14 Trichoderma from Extreme Environments: Physiology, Diversity, and Antagonistic Activity

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Abstract

The fungus *Trichoderma* is spreading throughout different climate zones. Therefore, this enhances the chance to get some isolates having the ability to confront poor conditions. Several extreme conditions affect *Trichoderma*. In this chapter I focus on important parameters that have large effects on growth, bioactivity, and antagonism as biological control agents. On the basis of these effects, some parameters are appropriate for every strain of *Trichoderma*: main factors such as temperature, pH, nutrient substrate, and water potential, and minor factors such as light and humidity. The temperature parameter is the first main factor that is suggested here to be responsible for alteration in *Trichoderma* life phases and bioactivity. *Trichoderma* has shown a high tolerance for temperature (range 0–50 °C). Most *Trichoderma* spp. showed high efficacy at moderate temperatures. *Trichoderma* spp. can tolerate pH from 2.0 to 13, but more *Trichoderma* tend toward acidic media. Nutrient substrate, water potential, light, and humidity were effective factors related to one or two activities of *Trichoderma*. However, parameters are very important in determining the efficacy of *Trichoderma* for use in controlling plant pathogens. Therefore, we can consider four points to confront these weaknesses of some *Trichoderma*-derived biopesticides and biofertilizers to control plant pathogens.

Keywords

Trichoderma · Extreme soils · Diversity · Biology · Plant

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14.1 Introduction

Trichoderma can spread throughout a wide range of ecological niches. It is ubiquitous in soil and the rhizosphere. The environment for this genus is very attractive because of its ability to attack and compete within different habitats. *Trichoderma* spp. have unique properties that help them grow at high densities in any habitat (Chet et al. 1997). The efficacy of *Trichoderma* activity is depending on an asexual cycle. Indeed, in a habitat under optimal conditions, *Trichoderma* spp. produce enzymes, secondary metabolites, and proteins to compete and that are useful for getting nutrients to grow and disperse through the asexual cycle. Hjeljord et al. (2000) suggested that the growth and antagonism of *Trichoderma* against plant pathogens are decreasing because of poor nutrient levels. The enzymes and secondary metabolites of *Trichoderma* are used in different fields of study. Mastouri et al. (2010, 2012) showed that *Trichoderma* has a high ability to improve the resistance of plants against abiotic and biotic stresses. Therefore, many bioproducts (e.g., biopesticides and biofertilizers) with *Trichoderma* formulations are used to control plant pathogens and to enhance plant growth, as well as, Trichoderma is having the ability to enhance for the tolerance the hard condition such as Salinity, extreme temperature, and water stress (Balestrini et al. 2017). In addition, *Trichoderma* produces several enzymes with high activity that are helpful in biotechnology and remove waste from the environment. Conidial suspension are used to control plant pathogens and other activity by *Trichoderma*. Carreras-Villaseñor et al. (2012) mention of the role of conidia in an "asexual cycle"; it has different beneficial functions including in the biocontrol of plant pathogens and in the industry. Such as textile, medical/pharmaceutical, and animal feed by utilizing the compounds and enzymes that produced of *Trichoderma*.

Interestingly, *Trichoderma* suspensions are used in different industries, such as agriculture. A conidial suspension of *T. harzianum* (1×10^{-7} spores/ml) can control *Sclerotinia sclerotiorum* (Zhang et al. 2016). A high density (10^{-10}) of *T. harzianum* and *T. viride* have efficacy to control *Meloidogyne javanica* on tomato (Al-Hazmi and TariqJaveed 2016). The growth of peas improved after seeds were treated with 10^6 spores from two *Trichoderma* strains (T4 and N47) (Naseby et al. 2000). Conidia of *Trichoderma* are used in various activities because they spread quickly and germinate easily. Extreme environments are, however, certainly affecting the efficacy of *Trichoderma* in biocontrol of the life cycle of plant pathogens. In general, conidia are available in normal environments but not under difficult conditions. *Trichoderma* spp. are sensitive to changes in the environment (Carreras-Villaseñor et al. 2012).

