Chapter 16
Biological Control of Soft-Rot of Ginger: Current Trends and Future Prospects

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Abstract Ginger (*Zingiber officinale* Roscoe) is an important crop having various medicinal, nutritional, and ethnomedicinal properties cultivated all over the world. *Pythium* and *Fusarium* spp. are pathogens responsible for the deteriorating disease in ginger known as soft- or rhizome-rot, causing more than 50% loss of ginger crop worldwide. The application of chemical fungicides is a promising method for control of soft-rot in ginger. But use of such fungicides is harmful to both environment and human health. Thus, there is an obligatory need for the search of an eco-friendly and economic approach for the control of soft-rot in ginger. Various physical, chemical, and biological methods have already been in practice since many years for managing soft-rot in ginger. This chapter primarily focuses on the advantages of biological control over chemical methods of *Pythium* and *Fusarium* spp. management using antagonistic fungi, bacteria, actinomycetes, and plant extracts. These biocontrol agents offer the best opportunity in control of diseases and also help to maintain the quality and crop yield. Moreover, the emerging role of nanotechnology in the management of these pathogens is also briefly discussed.

16.1 Introduction

Ginger (*Zingiber officinale* Roscoe) is an important plant crop cultivated all over the world for its promising medicinal properties (Rai et al. 2018). However, India is among the most leading producers and exporter of ginger (Anisha and Radhakrishnan 2015; Gupta and Kaushal 2017). Due to potential medicinal, nutritional, and ethnomedicinal properties, ginger is widely used as a spice, flavoring

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A. Varma et al. (eds.), *Plant Microbe Interface*,
https://doi.org/10.1007/978-3-030-19831-2_16

agent, and herbal medicines (Dhanik et al. 2017). The ginger crop is susceptible to various diseases caused by bacteria, fungi, or viruses which mainly include soft-rot, yellows, *Phyllosticta* leaf spot, storage-rot, bacterial wilt, mosaic, chlorotic fleck, etc. These diseases reduce potential yields drastically (Gupta and Kaushal 2017; Rai et al. 2018).

Soft-rot (rhizome-rot) is one of the most common and destructive diseases of ginger caused by various species of *Pythium* (mainly by *P. aphanidermatum* (Edson) Fitz, *P. deliense* Meurs, *P. graminicola* Subram, *P. myriotylum* Drechsler, *P. spinosum* Sawada, *P. splendens* Braun, *P. ultimum* Trow, *P. vexans* de Bary, and *P. zingiberis* Takahashi), *Fusarium* spp. (mainly by *F. oxysporum* f. sp. *zingiberi*), and bacteria (e.g., *Ralstonia* spp.) (Le et al. 2014, 2016; Gupta and Kaushal 2017; Rai et al. 2018). The disease is both seed and soilborne, and its development depends on moisture and temperature conditions of soil (Gupta and Kaushal 2017). Soft-rot caused by *Pythium* spp. is carried over and maintained through diseased rhizomes as oospores in scales and soil. Fungal pathogens have ability to survive as saprophytes in plant debris, which may contain a large number of oospores and thus acts as a source of primary inoculum (Gupta and Kaushal 2017).

Soft-rot is considered as a complex disease condition. There are various conventional strategies, namely, cultural practices and biological and chemical agents, commonly used for disease management. The application of these practices in ginger fields helps in controlling the diseases and also restricts the dissemination of fungal pathogens (Le et al. 2014; Gupta and Kaushal 2017; Rai et al. 2018). It is demonstrated that the management of soft-rot is difficult by using any one conventional approach. Therefore, combination of more than one approaches has been found to be more satisfactory in the control of this disease (Dohroo et al. 2015; Gupta and Kaushal 2017).

