improving soil health

Trichoderma, also referred to as *Hypocrea* in its teleomorph form, is a type of filamentous fungus with the unique ability to feed on other fungi, a process known as mycotrophism. It thrives in a wide variety of environments, including agricultural, forestry, mountainous, grassland, desert, and aquatic ecosystems, demonstrating both high adaptability and global distribution. *Trichoderma* species grow rapidly on diverse substrates and produce abundant green conidia, making them easily identifiable (Chaverri *et al.,* 2003). These fungi function as opportunistic and avirulent symbionts of plants, employing various mechanisms that contribute to their beneficial effects on plants and soil (Chaverri *et al.,* 2003). Notably, *Trichoderma* spp. play a vital role in sustaining soil biochemical properties, enhancing food security, and preserving biodiversity by offering numerous benefits to the soil (Asghar and Kataoka, 2021).

Trichoderma spp. in managing plant diseases

Beyond their growth-promoting attributes, *Trichoderma* spp. exhibit significant antagonistic activity against other fungi, showcasing their biocontrol potential (Naher *et al.,* 2014; ElKomy *et al.,* 2015). *Trichoderma* spp.'s fast growth, adaptability to diverse substrates, and resilience to toxins contribute significantly to their efficacy as biocontrol agents in soil ecosystems, especially in agricultural settings. Their role in preventing soil-borne diseases, maintaining soil health, and fostering plant development underscores their importance as valuable resources for sustainable agriculture.

Biological control is a contemporary approach that is considered efficacious in managing various phytopathogen infections (Peng *et al.,* 2021). This approach employs biological agents, such as bacteria, viruses, and fungi, as anti-phytopathogen agents, which provide advantages to the host plants (Thambugala *et al.,* 2020). These biological agents decompose more easily in the environment and are typically less harmful to non-target species (Saravanakumar *et al.,* 2017). Consequently, they provide sustainable disease management and serve as eco-friendly alternatives to chemical treatments for plant diseases (Palmieri *et al.,* 2022; Rawat *et al.,* 2022; Stenberg *et al.,* 2021).

Mycoparasitism

The process of identifying the target fungus hyphae and producing cell wall digesting enzymes is the first step in mycoparasitism (Manzar *et al.,* 2022). *Trichoderma* uses a mycoparasitic mechanism to impede the growth of other fungal mycelia and ultimately diminish them (Guzmán-Guzmán *et al.,* 2023). Mycoparasitism initiates with the binding of carbohydrates in the cell wall of *Trichoderma* to lectins from the target fungi, followed by the encirclement of *Trichoderma* hyphae around the target fungi and the formation of appressoria (Sood *et al.,* 2020). Appressoria are papilla-shaped structures that indicate the attachment of pathogenic fungi by *Trichoderma* (Sharma *et al.,* 2020).

During mycoparasitic interactions, *Trichoderma* spp. initiate the synthesis of hydrolytic or lytic enzymes, such as glucanase, chitinase and protease, which degrade the chitin polymers of the fungal pathogen cell wall (Mukhopadhyay and Kumar, 2020; Parmar *et al.,* 2015). *Trichoderma* may also create antibiotics or low-molecular-weight diffusible compounds such harzianic acid, tricholin, peptaibols, 6-pentyl-pyrone, viridin and heptelidic acid, all of which hinder the development of other microbes (Abdel-lateif, 2017). For these reasons, *Trichoderma* spp. can be used as effective biofungicides and alternative agents against phytopathogens (Belaidi *et al.,* 2022; Srivastava *et al.,* 2016).

Antibiosis

Antibiosis refers to the process by which *Trichoderma* produces antibiotics or low-molecular-weight secondary metabolites that have the ability to impede the growth of phytopathogens (Asad, 2022). Produced during the stationary phase, these secondary metabolites are organic substances that are not necessarily essential for the survival of an organism and are not directly engaged in its regular growth, development, or reproduction (Sharma *et al.,* 2017). These metabolites consist of various classes, including peptaibols, pyridones, viridiofungins, pyrones, koninginins, steroids, furanosteroids, pyridones, epipolythiodioxopiperazines, butenolides, azaphilones, anthraquinones, lactones, trichothecenes, isocyanides, polyketides, and peptides (Dutta *et al.,* 2023; Saldaña-Mendoza *et al.,* 2023; Zeilinger *et al.,* 2016).