This sensitivity is leading to change in attributes such as stop in the growth of hyphae for *Trichoderma* as the status of adaptation to confront the hard environment. These hyphae start the differentiation to specific structure by thickening the wall and create the resting spores as a tool for survival. Molecular mechanisms are responsible for adaptation and response to diverse cues from the environment (Bahn et al. 2007). Extreme conditions induce the fungus to produce resting or dormant spores such as thick-walled chlamydospores. However, some species of *Trichoderma* produce microsclerotia (Jackson et al. 2017). Difficult conditions and biological rhythms have a role in inducing the formation of chlamydospores and in the sexual cycle. Chlamydospores of *Trichoderma* are beneficial not only for survival and dispersal but also for export as a biological control agent (BCA), as mentioned by Mishra et al. (2012). Indeed, changes from useful gene expression to other expressions produce certain proteins and enzymes as a way to protect the survival of the fungal thallus . Interactions and sensing between fungi and the environment happen at the molecular level in response to environmental cues (Bahn et al. 2007). Some interesting factors affect the physiological activities of *Trichoderma*. These factors place high stress on the success of *Trichoderma* in confronting plant pathogens. Also, *Trichoderma* is a very interesting agent in different fields and is used within industry and production as a biopesticide and biofertilizer. Conditions of an extreme environment—major factors such as pH, temperature, nutrient substrate, and water potential, and some minor factors such as light and humidity—affect the success of *Trichoderma* products. Some parameters such as pH, Carbon content, and carbon : nitrogen (C:N) ratio were affected Trichoderma including the growth, sporulation, and the time of spore production (Agosin et al. 1997).

On the other hand, three points are important to discuss here in order to explain the effect of extreme environments on *Trichoderma* used as a BCA. For example, *Trichoderma* biopesticides and biofertilizers may be not beneficial for use in fields. Many farmers think *Trichoderma* products have low efficacy in controlling plant pathogens and enhancing plant growth. Also, many researchers think isolates or strains of *Trichoderma* are not suitable for use as antagonists or to improve plant growth in fields. Therefore, we must determine the parameters of extreme environments to provide some information that may be of benefit in improving *Trichoderma*-derived bioproducts. However, extreme environments include many factors that affect physiological activities and diversity, and that antagonize *Trichoderma*. This chapter shows the relation between extreme environmental conditions and the life cycle of *Trichoderma*.

14.2 Growth of *Trichoderma*

Determining optimal and extreme conditions is very helpful in determining the ability of *Trichoderma* to grow in different habitats. *Trichoderma* species can grow within a specific temperature range. Its growth comprises germination of spores and mycelia, and sporulation, which allow the fungus to spread. This study is useful for understanding the utilization of *Trichoderma* in many actions as mentioned previously such as biopesticides, biofertilizer, and industry. Therefore, it must invoke the role of extreme conditions affecting the very interesting part of a life cycle for *Trichoderma*, as following.

14.2.1 Germination

Fungal growth begins with conidia (spore) germination and mycelial growth. In general, the best and fastest growth of conidia and mycelial mass occurs under optimal circumstances. These conditions are limited to a particular range, which is different among *Trichoderma* species. Conidia and hyphae are exposed to different conditions including water availability, temperature, and pH. These factors are important for determining the rate and density of growth, rate of hyphal extension, and tube length; water availability and temperature are most important and most effective (Hjeljord and Tronsmo 2003). Danielson and Davey (1973) mention the large role of temperature and pH in the growth of seven species of *Trichoderma*, such as *T. pseudokoningii* and *T. saturnisporum*; they showed no growth at low and medium temperatures, and growth was very effective in extremely acidic or alkaline conditions. Gervais et al. (1988) suggested that the main factor affecting germination of *Trichoderma* was water potential. And Jackson et al. (1991) mentioned pH, temperature, and water potential as three factors affecting germination of *Trichoderma*. The duration of radiation did not affect conidial germination or growth of *Trichoderma* (Wibowo 1999). However, Hjeljord and Tronsmo (2003) indicated that the nutrient substrate is an effective factor in the germination of *Trichoderma* conidia; therefore, some of the conidia population fails to initiate germination on nutrient-poor substrates and in dilute inocula. According to the temperature factor, two levels of the conidia germination for *Trichoderma* such as low tolerance range and high tolerance range are noticed. Germination can occur within two temperature ranges: a low-tolerance range (<20 °C) and a high-tolerance range (≥20 °C).