Cultural practices like seed selection, crop rotation, organic amendment, drainage and quarantine, and chemical fungicides are most frequently used to control soft-rot of ginger. There are two types of chemical fungicides: one is applied to soil (zineb, captafol, methyl bromide, mercuric chloride, thiram, phenylmercury acetate, copper oxide, mancozeb, and many more), and another is commonly used for seed treatment (Ridomil MZ, Fytolan, Bavistin, Thimet, etc.). However, these fungicides are more effective when used in combination (Mathur et al. 2002; Rajan et al. 2002; Singh 2011; Smith and Abbas 2011; Le et al. 2014). Although chemical fungicides can be effectively used for the control of soft-rot of ginger, their continuous use may cause harm to both environmental and human health (Rai et al. 2018). Moreover, the frequent use of chemical fungicides leads to increase in resistance of fungi toward such fungicides and also reduces soil fertility (Ponmurugan et al. 2016). Therefore, search for novel eco-friendly agents such as biological agents (microorganisms, plants) for control of soft-rot is essentially required. Among microorganisms, *Trichoderma* spp. are the most widely used biocontrol agents of rhizome-rot of ginger caused by *Fusarium* and *Pythium* spp. (Selvakumar et al. 2013; Shanmugam et al. 2013a, b). However, combined applications of bioagents such as *Trichoderma harzianum*, *Pseudomonas fluorescens*, and *Bacillus subtilis* were found to be more effective when compared to the individual treatments (Dohroo and Gupta 2014). Moreover, many other bacteria (*Enterobacter* sp., *Rhizobium* sp.), actinobacteria (*Nocardiopsis* sp., *Streptomyces* sp., *Micromonospora* sp.), and plants (*Lawsonia inermis*, *Nigella sativa*, *Azadirachta indica*, *Zingiber zerumbet*, etc.) have also been used as biocontrol agents against disease caused by *Pythium* (El-Tarabily et al. 1997; Chin-A-Woeng et al. 2003; Bardin et al. 2004; Bhai et al. 2005; Gupta et al. 2013; Loliam et al. 2013; Parveen and Sharma 2014; Ravi et al. 2017).

In the present chapter, we focused on biological control strategy used for the control of soft-rot disease of ginger caused by fungal pathogens. In addition, advantages of biocontrol methods over chemical control have also been discussed.

16.2 Soft-Rot: Causal Organisms (Mainly Different Species of *Pythium*)

Several species of *Pythium* have been reported from various parts of world which have ability to cause soft-rot disease in ginger. *Pythium gracile* (de Bary) was reported for the first time to cause rhizome-rot of ginger by Butler (1907) from Surat (Gujarat), and in Bengal, from Kerala by Sen (1930), and from Assam and Fiji by Parham (1935) in India. Apart from these, various other *Pythium* species have been found associated with soft-rot of ginger. For instance, *P. aphanidermatum* (Edson) Fitz. in Pusa (Bihar) (Mitra and Subramaniam 1928), in Nagpur (Maharashtra) (Sahare and Asthana 1962), in Madhya Pradesh (Haware and Joshi 1974), and in Kerala (Sarma et al. 1979). Similarly, 11 species of *Pythium* were recovered from infected rhizome of ginger showing symptoms of soft-rot, and it was reported that *P. aphanidermatum* and *P. myriotylum* were the most prevalent species (Dohroo 2005). *P. butleri* Subram. exists from 1918 in the Malabar and South Kanara district of South India (Thomas 1938) as a causative agent of rhizome-rot, and it was reported afterward in Ceylon (Park 1934). *P. complectans* Braun was isolated from infected rotted part of ginger in Ceylon (Park 1934). *P. graminicolum* Subram was reported from Ceylon (Park 1935). *P. delense* Meurs was described from Madhya Pradesh (Haware and Joshi 1974).

In Bombay, Ceylon, Hong Kong, Kerala, Nagpur, Poona, and Taiwan, *P. myriotylum* Drechsler was found to be the main causative agent that affected the ginger rhizome (Park 1937; Uppal 1940; Bertus 1942; Patel et al. 1949; Sahare and Asthana 1962; Lin et al. 1971; Dake and Edison 1989). *P. zingiberum* was reported from Osaka (Japan) and Korea (Takahashi 1954; Yang et al. 1988). *P. pleroticum* T Ito causes disease in Solan of Himachal Pradesh (Sharma and Dohroo 1982). *P. ultimum* affected the rhizomes of ginger in Himachal Pradesh (Dohroo 1987). In Rajasthan *P. myriotylum* was found in association with *Fusarium solani* causing soft-rot of ginger (Mathur et al. 1984; Drojee 1986). According to Le et al. (2014), more than 15 *Pythium* species may cause soft-rot in ginger, and *P. aphanidermatum* causes about 60% of yield loss. In another study, they have recovered 11 different species of *Pythium* from infected rhizome of ginger from farms in Queensland, Australia, and assessed them for their pathogenicity on ginger (Le et al. 2016). Out of these *Pythium* isolates, *P. aphanidermatum*, *P. deliense*, *P. myriotylum*, *P. splendens*, *P. spinosum*, and *P. ultimum* were found to be most pathogenic.