The antibacterial substances (dimethyl disulfide, dibenzofuran, methanethiol, ketones, etc., which were effective ingredients for antagonistic activity) produced by *Trichoderma* can prevent pathogenic microorganisms from colonizing the rhizosphere of plants and inhibit pathogenic fungi by competing for nutrition and space, hyperparasitism, bacteriolysis, and the production of antibiotic and secondary metabolites (Chen *et al.,* 2016; Zin, Badaluddin, 2020).

Some non-polar compounds (cerinolactone, harzianolide, dehydroharzianolide, T39 butenolide, etc.) with a low molecular weight produced by *Trichoderma* are resistant to *Botrytis cinerea* such as butyrate lactone T39 and harzianolide secreted by *T. harzianum* T39, and azaphilone and harzianopyridone secreted by *T.harzianum* T22 (Vinale *et al.,* 2012). These compounds are also reported to be active against *Gaeumannomyces graminis var. tritici* and *R. solani* (Vinale *et al.,* 2012).

More recently, Baiyee *et al.,* (2019) collected the extracellular metabolites such as alcohols (ethanol and phenylthyl alcohol), pyran (6-pentyl-2H-pyran-2-one), and other volatile compounds (ethyl 2-methylbutyrate and 2-amylfuran) from *Trichoderma spirale* T76-1 culture filtrates and evaluated their antibiosis against *Corynespora cassiicola and Curvularia aeria*. The isolates *T. spirale* T76-1 have produced the above five isolated metabolites that inhibited the growth of *C. cassiicola* and *C. aeria* by 84.68% and 93.03%, respectively. Generally, *Trichoderma* has a broad-spectrum antifungal activity against plant pathogens (Baiyee *et al.,* 2019).

Trichoderma spp. in bioremediation

Trichoderma is a soil-borne fungus that plays a key role in the bioremediation of contaminated soils and can be effectively integrated into pest management strategies. *Trichoderma* species act as hyperaccumulators, helping to concentrate and absorb heavy metals. They also aid in breaking down toxic substances, thus promoting soil health and sustainability. Additionally, *Trichoderma* spp. produce organic acids such as gluconic acid, fumaric acid, and citric acid, which help lower soil pH and facilitate the dissolution of phosphate, as well as macro- and micronutrients like iron, manganese, and magnesium, all of which are essential for plant metabolism. Moreover, *Trichoderma* has the ability to remove and concentrate various ions, including Pb, Cd, Cu, Zn, and Ni, which is recognized as a primary mechanism of metal uptake (Srivastava *et al.,* 2011).

Bioremediation of inorganic pollutants by *Trichoderma* spp.

Heavy metals persist in soil for a long period of time. It makes soil infertile. Metals such as cadmium, mercury, copper, zinc, and arsenic are increasingly released into the environment through the use of pesticides, fertilizers, and other human activities. (Errasquin and Vazquez 2003; Tripathi *et al.,* 2007). Fungi like *Trichoderma* spp. play an important role to degrade and detoxify toxic substances.

Bioremediation of organic pollutants by *Trichoderma* spp.

Polycyclic aromatic hydrocarbons (PAHs) are harmful environmental pollutants composed of three or more fused benzene rings in a linear structure. PAHs are sparingly soluble, hydrophobic, and strongly adsorbed to soil particles. They are known to damage genetic material and alter cell structure (Pashin and Bakhitova, 1979).

Trichoderma, a fungus identified as dominant in diesel-contaminated compost, has shown potential for colonizing and aiding in the degradation of diesel-polluted soil (Hajieghrari, 2010). Additionally, Mishra and Nautiyal (2009) demonstrated that *Trichoderma reesei* can promote plant growth in soils contaminated with diesel.

In addition, *Trichoderma* spp. functioning as natural decomposers, *Trichoderma* spp. accelerate the breakdown of organic materials, particularly hemicellulose and cellulose present in plant cell walls (Ochoa-Villarreal *et al.,* 2012). Through enzymatic actions, *Trichoderma virens* effectively degrades these substances, releasing nutrients and energy that not only support its own growth but also foster the flourishing of other microorganisms in the soil. Additionally, *Trichoderma* spp. contribute to the acceleration of organic material decomposition and the detoxification of hazardous substances, thereby further supporting soil health and promoting plant growth (Vazquez ´ *et al.,* 2015; Zafra *et al.,* 2015).

Bioremediation of agrochemicals by *Trichoderma* spp.

