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Trichoderma: Biology, ecology and *Trichoderma*-plant and *Trichoderma*-pathogen interactions

Payungsak Rauyaree[1*] and Tassanaporn Tadsakorn[2]

[1]Biotechnology Research and Development Office, Department of Agriculture, Rangsit-Nakhon Nayok Road, Thanyaburi District, Pathumthani 12110, Thailand
[2]Plant Protection Research and Development Office, Department of Agriculture, 50 Phaholyyothin Road, Ladyao, Chatuchak, Bangkok 10900, Thailand

***Corresponding author**: *payungsak_r@yahoo.com*

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ABSTRACT

The fungal genus *Trichoderma,* belonging to the family *Hypocreaceae,* Euascomycetes, Ascomycota, Eukaryota, consists of more than 200 species and ecologically resides in most soils in the roots of plants as a rhizosphere-competent and in the part of plants as avirulent opportunistic symbionts, in the decaying woods and organic matters as saprophytes. However, to study the biology, ecology, and plant-*Trichoderma*-pathogen networking, it is essential to understand the colonization of host plant roots, plant growth promotion, root hair development, yield or crop productivity, induced systemic resistance, and prime plant defense. The objective of this review paper was to describe the *Trichoderma* functions which can attack, invade, and inhibit other types of fungi or microbes as biocontrol agents through the mechanisms called antagonistic organisms, antibiosis, nutrient and space competition, mycoparasitism, endophytic colonization, and inactivation of plant pathogen's enzymes. This review summarizes an overview of the biology, ecology, and knowledge background of *Trichoderma*-plant and *Trichoderma*-pathogen interactions.

Keywords: *Trichoderma*, biocontrol agents, *Trichoderma*-plant-pathogen interactions

INTRODUCTION

The hyphomycetes genus biocontrol agents, *Trichoderma* is a soil-well-grown or saprophyte organism (Klein and Eveleigh, 1998). The genus includes more than 200 recognized species (Samuels, 2006; Barroncelly et al., 2015). *Trichoderma* are naturally free-living organisms and abundantly found in many different substrates, living plant-animal, organic debris, and virtually most soils. The utilization of *Trichoderma* spp. resulted in many agricultural advantages such as plant physiology, productivity, and plant disease suppression. They colonize plant roots and attack other plant pathogenic fungi, recognized as biocontrol agents for controlling or reducing many important severe plant diseases. Plant roots are one of the essential parts of the plants where *Trichoderma* can be found, resulting in plant development and crop productivity (Ming et al., 2012; Pecoraro et al., 2012; Chaverri and Samuels, 2013).

Overall, the interaction of the *Trichoderma*, host plants, and pathogens includes plant nutrient sequestration, space competitions, antibiosis, cell-wall-degrading enzyme production, endophytic and rhizosphere colonization. (Benítez et al., 2004; Engelberth et al., 2003; Reino et al., 2008; Bhale and Rajkonda 2012; Munir et al., 2014; Ranveer et al., 2018). As mentioned, even though synthetic fungicides or chemical use are widely used to control plant diseases, a potentially high risk to humans and the environment makes this biocontrol agent *Trichoderma*, even more effective. (Harman, 2006; Akrami and Yousefi, 2015).

At the molecular level, it has been found that *Trichoderma* phenolic and signaling compounds are transferred to other parts of the plants, resulting in PR gene (resistant gene production) (Yedidia et al., 2000), and the pathogenic resistance called SR (systemic acquired resistance). PR proteins (pathogenesis-related proteins) result from the PR gene (Van Loon and Van Strien, 1999; Parker, 2000; Heil and Bostock, 2002; Sallam et al., 2019).

Trichoderma can be used as a low-cost, effective, and eco-friendly alternative biofungicide to control plant diseases instead of using synthetic and toxic fungicides. (Sharma et al., 2019; Sallam et al., 2019). This makes many *Trichoderma* species beneficial microorganisms as commercial biofertilizers and biopesticides (Whipps and Lumsden, 2001; Perotto et al., 2013) and climate resilient agriculture.

Biology

Trichoderma spp. is a soil-borne or saprophyte organism (Klein and Eveleigh, 1998). The shaped-form concentric pattern is a common characteristic of *Trichoderma* spp. Natural carbon in the form of monosaccharides, disaccharides, and nitrogen sources could be utilized by this type of fungi for their growth purposes (Danielson and Davey, 1973b). The *Trichoderma* sporulation characteristic, called conidia, makes this genus grow well on both natural and artificial substrates. This is due to the light and dark responses on the particular day in which conidia will be produced in the period of daylight (Gressel and Hartmann, 1968). The germination of *Trichoderma* conidia could be easily found in various nutrient sources (Danielson and Davey, 1973c). Lewis and Papavizas (1983) reported that 75% of chlamydospores or fresh conidia of *Trichoderma* can be grown on agar media. One main characteristic of this fungi is to produce secondary metabolite or synthetic compounds such as terpenoids, pyrones, indolic-derived compounds, etc. (Contreras-Cornejo et al., 2016).