However, several other species of *Pythium*, viz., *P. myriotylum* Drechsler (Wang et al. 2003) and *P. aphanidermatum* (Edson) Fitzpatrick (Kavita and Thomas 2008), were reported from various countries such as Taiwan, Malaysia, the USA, Japan (Moreira et al. 2013), India (Ravindran and Babu 2005), Australia, and Fiji (Stirling et al. 2009).

16.3 Current Physical and Chemical Methods to Control Infection

As discussed earlier, various physical, chemical, and biological methods are commonly used for the management of soft-rot of ginger; all these methods are briefly described below.

16.3.1 Physical Methods

One of the most important criteria to avoid the soft-rot is the selection of healthy and disease-free seeds or rhizomes; such selection helps to minimize the probability of contamination by *Pythium* spp. (Dake 1995). In order to obtain good quality of seeds, there are various approaches of seed treatment like seed fortification (using biological or physical approaches or their combinations), seed disinfestations (to kill the pathogens present on the seed surface), and seed disinfection (using various disinfection agents kill the pathogens present in the cells). All these approaches are promisingly helpful in the management of pathogen without causing any harm to embryo or potential of seed germination (Bennett et al. 1991; Rai et al. 2018). Prevalence of the pathogen in soil is also responsible for setting the infections, if a particular crop or any other crop which acts as host for the same pathogen is cultivated every year. In this context, there is necessity to cultivate the different crops, i.e., crop alternation or rotation can be the prominent approach which avoids the recurrence of pathogen in the subsequent harvesting. It was suggested that crops like corn and rice can be used as alternate crops after cultivation of ginger in the same field because corn and rice are tolerant to pathogens of ginger (Pordesimo and Raymundo 1963; Quimio and Chan 1979; Bennett et al. 1991).

In conventional agricultural practices, application of suppressive soil for fastidious pathogens is another approach for better crop protection. Lee et al. (1990) proposed that soil with higher clay content and lower pH is suitable for ginger cultivation as it suppress the growth of *Pythium zingiberum* and *F. oxysporum* f. sp. *zingiberi* as compared to conductive soils. Soil solarization is another important approach which helps to destruct molds present in the soil for better growth and health of crop. The heating of soil covered with plastic films using solar energy in the summer season for 1–2 months reduces load of pathogens and various other pests and weeds. In addition to soil solarization, use of biocontrol agents is advantageous to growth of plants and to restrict the growth of a variety of pathogens. Soil solarization is considered as one of the most suitable approaches for home gardens, nurseries, landscaping, and greenhouses due to its low-cost and long-term benefits (Dake 1995; Stapleton and Devay 1986). Moreover, use of silicon (Si) (may be in the form of potassium silicate) as supplement in the soil is reported to enhance the plant growth and also inhibits the growth of *P. aphanidermatum* (Chérif et al. 1994). Routine phytosanitation is recommended as soon as disease symptoms appear in the field to decrease its spread to the other healthy plants. Similarly, rouging of diseased plants and demolishing them followed by disinfection of tools used for phytosanitation to avoid transfer of inocula to healthy plants is an essential practice (Dake 1995).