The frequent use of pesticides renders fields unsuitable for sustainable agricultural practices. Pesticide solutions containing organic compounds that run off directly into the soil create a worrying situation. These xenobiotics pose significant risks to human health and also contribute to a decline in microbial populations in the soil. Removals of pesticides become difficult for scientific community. Conventional treatment appears inefficient (Badawy *et al.,* 2006). *Trichoderma* are able to biodegrade toxic pollutant efficiently (Harman *et al.,* 2004a; Cao *et al.,* 2008). Extracellular enzymes system of the fungi and their catalytic reaction help to degrade toxic aromatic compounds. *Trichoderma viride* was reported most efficient among tested fungi for the degradation of chlorpyrifos and photodieldrin (Tabet and Lichtenstein, 1976; Mukherjee and Gopal, 1996).

Furthermore, *Trichoderma* and other microorganisms in soil can detoxify toxic compounds and accelerate the degradation of organic material (Zin and Badaluddin, 2020). Recent research has shown that *Trichoderma* spp. can degrade chemical pollutants by acting on chemicals and metal contaminants *via* the activity of various enzymes, as well as improve soil physical and chemical properties and make nutrients available to plants from agrochemicals (Tripathi *et al.,* 2013; Awad-Allah *et al.,* 2022).

Trichoderma spp. helps to concentrate and absorb heavy metals (HMs), it acts as hyper accumulator. It helps in breaking down of various toxic substances for sustain soil health. *Trichoderma* spp. have great potential against soil borne pathogens, and it may be able to replace chemical pesticides in the near future (Manish Kumar *et al.,* 2020).

Trichoderma spp. as Biofertilizers

In contrast, the adoption of organic-based fertilizers has emerged as an alternative to address nutrient deficiencies and maintain a nutrient balance in agroecosystems (Tewari *et al.,* 2020). Yet, the excessive and improper application of organic fertilizer can also result in adverse ecological impacts. As a result, there is an increasing need to explore bio-based fertilization methods that improve soil fertility through organic and natural approaches, while simultaneously promoting long-term soil health.

As a cosmopolitan fungus, *Trichoderma* flourishes in various soil conditions (Kumar *et al.,* 2023; Shanmugaraj *et al.,* 2023; Zin & Badaluddin, 2020). *Trichoderma* is acknowledged as a versatile biological agent that performs various functions in the environment, functioning as a biotic agent, contributing to the formation of biofertilizers, and enhancing plant resilience against biotic and abiotic stresses (Harman *et al.,* 2021; Hossain *et al.,* 2017; Sood *et al.,* 2020; Thakur, 2021).

Research suggests that *Trichoderma* biofertilizers have significant consequences for soil man agement, encompassing the regeneration of *Trichoderma* populations, organic matter degradation, and the provision of energy to other microorganisms, ultimately contributing to increased plant biomass (Zhang *et al.,* 2018). The multifaceted benefits of *Trichoderma* spp. in agriculture underscore their potential as a critical tool for sustainable soil management practices, encouraging soil health and improving overall crop productivity. Recent findings understanding the remarkable capabilities of *Trichoderma* spp. have paved the way for the development of biopreparations based on various *Trichoderma* strains, benefiting both soil and plants.

These biopreparations are particularly advantageous for organic farming, offering comprehensive protection against a range of plant diseases without resorting to chemical pesticides. *Trichoderma* spp. can accelerate the composting process and play a positive role in the process of compost humification (Mehetre and Mukherjee, 2015; Randhawa *et al.,* 2020). Therefore, combining organic fertilizers (compost) with *Trichoderma* spp. as biofertilizers may be a more effective way to increase plant biomass than only using organic fertilizers or *Trichoderma* separately (Zhang *et al.,* 2018). Srinivasulu *et al.,* (2002b) reported that *Trcihoderma* spp *viz., Trichoderma viride* Per., *T.harzianum* Rifai, and *T.hamatum* (Bun.) Bain were found to inhibit the mycelial growth of *G.applanatum* and *G.lucidum* under *in vitro* conditions and talc formulation of these bioagents in combination with neem cake were also found to check the basal stem rot disease in coconut under field conditions.

Influence of *Trichoderma* spp. in improving soil physico-chemical properties

Unreasonable fertilization and management practices frequently cause severe damage to the soil ecological environment and degradation of soil functions impeding the sustainability of agricultural production (Hung *et al.,* 2006). To effectively improve the degraded soil and quickly restore the soil ecological environment has emerged as a pressing issue in agricultural production.