T. harzianum, *T. longibrachiatum*, and *T. viride* grow in the low-tolerance range at 12–20 °C (they cannot grow at high temperatures) and at water potential between −0.7 and −2.8 MPa (Magan 1988). Some strains of *Trichoderma* are, however, able to tolerate the extreme environments. Cold-tolerant *Trichoderma* strains such as *T. aureoviride*, *T. harzianum*, and *T. viride* isolated from a forest at Asotthalom in southern Hungary grew at a low temperature (5 °C) (Antal et al. 2000).

T. viride grew at 5 °C but did not grow at 40 °C; it grew at pH ranging between 4.6 and 6.8; and the water potential decreased over the range of −0.7 to −14.0 MPa, but germination or growth occurred at −14.0 MPa (Jackson et al. 1991). Conidial germination and growth of *T. harzianum* occur within a pH range of 5–9; conidial germination prefers a temperature between 20 and 30 °C and was inhibited at 10 °C and 40 °C; mycelia grew within a temperature range of 10–30 °C, but their growth was inhibited at 40 °C (Wibowo 1999). *T. koningii* can grow at high temperatures (5–29 °C), in soil containing 10–80% moisture (water holding capacity), and a pH 5.8 (Wakelin et al. 1999). *T. koningii* growth increased after the ammonium (NH^{+4}-N) was added, which affected the acidity, but was suppressed when nitrate (NO_3^-) was added (Wakelin et al. 1999). Upon initiation of germination, the conidia of *Trichoderma* are more sensitive to desiccation after only 2 h when incubated on a nutrient-rich substrate at 23 °C (Hjeljord and Tronsmo 2003).

The thermophilic strain of *T. reesei* (RL-P31) grows quickly at 37 °C but does not grow at 28 °C (Sharma 1992). *T. harzianum*, *T. viride*, and *T. koningii* grew at temperatures between 9 and 35 °C and at pH within the range of 4–12, but the best growth occurred at 24 °C and pH 5.5 (Ghildiyal and Pandy 2008). Some *Trichoderma* species—*T. harzianum*, *T. viride*, *T. asperellum*, *T. koningii*, *T. atroviride*, *T. longibrachiatum*, and *T. virens*—were able to grow at temperatures of 25–30 °C and at pH values between 5.5 and 7.5 (Singh et al. 2014). Two strains of *Trichoderma*—*T. viride* (Td50) and *T. pseudokoningii* (Td85)—grow between 25 °C and 30 °C (and grow very slowly at 15 °C) and favor a pH from 4.5 to 5.5 (Petrisor et al. 2016). *T. asperelloides* IBLF 908 is able to grow at 12–37 °C, but maximum growth occurred at 27 °C (Domingues et al. 2016). *T. asperellum* can grow at 50 °C (Montoya-Gonzalez et al. 2016). Indeed, *T. polysporum* strains from Norway (a polar region) grew at temperatures between 0 °C and 28 °C, with higher growth at 20 °C (Kamo et al. 2016). *T. harzianum*, *T. viride*, *T. asperellum*, and *T. hamatum* showed favorable growth at pH ranging from 4.6 to 7.6, but the species grew best at different temperatures: *T. harzianum* and *T. viride* grew at temperatures between 25 °C and 40 °C, and *T. asperellum* and *T. hamatum* preferred 25–35 °C (Zehra et al. 2017). Isolates of *T. harzianum*, *T. viride*, and *T. koningii* could tolerate high reductions in temperature and grew under conditions between 4 and 42 °C and at a pH of 3–13 (Sharma et al. 2013). Finally, the spores and mycelia of *T. harzianum* strain T22 could germinate at 25 °C and at a water potential between −0.03 and −0.50 MPa (Innocenti et al. 2015). On the other hand, the concentration of salt in the habitation of Trichoderma is affecting the germination. Zehra et al. (2017) found that 1000 μM NaCl (salt) affects Trichoderma species, including T. harzianum, T. viride, T. asperellum, and T. hamatum.