16.3.2 Chemical Methods

A variety of fungicides are commonly used around the globe for controlling postharvest diseases in ginger since 1940. *Pythium* spp. have the ability to survive in the soil for years together once introduced (Hoppe 1966), and hence the management of soft-rot is more difficult. Till date, a large number of chemical fungicides have been discovered and routinely used worldwide. Some of the important fungicides include mancozeb, ziram, guazatine, propineb, and copper oxychloride. These fungicides are considered as most promising in the effective control of soft-rot (Dohroo and Sharma 1986; Thakore et al. 1988). In addition, metalaxyl (fosetyl-aluminum/Ridomil) is one of the most commonly used chemical fungicides. This fungicide is useful in both soil application and also as drench alone or in combination with other fungicides for the significant control of soft-rot caused by *Pythium* (Chase et al. 1985; Ramachandran et al. 1989; Dake 1995; Hwang et al. 2001; Luong et al. 2010). Singh (2011) performed a comparative study on seed treatment with Ridomil MZ (1.25 g/L) and hot water (51 °C for 30 min) in a naturally contaminated field with *P. aphanidermatum* in Raigarh, India, and reported 30% more survival of rhizomes treated with Ridomil MZ. Similarly, in a pot trial experiment, it was observed that seed coated with Fytolan (copper oxychloride 0.2%) + Ridomil (500 ppm) + Bavistin (carbendazim 0.2%) + Thimet keep ginger rhizomes free from soft-rot (Rajan et al. 2002). In addition, seed treatment with Smith and Abbas (2011) proposed that fungicides like metalaxyl, Ridomil, Maxam XL (fludioxonil) and Proplant (propyl carbamate hydrochloride) considerably helps in the management of soft-rot caused by *P. myriotylum* than sole carbendazim seed treatment in a pot trial.

Various other antifungal agents like zineb, captafol, methyl bromide, mercuric chloride, thiram, phenyl mercury acetate, copper oxide, mancozeb, etc. reported to have effective antifungal activity against different *Pythium* species (Doshi and Mathur 1987). Dohroo et al. (1984) reported significant efficacy of metalaxyl in the control of rhizome-rot. Similarly, treatment of seed (1 day before) and soil drenching (3 months after planting) with the mixture of metalaxyl and captafol effectively controlled the soft-rot of ginger (Rathaiah 1987). Apart from these, fosetyl-Al, metalaxyl, oxadixyl, propamocarb and ethazole (epidiazole) were also evaluated against *P. aphanidermatum*. Among these, metalaxyl formulations (Ridomil 5G and Apron 35 WS) were found to be most effective when used in soil and seed treatments (Ramachandran et al. 1989). Srivastava (1994) effectively controlled the soft-rot of ginger by inhibiting growth of causative agent (*P. aphanidermatum*) in Sikkim by drenching the soil with zineb or mancozeb following rhizome treatment with carbendazim and incorporating Thiodan dust into the soil to control insect invasion. Rhizome fly is a common insect pest found in association with rhizome-rot of ginger caused by *Pythium* sp. Gautam and Mainali (2016) demonstrated that the combination of Chlorpyrifos 20 EC (insecticide) + Dithane M-45 (Mancozeb 80 WP) (pesticides) and Bavistin (Carbendazim 50 DF) (pesticides) was significantly effective against rhizome fly and rhizome-rot (Gautam and Mainali 2016).

16.3.3 Biological Control of **Pythium** *spp.*

Eco-friendly methods of disease management are being practiced nowadays. The increasing use of hazardous fungicides in agriculture has been growing cause worldwide concern. Therefore, increased concern for the hazards associated with the use of synthetic pesticides and the use of biological agents for control of plant pathogens during the past 20 years has been driven in part by trends in agriculture toward greater sustainability. The biological control is defined as the reduction in disease producing ability or density of microbial inoculum by one or more organism accomplished naturally in its active state or through manipulation of the environment, by mass introduction of antagonists (Agrios 2005; Heydari and Pessarakli 2010). The new insights into the underlying mechanisms by which biocontrol agents function can be evolved by technologies from molecular biology and genetics which allowed the evaluation of the behavior of microbial inoculants in natural environments to a degree not previously possible (Thomashow and Weller 1996).