To improve degraded soil, physical, chemical, and microbial improvement technologies have been widely used. However, physical and chemical enhancement techniques frequently result in soil nutrient losses and secondary pollution. Microbial improvement technology can improve soil physico - chemical properties and regulate the structure of the soil microbial community via applying a combination of an organic fertilizer and functional microbes to promote the rapid release of soil nutrients, which is beneficial for soil restoration and brings certain ecological and economic benefits. *Trichoderma* exhibits a strong colonization ability in soil, which helps to improve the soil physico-chemical environment, encourage the development and maintenance of advantageous soil microbial communities, increase crop resistance and ultimately foster crop growth, and increase agricultural production (Zin, Badaluddin, 2020; Poveda, 2021). *Trichoderma* thus plays a crucial role in restoring deteriorated soil and is of great significance in promoting the development of sustainable agriculture.

Effect of *Trichoderma* spp. on soil physical properties

The use of *Trichoderma* as an organic fertilizer caused increases of 52% and 70% in the organic carbon (C) content of aggregates >0.25 mm and the whole soil contributing to the improvement of soil fertility (Zhu *et al.,* 2021). *Trichoderma* can activate not only soil nutrients but also improve soil physical properties.

Effect of *Trichoderma* spp. on soil chemical properties

Trichoderma can generally lower soil pH and activate soil nutrients by secreting organic acids such as gluconic, citric, and fumaric ones (Fu *et al.,* 2019 and Poveda, 2021) with the lower soil pH mainly contributing to the improvement of soil nutrient availability.It was found that the tomato seedlings inoculated with *T. harzianum* under salinity and drought stress conditions resulted in the maintenance of photosynthetic efficiency and effectively reduced reactive oxygen species (ROS) accumulation (Azad and Kaminskyj, 2016). Moreover, inoculation of wheat seedlings with *T. longibrachiatum* strain conidia enhanced the tolerance of wheat to salt stress and significantly increased the concentration of antioxidant enzymes (Zhang *et al.,* 2016).

Influence of *Trichoderma* spp. on soil enzyme activity

Soil enzyme, such as that of urease, phosphatase, catalase, and saccharase are derived from the production of various soil microorganisms, including, bacteria, fungi and actinomycetes, animals and plants. These biochemical components play potent role in soil fertility, energy conversion and in soil organic matter conversion.

Soil enzymes are involved in various biochemical processes and nutrient circulation, whose activities can reflect the intensity and direction of soil biochemical processes and objectively indicate soil fertility. *T. hamatum* FB10 significantly increased the soil catalase activity (Baazeem *et al.,* 2021), while *T. harzianum* increased the activities of shikimate dehydrogenase, glucose-6-phosphate dehydrogenase, and polyphenol oxidase in the tomato rhizosphere soil by 53.37%, 69.79%, and 71.71%, respectively (Yan *et al.,* 2021). Thus, *Trichoderma* can slow down the toxic effects of toxic and harmful substances in soil on crops by reducing the accumulation of hydrogen peroxide and phenolic substances in soil.

According to Liu *et al.,* (2020), the biofertilizer containing *T. guizhouense* significantly increased the soil urease activity accelerating the transformation of soil organic N and increasing the available N content in the pepper rhizosphere soil, which increased the pepper yield. *Trichoderma* can also increase the soil urease activity and boost the soil alkaline phosphatase activity.

Soil phosphatase activity was increased by more than 10% after the inoculation with *Trichoderma* RW309 in a two-month incubation experiment (Asghar, Kataoka, 2021). The inoculation of *Trichoderma* increased the soil phosphatase activity and accelerated the transformation of organic P compounds or inorganic P in the soil. Therefore, *T. harzianum* can significantly improve the soil N and P supply. Furthermore, *Trichoderma* inoculation caused an increase of 45% in the soil invertase activity in an experiment cultivated with Chinese cabbage (Shi *et al.,* 2021), which effectively promoted the soil C turnover and improved the soil ecological environment. Thus, *Trichoderma* can boost the soil enzyme activity related to C, N, and P transformation in soil and improve the soil nutrient supply and crop rhizosphere ecological environment, all of which are conducive to crop growth and yield improvement (Asghar, Kataoka, 2021).

Trichoderma spp. in plant root colonization

Numerous rhizosphere *Trichoderma* species can colonize the root surfaces of both monocotyledonous and dicotyledonous plants, leading to significant changes in plant metabolism (Contreras-Cornejo *et al.,* 2016). Colonization by the *Trichoderma* species involves the recognition of host plant, attachment and penetration of plant roots, and resistance of *Trichoderma* to metabolites produced by the plants in response to invasion by foreign organisms (pathogenic or non-pathogenic) (Benítez *et al.,* 2004). Due to the colonization of a wide range of host plants, *Trichoderma* presumably developed effective strategies to overcome plant defense mechanisms (Contreras-Cornejo *et al.,* 2016).