14.2.2 Sporulation

Many different environmental factors affect sporulation of *Trichoderma* spp.: Nutrient substrate, temperature, humidity, light, and pH are very important factors in this context (Galun and Gressel 1966; Wibowo 1999; Berrocal-Tito et al. 1999; Jayaswal et al. 2003; Casas-Flores et al. 2004). The sporulation of *T. harzianum* was enhanced when receiving 24 h of light and at temperatures between 10 and 30 °C, but it did not produce conidia at 40 °C. In addition, acidity increases sporulation but alkaloids greatly affect it (Wibowo 1999). Blue light (400–480 nm) induces synchronous sporulation (Casas-Flores et al. 2004).

T. stromaticum can sporulate at temperatures from 20 to 25 °C and at 100% humidity, but it cannot sporulate at 75% humidity (Sanogo et al. 2002). *T. viride* produces maximum conidia at pH of 4.5–5.5 and a temperature of 20–37 °C, but this production is inhibited at temperatures below 20 °C, and is very poor with carbon sources (rhamnose, sorbitol, and pyruvic acid) (Jayaswal et al. 2003). *T. harzianum* was produced at 30 °C in a medium containing 30 g/L glucose and a carbon-to-nitrogen ratio of 24 (Said 2007). *T. hamatum* and *T. asperellum* preferred temperatures between 25 and 35 °C for sporulation, but *T. harzianum* and *T. viride* preferred 25–40 °C; the best sporulation for these four species of *Trichoderma* occurred in the pH range of 4.6–7.6 (Zehra et al. 2017). It is striking that *Trichoderma* can sporulate in extreme environments. Sharma et al. (2013) note that sporulation was induced at 0 °C in three isolates of *Trichoderma*—*T. harzianum*, *T. viride*, and *T. koningii*.

14.3 Bioactivity of *Trichoderma*

This genus has a high ability to attack and kill other fungi. This bioactivity is a part of the *Trichoderma* life cycle; production changes in accordance with alterations in the environment.

14.3.1 Production of Enzymes

Trichoderma secretes several important enzymes that are used for survival and to compete with and attack other organisms. *Trichoderma* can produce enzymes within appropriate temperature and pH conditions, and on appropriate nutrient substrates. Water potential and pH affect the production of enzymes by *Trichoderma* species (Kredics et al. 2004). Different conditions discriminate between isolates and species of *Trichoderma*.