Presently, a variety of organisms, mainly bacteria and fungi that counteract important agronomical pests and diseases, have been described. These include *Trichoderma* species (Harman 2006; Rai et al. 2018); mycoparasitic (where a fungus directly attacks and feeds on other fungi, resulting in the direct destruction or lysis of propagules and structures) members of the genus *Verticillium* (Gajera et al. 2013); *Pseudomonas*, *Bacillus*, and *Streptomyces* (Ashwini and Srividya 2012; Beneduzi et al. 2012; Fróes et al. 2012; Sivasakthi et al. 2014; Menendez and Garcia-Fraile

2017); and *Lecanicillium* species (Fenice and Gooday 2006). Fungal species against plant pathogens have attracted a great deal of attention from the researchers around the globe as potential biocontrol agents in many crops, of which one of the most well-studied fungal genera is *Trichoderma/Hypocrea* (Gajera et al. 2013; Yacoub et al. 2017; Rai et al. 2018). Biocontrol agents may also induce plant physiological processes that lead to plant defense mechanism activation such as production of phytoalexins, the hypersensitive response, or synthesis of chitinase and glucanase (lytic enzymes) (Thakur and Sohal 2013).

Biological control of *Pythium* species is considerably difficult because of immediate infection of sporangia in seed or root the ability to cause long-term root rots (Whipps and Lumsden 1991). In spite of these constraints, many important diseases have been controlled with antagonistic fungi, bacteria, and actinomycetes (Nayak et al. 2017; Rai et al. 2018). In vitro tests using *T. viride*, *T. harzianum*, and *T. hamatum* against *P. aphanidermatum*, *F. equiseti*, and *F. solani* showed inhibitory effect (Dohroo et al. 2012; Shanmugam et al. 2013a, b; Hudge 2015; Mudyiwa et al. 2016). Good control of storage-rot caused by *P. aphanidermatum* and *F. equiseti* was obtained when *T. viride* and *T. hamatum* were applied to rhizomes either by socking them in smear or spore suspension with the antagonists (Khatso and Tiameren Ao 2013; Hudge 2015; Mudyiwa et al. 2016). Effective suppression of soft-rot of ginger was reported under field condition, when *T. viride* and *T. harzianum* was applied to soil in combination with sawdust (Kulkarni and Hegde 2002). The effective control of *P. aphanidermatum* causing soft-rot of ginger was observed when *T. harzianum* or *T. hamatum* was applied to soil along with neem oil cake (Abbasi et al. 2005). The potential inhibition of growth of *Fusarium oxysporum f.* sp. *zingiberi* and *P. aphanidermatum* causing yellows and rhizome-rot of ginger was observed after use of *T. harzianum*, *T. virde*, *Azadirachta indica* Juss, and *Agave americana* L. as biocontrol agents (Rajan et al. 2002; Singh 2011; Gupta et al. 2013; Parveen and Sharma 2014; Gupta and Kaushal 2017). Ram et al. (2000) demonstrated the role of different biocontrol agents like *T. harzianum*, *T. aureoviride*, and *T. virens* in the control of ginger rhizome-rot. It was reported that all the abovementioned biocontrol agents significantly reduced the population density of both *F. solani* and *P. aphanidermatum*. Similarly, when *T. harzianum* was applied in the soil for the management of rhizome-rot of turmeric (*F. solani*), this resulted in reduced disease incidence and increased yield (Reddy et al. 2003).

16.3.4 Bacteria and Actinomycetes as a Biocontrol Agents

The bacteria are potentially used as biocontrol agent due to its ability to produce important metabolites like lipopeptides which possess strong antifungal activity (Meena and Kanwar 2015; Fira et al. 2018). Among the bacteria and actinomycetes, fluorescent pseudomonads, *Bacillus* spp., and *Streptomyces* received maximum attention because these microorganisms can be grown easily in large-scale and applied to the both seed and soil. Similarly, the fluorescent *Pseudomonas* includes the species of *P. fluorescens*, *P. putida*, *P. aeruginosa*, *P. chlororaphis*, *P. aureofaciens*, and *P. syringae* (Hagedorn et al. 1990; Howie and Suslow 1991; Zheng and Sinclair 2000; Naseby et al. 2001). These species produces various secondary metabolites with antagonistic characteristics most of which are nitrogen containing heterocyclic compounds or unusual amino acids and peptides. However, the members of the genus *Trichoderma* are most widely used biocontrol agents all over the world.