During colonization, *Trichoderma* can produce volatile or non-volatile antibiotic substances such as pyranones and antimicrobial peptides, thereby inhibiting pathogenic soil bacteria and reducing the harm of pathogenic bacteria to plant roots and promoting crop growth (Zin, Badaluddin, 2020).

Trichoderma is known as an aggressive colonizer of plant roots that competes for space, nutrients, water, or oxygen by mobilizing immobile soil nutrients, thereby eliminating other micro-organisms that inhabit their niche (Elad *et al.,* 2000; Dutta *et al.,* 2022b) due to the diversified composition of root exudates secreted by plants.

Competition among micro-organisms is a strategy to utilize the nutrient hotspots present in the rhizosphere by eliminating other competitors (Guzman-Guzman *et al.,* 2023). Sucrose-rich root exudates of the host plant attract *Trichoderma*. The soluble secretome of *Trichoderma* plays a significant role in attachment to and penetration and colonization of plant roots, as well as modulating the mycoparasitic and antibiosis activity of *Trichoderma.*

Therefore, to be an effective colonizer of plant roots, those organisms must have metabolic versatility and the competitive capacity to occupy the nutrient hotspots. In this regard, *Trichoderma* can be considered as an aggressive competitor because it has the capacity to secrete a plethora of chemically diverse secondary metabolites that have an antagonistic effect on other micro-organisms (i.e., competitive capacities) and it also exhibits rapid growth and colonization strategies (indicating metabolic versatility) that enable it to occupy space in rhizosphere, enhance plant growth, and restrict further growth of potentially pathogenic micro-organisms (Saravanakumar *et al.,* 2017).

Induction of systemic resistance

The activation of plant defense mechanisms is initiated by several stimuli, such as microorganism cells (*exsoelicitors*) and plant tissues (*endoelicitors*) (Doni *et al.,* 2022; Tyśkiewicz *et al.,* 2022). Both elicitors modify the transcriptomic and proteomic processes in plants, resulting in improved plant growth, increased nutrient absorption, and the activation of resistance pathways in plants (Abdullah *et al.,* 2024; Doni *et al.,* 2022; Thambugala *et al.,* 2020). *Trichoderma* modulates the activity of defensive hormones, including JA, ET, and SA (Akbari *et al.,* 2024; Guzmán-Guzmán *et al.,* 2023).

Trichoderma has the ability to trigger plants to develop their own defense mechanisms in order to gain resistance against diseases that affect either specific areas or the entire plant, a phenomenon referred to as induced systemic resistance (ISR) and systemic acquired resistance (SAR) when pathogenic fungi hinder the growth of the plants (Doni *et al.,* 2019; Romera *et al.,* 2019; Yao *et al.,* 2023; Zehra *et al.,* 2021). Pathogen-induced systemic acquired resistance is characterized by alterations in salicylic acid (SA) levels, the activation of pathogenesis-related (PR) genes, and redox-regulated protein non-expressor of PR Genesis 1 (*NPR1*) expression, while beneficial microorganisms induced systemic resistance, which is typified by changes in jasmonic acid (JA) and ethylene (ET) levels, along with the activation of genes other than PR genes (Doni *et al.,* 2019; Romera *et al.,* 2019; Zehra *et al.,* 2021).

In summary, the remarkable attributes of *Trichoderma* spp. offer promising solutions for sustainable agriculture. Through their biocontrol capabilities, promotion of plant growth, and enhancement of soil health, *Trichoderma*-based strategies can foster a more productive and environmentally sustainable agricultural system. Incorporating *Trichoderma* into farming practices is a crucial step toward achieving long-term sustainability and mitigating the negative impacts of current agricultural methods. Among non-pathogenic microorganisms, *Trichoderma* stands out as an ideal candidate for green technologies due to its extensive biofertilization and biostimulatory potential.

Author Contributions

K. Aruna: Investigation, formal analysis, writing—original draft. K. Sucharita: Validation, methodology, writing—reviewing. P. Suresh:—Formal analysis, writing—review and editing. S. Priyadarshini: Investigation, writing—reviewing. D. R. S. Vineela: Resources, investigation writing—reviewing. K. Vijay Krishna Kumar: Validation, formal analysis, writing—reviewing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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