At high temperatures, *T. reesei* strain RL-P37, cultivated at 37 °C in medium containing lactose, hypersecreted the xylanase enzyme (Suh et al. 1988). *T. viride* SL-1 produced cellulase at temperatures ranging from 30 to 50 °C (Tao et al. 1997). Temperature can change the cellulase enzyme in the subsequent stages. The activity of cellulase from *T. reesei* was not affected until the temperature reached 37 °C; enzyme activity decreases at temperatures from 37 to 50 °C, an no activity occurred at temperatures above 70 °C (Andreaus et al. 1999). *T. harzianum* 1073D3 produced the xylanase enzyme, with high activity at 60 °C and pH 5 in medium containing 1% xylan (Isil and Nilufer 2005). *T. lignorum* (Tode) Harz produced cellulolytic enzymes on banana waste at an optimal temperature of 45 °C and at a pH of 5.6–5.8 (Baig 2005). *Trichoderma* sp. produced cellulase at an optimal temperature (45 °C) and pH (6.5), on a nutrient substrate with an appropriate carbon-to-nitrogen ratio, such as cellulase (municipal solid waste residue), peptone, and yeast extract (Gautam et al. 2011). Cellulase was produced by *T. reesei* strain HY07 cultivated on a nutrient substrate (1.5% ammonium sulfate) at 30 °C (Guoweia et al. 2011). *T. harzianum* and *T. viride* produced the active enzyme chitosanase at pH 5.0; *T. koningii* and *T. polysporum* produced this enzyme at pH 5.5, and a temperature between 40 and 50 °C did not affect chitosanase activity (Da Silva et al. 2012). The highest production of glucose through secretion of the cellulase enzyme by *T. reesei* occurred at 30 °C and pH 4.5 (Silas et al. 2017). *T. asperellum* was producing the cell wall-degrading enzymes (CWDEs) and be high activity at 36°C (Qiu et al. 2017).

At moderate temperatures, *Trichoderma* strains such as *T. aureoviride* T122, *T. harzianum* T66 and T334, and *T. viride* T114 and T228 produce different extracellular enzymes, including of β-glucosidase, cellobiohydrolase, and β-xylosidase; at 25 °C, this production is related to two factors: water potential and pH (Kredics et al. 2004). Some isolates of *Trichoderma* produce enzymes at low temperatures (extreme environments). *T. aureoviride*, *T. harzianum*, and *T. viride* were cold-resistance strains and produced high levels of various extracellular enzymes that are active highly at 5 °C: chitinases, proteases, and β-glucosidases (Antal et al. 2000).

14.3.2 Production of Secondary Metabolites

Trichoderma produces secondary metabolites (volatile and nonvolatile compounds) within particular environments. Extreme environments already affect the capacity of *Trichoderma* to produce these compounds. Temperature and pH affect the efficacy of *Trichoderma*. A new isolate of *T. harzianum*, SQR-T037, was highly efficacious in producing volatile and nonvolatile compounds at 30 °C and pH 6, but very few compounds were produced under extreme conditions (Raza et al. 2013). Tronsmo and Dennis (1978) mention the high ability of some *Trichoderma* isolates to produce nonvolatile antibiotics at low temperatures; others, however, produce at high temperatures. Mukherjee and Raghu (1997) suggested that the fungitoxic metabolites are produced with higher concentrations of *Trichoderma* at higher temperatures. Also, six new peptaibol compounds, asperelines A–F (1–6), were produced by *T. asperellum* isolated from Penguin Island in the Antarctic (Ren et al. 2009). Four isolates of *Trichoderma*—*T. parareesei* T26, *T. koningii* TR102, and *T. harzianum* Tveg1 and TL5—produced 30 possible antifungal compounds at 28–30 °C under 12 h of darkness and 12 h of light (Al-Ani 2017).

14.4 Diversity of *Trichoderma*

The genus *Trichoderma* is widely diverse worldwide. The varying diversity of *Trichoderma* is dependent on climate and soil traits. *Trichoderma* spp. are predominant in all climate zones and are free-living organisms that grow in soil, root, and foliar environments (Harman et al. 2004). The four main climate zones globally are tropical, subtropical, temperate, and polar. Extreme environments are found in all climate zones that comprise characteristics such as lack of water potential (drought), high or low temperatures, high elevation, and extremely high pH. Lupo et al. (2002) classified the genus *Trichoderma* as mesophilic organisms. Kredics et al. (2003) mention that most *Trichoderma* isolates are mesophiles.