Recently, Zouari et al. (2016) reported broad-spectrum antifungal potential shown by *Bacillus amyloliquefaciens* strain CEIZ-11 against various plant pathogens especially *P. aphanidermatum.* Sellem et al. (2017) demonstrated the potential activity of actinomycetes, *Streptomyces* strain TN258 isolated form Tunisian Sahara soil against *P. ultimum* responsible for potato tubers leak. The results suggest that mycelial growth of *P. ultimum* was completely inhibited by total destruction of hyphae after application of *Streptomyces* strain TN258 extract. Further, author reported that there was significant decrease in pathogen penetration activity was observed on treatment of *Streptomyces* strain TN258 filtrate to potato tubers. *Stenotrophomonas maltophilia*, *Lysobacter enzymogenes*, *Paenibacilli*, *Serratia entomophila*, *E. faecalis*, and *Streptomyces rubrolavendulae* were reported for their ability to control different diseases caused by several *Pythium* species including *P. ultimum*, *P. aphanidermatum*, etc. (Palumbo et al. 2005; El-Tarabily 2006; Chairat and Pasura 2013; Loliam et al. 2013; Fira et al. 2018).

16.3.4.1 Fungi as Biocontrol Agent

The use of endophytic *Trichoderma* as a biocontrol agent is widely applicable for control of various *Pythium* species. The endophytic *Trichoderma* exhibits various significant activities like production of cell wall degrading activity, production of hydrogen cyanide and indole acetic acid, solubilization of phosphate, etc. These activities are important in destruction of cell wall of oomycetes of *Pythium* spp. (Mishra 2010; Vinayarani and Prakash 2018). Recently, Vinayarani and Prakash (2018) reported the control of soft-rot disease in turmeric plant caused by *P. aphanidermatum*. The study revealed that endophytic *T. harzianum* showed significant inhibition of mycelial growth of causative agent of rhizome-rot disease in turmeric. The preemergence of diseases caused by *Pythium* species can be achieved by coating the seeds with fungal extract. El-Katatny et al. (2001) described the preemergence of damping-off induced by *Pythium* species in radish and pea seeds by coating them with *T. harzianum* and *T. koningii* as a biocontrol agent. Besides, control of *Pythium* spp., by application of various *Trichoderma* spp., in cauliflower, sugar beet, tobacco, chili, cucumber, and tomato has been reported (Das et al. 2002; Jayaraj et al. 2006; Muthukumar et al. 2011; Mbarga et al. 2012; Kipngeno et al. 2015).

16.3.5 Plants as a Biocontrol Agent

Use of various plants as a biocontrol agent is eco-friendly and cost-effective approach for the management of plant diseases caused by *Pythium* spp. Gholve et al. (2016) demonstrated the antifungal potential of different plant extracts, namely, *Ocimum sanctum* (tulsi), *Parthenium hysterophorus* (*Parthenium*), *Lawsonia inermis* (mehndi), *Datura metel* (*Datura*), *Zingiber officinale* (ginger), *Azadirachta indica* (neem), *Asparagus racemosus* (shatawari), *Allium sativum* (garlic), *Curcuma longa* (turmeric), etc. against *P. ultimum* causing damping-off disease in Brinjal. The study revealed that all tested plant extract showed significant antifungal potential against *P. ultimum* by inhibiting mycelial growth. Similar studies on effective management of *Pythium* spp. causing damping-off disease by using botanical extracts were reported by Muthukumar et al. (2010) and Ambikapathy et al. (2011). Pandey et al. (2016) also reported the efficacy of different plant extracts, namely, *Azadirachta indica*, *Eucalyptus globulus*, *Catharanthus roseus*, *Lawsonia inermis*, *Ocimum sanctum*, *Murraya koenigii*, and *Lantana camara*, against *P. aphanidermatum* causing damping-off disease in chili.