Ecology

The fungal *Trichoderma* can be isolated from well-degrading organic materials (Danielson and Davey, 1973a) and found in nearly all natural nutrient supplies (Cai et al., 2022). The ecology study of *Trichoderma* spp. would help to increase the information regarding this genus's lives and activities in different habitats. This will also help to increase the knowledge about population dynamics in nature, including soils, root rhizosphere, root surface, and physical, chemical, and biological environments affecting fungal lives, activities, and survives. The sporulation of *Trichoderma* called conidia grows well on both natural and artificial substrates. On the chemical substrate, Lewis and Papavizas (1983) indicated that the germination rate of fresh conidia or chlamydospores is 75% on agar media. The shaped-form concentric pattern is a common characteristic of *Trichoderma* spp. This is due to the responses of light and dark in the individual day in which conidia will be produced in the daylight period (Gressel and Hartmann, 1968).

Trichoderma-plant and *Trichoderma*-pathogen interactions

Trichoderma-plant interactions

According to its free-living organism characteristic, several *Trichoderma* strains induce root branching, plant root colonization, and increase root biomass as a consequence of cell division, expansion, and differentiation by the presence of fungal auxin-like compounds (Contreras-Cornejo et al., 2016). *Trichoderma* is attracted by chemical signals released by plant roots. The initial steps of symbiosis establishment involve the attachment and penetration process. During plant-*Trichoderma* interactions, this process promotes plant growth-promoting biocontrol agents for crop plants, enhances plant fitness under biotic and abiotic stresses, alleviates environmental in plants, nutrient uptake, signaling pathways of induced disease resistance or induced-resistance in the plant, and environmental effects in soil on plants (Kuc, 2001; Colla et al., 2015; Shoresh et al., 2010).

The fungal genus of *Trichoderma* is also crucial due to its plant growth and performance-promoting effects, such as improved nutrient supply, mycoparasitism of plant pathogens, and priming of plant defense. *Trichoderma* is considered the filamentous fungi that can be used in agriculture PGRF or as plant growth-promoting fungi, which is essential in increasing plant defense, in controlling plant diseases or even nematodes (Hermosa et al., 2013; Stewart and Hill, 2014; Monfil and Casas-Flores, 2014; Oskiera et al., 2015). *Trichoderma* species could be used to sustain crop productivity. Many *Trichoderma* species are used as biofertilizers (Mahato et al., 2018; Ranveer et al., 2018). For example, biofertilizers use against many pathogenic fungi to increase crop growth, such as *Fusarium*, *Rhizoctonia*, *Pythium*, *Schlerotinia*, *Verticillium*, *Alternaria*, *Phytopthrora* and other plant pathogenic fungi (Abu-Taleb et al., 2011, Whipps and Lumsden, 2001). They are reported to improve photosynthetic efficiency, enhance nutrient uptake, and increase crop nitrogen use efficiency. In addition, they can be used to facilitate plant adaptation and mitigate adverse effects of climate change. From the study of Colla et al. (2015), the co-cultivation of *Glomus intraradices* and *Trichoderma atroviride*, acts as a biostimulant to promote growth, yield, and nutrient uptake of vegetative crops.

Trichoderma-pathogen interactions

Trichoderma acts as plant disease control, antibiosis and secondary metabolite or volatile organic compound synthesis, mycoparasitism, and competition characteristics against various plant pathogens. The important mycoparasitic biocontrol agents against plant pathogen *Trichoderma* can inhibit growth, penetrate, and kill various fungal plant pathogens involving the hydrolytic enzymes through cell-wall-degrading enzymes (CWDE) activities (Bae et al., 2017; Mukherjee et al., 2012a).

The antibiotics and competition with pathogens (carbon and nitrogen sources, space and infection sites and soil microbial community, and enzymes responsible for secondary metabolite production and also antifungal compounds called volatile organic compounds (Guo et al., 2019; Vinale et al., 2008; Mukherjee et al., 2012b). For example, Crutcher et al. (2013) identified a putative terpene cyclase, vir4, is responsible for the biosynthesis of volatile terpene compounds in *T. virens*.

CONCLUSIONS

Trichoderma biology, ecology, *Trichoderma*-plant, and *Trichoderma*-pathogen interactions have been well-studied. This review paper may lead to a better understanding related to genomics and proteomics study, bioinformatics, CAZymes, comparative genome sequence analysis, CRISPR-Cas or gene editing, metabolomics, transcriptomics, and *Trichoderma* gene and protein database development. This knowledge toward the collated information will allow to gain more information in important *Trichoderma* species in the future.

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