T. harzianum, *T. virens*, *T. spirale*, *T. koningii*, *T. atroviride*, *T. asperellum*, *T. reesei*, *T. viride*, *T. hamatum*, and *T. ghanense* were isolated from Taiwan and Western Indonesia in Southeast Asia (the tropical zone) (Kubicek et al. 2003). *T. koningii* growth is restricted in eastern North America and Europe, but other species, such as *T. koningiopsis*, *T. caribbaeum* var. *aequatoriale*, *T. ovalisporum*,

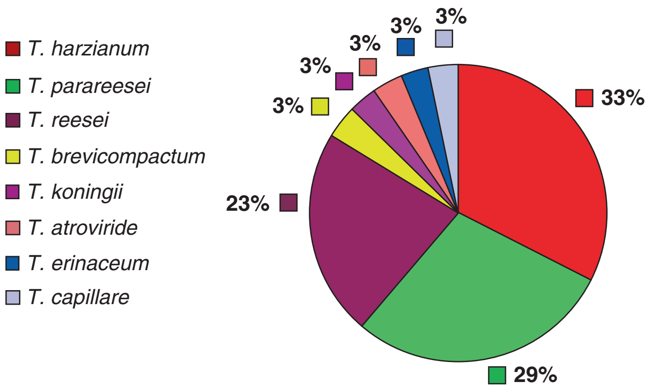

Fig. 14.1 Percentages of several species of *Trichoderma* (*T. harzianum*, *T. reesei*, *T. parareesei*, *T. brevicompactum*, *T. koningii*, *T. atroviride*, *T. erinaceum*, and *T. capillare*)

T. ovalisporum, and *T. stilbohypoxyli*, grow in tropical areas (Samuels et al. 2006). Many isolates of *Trichoderma* species—*T. harzianum*, *T. hamatum*, *T. asperelloides*, and *T. spirale*—were detected in the rhizosphere in the coffee-growing region in the highlands of Ethiopia and are more endemic in tropical regions such as Africa (Mulaw et al. 2010). *T. reesei* and *T. parareesei* are widespread throughout the pantropical region (Druzhinina et al. 2010). many strains of *Trichoderma* were identified in the neotropical region of Mexico, including *T. asperellum*, *T. brevicompactum*, *T. harzianum*, *T. koningiopsis*, *T. longibrachiatum*, *T. pleuroticola*, *T. reesei*, *T. spirale*, and *T. virens* (Torres-De la Cruz et al. 2015). Most species of *Trichoderma*, such as *T. harzianum*, *T. reesei*, and *T. parareesei*, show diverse isolates from Pulau Penang, Malaysia (Al-Ani 2017) (Fig. 14.1).

Three strains of *Trichoderma*—one strain of *T. harzianum* and two of *T. asperellum*—were isolated from a subtropical desert (Montoya-Gonzalez et al. 2016). *T. asperellum*, *T. virens*, *T. harzianum*, *T. sinensis*, *T. citrinoviride*, *T. longibrachiatum*, *T. koningii*, *T. atroviride*, *T. viride*, *T. velutinum*, and *T. cerinum* were isolated from subtropical and temperate zones in northern, southern, and eastern China; almost half of those species were *T. harzianum* (Zhang et al. 2005). *T. viride* and *T. harzianum* were found on Mount Moosilauke in New Hampshire in the United States (temperate zone), where they grew under cold temperatures in winter and moderate temperatures in summer, ranging from −10 to 25 °C. Several isolates of *T. harzianum* (21 strains), *T. rossicum* (13 strains), *T. cerinum* (4 strains), *T. hamatum* (2 strains), and *T. atroviride* and *T. koningii* (1 strain each) were identified in southeast Austria (Wuczkowski et al. 2003). *T. harzianum*, *T. koningii*, *T. longibrachiatum*, *T. viride*, and *T. citrinoviride* were collected from decaying wood in Poland (Błaszczyk et al. 2011). Many species of *Trichoderma* were isolated from three mountains in different regions of Poland, including *T. atroviride*, *T. citrinoviride*, *T. cremeum*, *T. gamsii*, *T. harzianum*, *T. koningii*, *T. koningiopsis*, *T. longibrachiatum*, *T. longipile*, *Trichoderma* sp. (*Hypocrea parapilulifera*), *T. viride*, and *T. viridescens*;

one species, *T. viride*, comprised 53% of the isolates (Błaszczyk et al. 2016). *T. orientale*, *T. spirale*, *T. tomentosum*, *T. albolutescens*, and *T. asperelloides* were found to be the first recorded *Trichoderma* species in Korea (Jang et al. 2017).