Previously, extracts from leaves, stem, and flowers of *Euphorbia macroclada* were found to be effective against *Pythium* spp. (Al-Mughrabi 2003). Uma et al. (2012) reported the antifungal potential of *C. papaya*, *P. granatum*, *V. vinifera*, *A. zapota*, *A. squamosa*, and plant extracts against *Pythium capsici*, and *T. indica*, *C. papaya*, *P. granatum*, *V. vinifera*, *C. colocynthis*, and *A. zapota* plant extracts showed antifungal efficacy against *P. aphanidermatum.* Vinayaka et al. (2014) reported the inhibitory activity of *Usnea pictoides* against *P. aphanidermatum* which causes rhizome-rot disease of ginger. Bahraminejad (2012) reported the antifungal activity of Iranian plants' methanolic and aqueous extract against *Pythium* sp. Kim et al. (2000) reported antifungal potential of *Xanthium strumarium* and *Cinnamomum zelanicum* against *Pythium drechsleri*. Tahira and Sharma (2014) stated the antifungal activity of crude aqueous, alcoholic, and partial hydroalcoholic extracts of *Cassia fistula*, *Clitoria ternatea*, *Eucalyptus globulus*, *Jacaranda mimosifolia*, *Azadirachta indica*, *Aegle marmelos*, *Polyalthia longifolia*, *Tecomella undulata*, and *Terminalia arjuna* against *P. aphanidermatum* and *P. myriotylum.* Hence, according to abovementioned studies, the management of *Pythium* causing different plant diseases can be controlled by use of biocontrol agents, which offers the best opportunity in control of diseases and also helps to maintain the quality and crop yield (Table 16.1).

Table 16.1 Biological control agents of *Pythium* species

Biocontrol agent	Phytopathogens	References
Fungi		
Trichoderma hamatum	*Pythium* sp.	Bhardwaj et al. (1988), Hudge (2015), Mudyiwa et al. (2016)
Trichoderma sp., *Gliocladium* sp.	*Pythium* sp.	Howell and Stipanovic (1983), Fravel (2005)
Trichoderma spp.	*Fusarium* sp.	Selvakumar et al. (2013)
Gliocladium virens, *Glomus* sp.	*Pythium ultimum*	Lumsden and Locke (1989)
Trichoderma harzianum	*P. aphanidermatum* *Pythium* sp. *Fusarium* sp.	Dohroo et al. (2012), Singh (2011), Rajan et al. (2002), Khatso and Tiameren Ao (2013)
Trichoderma viride	*Fusarium* sp.	Khatso and Tiameren Ao (2013)
Bacteria		
Pseudomonas sp. *Enterobacter* *Erwinia* *Bacillus* *Burkholderia* *Stenotrophomonas* *Rhizobium*	*Pythium* sp.	Chin-A-Woeng et al. (2003), Bardin et al. (2004)
Pseudomonas fluorescens *Bacillus* sp. *B. lentus* *B. polymyxa* *Enterobacter agglomerans* *Glomus* sp.	*Pythium myriotylum*	Bhai et al. (2005)
Bacillus mycoides	*Pythium aphanidermatum*	Peng et al. (2017)
Pseudomonas fluorescens	*Pythium ultimum*	Callan et al. (1991)
Rhizobium japonicum	*Fusarium solani*	Smitha and Singh (2014), Al-Ani et al. (2012)
Bacillus subtilis	*Pythium ultimum*, *Fusarium solani*	Mohammady and Abbas (2017)
Actinomycetes		
Streptomyces, *Actinoplanes*, *Micromonospora*	*Pythium coloratum*	El-Tarabily et al. (1997)
Streptomyces rubrolavendulae S4	*Pythium aphanidermatum*	
Nocardiopsis sp.	*Pythium myriotylum*	Sabu et al. (2017)
Plants		
Jacaranda mimosifolia, *Moringa oleifera* *Polyalthia longifolia,*	*Pythium aphanidermatum*	Parveen and Sharma (2014), Gupta et al. (2013)

(continued)

Table 16.1 (continued)

Biocontrol agent	Phytopathogens	References
Terminalia arjuna *Lawsonia inermis* *Aegle marmelos* *Nigella sativa* *Azadirachta indica*		
Zingiber zerumbet (wild ginger)	*Pythium myriotylum*	Ravi et al. (2017)