Six strains of *T. polysporum* were isolated from arctic wetlands in Norway (polar zone) (Yamazaki et al. 2011). *T. asperellum* was isolated from sediment on Penguin Island in the Antarctic (Ren et al. 2009). The pH factor is affecting the diversity of Trichoderma in some time. *Trichoderma* did not grow, or grew only little, at pH below 2.0 or above 6.0 (Kredics et al. 2003). For example, soil pH might be affected on the distribution of T. harzianum under pH 6.2 and over pH 7.9 (Eastburn and Butler 1988). In addition, the distribution of T. koningii was related with a soil pH (Muniappan and Muthukumar 2014).

14.5 *Trichoderma* as an Antagonistic BCA

Trichoderma is used widely as a BCA against many plant pathogens. The *Trichoderma* fungus is important worldwide as an alternative to chemical pesticides. *Trichoderma* spp. are used as BCAs (biopesticides) and are safe for the ecosystem. For successful biocontrol of plant pathogens, the isolate, strain, or species must be selected appropriately based on the ecology in the location of use. Therefore, environmental conditions are an influential factor in the antagonism of *Trichoderma* through use as a biopesticide. pH, temperature, and water potential affect it's biocontrol status against plant pathogens. Mukherjee and Raghu (1997) mention that temperature is the critical factor that influences BCAs. In addition, Kredics et al. (2004) presented the importance of water potential and pH in antagonism.

In low-temperature environments, *Trichoderma* increasingly suppressed plant pathogens such as *Gaeumannomyces graminis* var. *tritici*; the suppression for this pathogen can be highly in acidic soils through the addition of ammonium sulfate at 15 °C (Simon et al. 1988). Three cold strains of such as *T. aureoviride*, *T. viride*, and *T. harzianum* used as BCAs were actively antagonistic and showed high interactions that produced appressoria at different temperatures (5 °C, 10 °C, and 20 °C) (Antal et al. 2000). By producing the antibiotics, an arctic strain of *T. polysporum* could control *Pythium iwayamai*, which causes snow rot (Kamo et al. 2016).

In moderate temperatures, *Trichoderma* spp. were antagonistic against the pathogen *Sclerotium rolfsii* in dual cultures at temperatures ranging from 25 to 30 °C, but *Trichoderma* spp. do not suppress *S. rolfsii* at temperatures above 30 °C (Mukherjee and Raghu 1997). Water potential and pH affected the mycoparasitism of some species of *Trichoderma* (*T. harzianum*, *T. viride*, and *T. aureoviride*) at 25 °C (Kredics et al. 2004). At 25 °C, the ability of *T. harzianum* to antagonize *Verticillium dahliae* was reduced in high-salinity soils (Regragui and Lahlou 2005). *T. harzianum* strain T22 was very antagonistic against *Fusarium oxysporum* f. sp. *lactucae* strain 365.07; *T. harzianum* caused this *Fusarium* to wilt at 25 °C and at high extremes of water potential (−0.03 and −0.50 MPa) (Innocenti et al. 2015). *T. harzianum* LU698 has more influence on *Sclerotinia sclerotiorum* and reduced the viability of sclerotia under water potential values of −0.1 and −0.3 MPa, but *T. asperellum* LU697 was affected at water potentials of −0.01 and −1.5 MPa and at 25 °C (Jones et al. 2016). Al-Ani (2017) isolated 32 different strains of *Trichoderma* from regions in northern and in the middle of Malaysia and found that more of these isolates were highly antagonistic against *F. oxysporum* f. sp. *cubense* Tropical Race 4 that was isolated from the same region.

In high-temperature regions, strains of *T. harzianum*, *T. viride*, *T. hamatum*, *T. pseudokoningii*, *T. koningii*, and *T. longibrachiatum* could control *Macrophomina phaseolina* and showed maximal inhibition at 35 °C, but *T. pseudokoningii* was inhibitory at a temperature of 40 °C (Malathi and Doraisamy 2003). *T. harzianum* Th2 inhibited the growth of *F. oxysporum* f. sp. *ciceri* to a minimal level (10–12%) in sandy clay at 35 °C and water potential of −0.3 MPa (Inam-Ul-Haq et al. 2009). In addition, 14 *Trichoderma* species isolated from soils in a desert in Algeria were very antagonistic against three plant pathogens. *T. harzianum* 8.4, *T. asperellum* 12-2, and *T. asperellum* BP60 were isolated from sandy soils in a desert but only the *T. asperellum* BP60 isolate was active at temperatures below 50 °C (Montoya-Gonzalez et al. 2016). This isolate was able to control *Setophoma terrestris*, which causes pink root rot on green onions, under extreme temperatures and produced siderophores and chitinases (Montoya-Gonzalez et al. 2016). *Trichoderma* isolates had highly antagonistic activity against *F. oxysporum* f. sp. *cubense* Tropical Race 4 at temperatures ranging from 28 to 32 °C (Al-Ani et al. 2013; Al-Ani 2017; Al-Ani and Albaayit 2018).

14.6 Conclusion

Trichoderma has an amazing ability to survival in extreme environments, but this survival depends on the species and environmental factors. Indeed, temperature has more of an impact on *Trichoderma* than other factors such as pH, water potential, and nutrient substrate. The optimal temperature for all physiological actions of *Trichoderma* (e.g., germination of conidia and hyphae, sporulation, production of active enzymes, and antagonism) lies within the temperate range. Temperatures in the range of 0–50 °C can be considered the main extreme factor affecting *Trichoderma* . The second most important factor that affects *Trichoderma* is pH. Species of the *Trichoderma* genus can grow at high or low pH values (2.0–13), but the level of growth differs from one species to another. The *Trichoderma* population is increasing in acidic soils that contain the ammonium sulfate.

The third factor affecting *Trichoderma* growth is the nutrient substrate, which can be efficacious but is not as important as temperature and pH. The nutrient substrate is important for inducing the growth and antagonism of *Trichoderma*. The fourth factor with an effect on *Trichoderma* growth and activity is water potential. This factor is also important in determining the diversity and distribution of *Trichoderma* in soil. The lack of water, and pH, have potential effects on the growth and mycoparasitic action of *Trichoderma*. Light and humidity are important factors in the sporulation and dispersal of *Trichoderma*, as well as, Highland is affecting the diversity of Trichoderma. These major and minor factors are the main parameters for estimating the effects of *Trichoderma* strains against plant pathogens.

Four points can be considered to clarify how to confront the decrease in efficiency of *Trichoderma* products used against plant pathogens and to enhance plant growth in fields. First, the appropriate parameters must be determined before being used. Second, *Trichoderma* must be isolated from the same climate zone or an area nearest the plant pathogens. Isolates of *Trichoderma* from the same area as the plant pathogens or plants will have higher efficacy when used. This may guarantee success in the biocontrol of plant pathogens, enhancement of plant growth, and use in other activities. Third, the genome of *Trichoderma* is responsible for controlling the cells upon confrontation of difficult conditions that affect germination, dispersal, and survival. Therefore, mutations in *Trichoderma* can improve the traits necessary to tolerate poor conditions. The fourth and final point is the importance of *Trichoderma* to resist unfavorable conditions in order to be beneficial in controlling phytopathogens; this helps the plants by enhancing their capability to resist the stress of a difficult environment. The high tolerance of *Trichoderma* strains to extreme environments is useful when applying it to the different crops and in helping growth and improving and increasing production within several climate zones.

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