16.4 Emerging Nanotechnological Strategies for the Management of *Pythium* sp. and *Fusarium*

Nanotechnology applied to agriculture for the effective management of plant diseases is an eco-friendly and outstanding tool over the conventional approaches, which are toxic and hazardous to the environment (Ismail et al. 2017; Abd-Elsalam and Prasad 2018). Ultimately, the nanotechnology will help in minimizing the use of synthetic chemical compounds used in the control of plants diseases (Gogos et al. 2012). The nanoparticles which can be used in agriculture include copper, titanium, zinc, silica, aluminum, chitosan, sulfur, silver, and gold. The broad-spectrum antimicrobial activity of nanoparticles can sustainably replace the existing ecotoxic chemicals commonly used in agriculture (Sabir et al. 2014; Fraceto et al. 2016; Banker et al. 2017). The nanoparticles are responsible for the suppression of the augmenting pathogens; at the same time, they promote the growth of plants by maintaining NPK content of the soil (Ponmurugan et al. 2016; El-Argawy et al. 2017). Recently, the market value of nanoparticles as antifungal and plant growth promoters is increasing enormously. Nanomaterials are beneficial in a controlled delivery of nutrients in agriculture with minimum nutrient loss during application (Prasad et al. 2014, 2017). The nanoparticles have small size, large surface area, greater stability, and easier availability to plants, imparting them property of delivering active ingredients or nutrients in a controlled manner and serving as a great fungicide delivery system in agriculture (Sekhon 2014; Manjuntha et al. 2016; Bhattacharyya et al. 2016; Gupta et al. 2018). Rai and Ingle (2012) have suggested the development of nano-based biosensors and kits for the detection and control of fungal pathogens in agriculture thus flourishing the agriculture-based nanotechnology industry. This will lend a hand in changing the present status of food and agriculture industries worldwide. The chemical fertilizers and fungicides have deleterious effect on human health and environment, mainly on endangered species posing high risk of their extinction. This may lead to imbalance of biodiversity and ultimately disturbing the ecosystem. The soft-rot of ginger is caused by fungal pathogen, i.e., *Pythium* spp., causing huge loss of yield around the world. Hence, there is an imperative need of a nanotechnological strategy for the management of soft-rot of ginger, to overcome the hazardous impact of traditional practices (Patel et al. 2014; Mishra et al. 2014).

Although there is no report on management of *Pythium* spp. and *Fusarium* spp. infection in ginger by nanotechnological approach, in vitro antifungal activity of some plant-mediated nanoparticles has been reported. Nanoparticles are found to be potential fungicidal agents against phytopathogens. Copper nanoparticles are shown to have antifungal activity against many fungal pathogens like *Alternaria alternata*, *Rhizopus stolonifer*, *F. oxysporum*, and *Mucor plumbeus* (Wani and Shah 2012; Viet et al. 2016; Shende et al. 2016; Brahmanwade et al. 2016). It has been found that CTAB (cetyltrimethylammonium bromide)-mediated copper nanoparticles have potential antifungal activity against *F. oxysporum*, *Curvularia lunata*, *A. alternata*, and *Phoma destructiva* as compared to the commercially used fungicide Bavistin (Kanhed et al. 2014). Ponmurugan et al. (2016) showed antifungal activity of biosynthesized *Streptomyces griseus*-mediated copper nanoparticles against root-rot causing soil pathogen *Poria hypolateritia* in tea plant. The morphology-dependent antifungal activity of CuS nanoparticles against *Mucor*, *Rhizopus*, *F. oxysporum*, *Alternaria* spp., and *Helminthosporium* was reported by Chakraborty et al. (2016).

Sulfur nanoparticles have demonstrated higher antifungal activity against pathogenic fungi of fruits like grape, strawberry, vegetables, and many other crops (Deshpande et al. 2008; Suleiman et al. 2013; Llorens et al. 2017). The pathogenic *Fusarium solani* and *Venturia inaequalis* causing wilt and apple scab disease, respectively, are found to susceptible to sulfur nanoparticles, efficiently inhibiting the cell wall of fungi (Rao and Paria 2013). Chitosan nanoparticles also have shown antifungal activity against *Pyricularia grisea*, *A. solani*, and *F. oxysporum* and growth promotion in chickpea seedlings contributing to the increased seed vigor index, enhanced germination, and increase in biomass of seeds (Sathiyabama and Parthsarthy 2016). Chitin and chitosan nanoparticles are found to enhanced defense in host plants against microbial attack by increasing the synthesis of defense proteins, proteinase inhibitors, and phytoalexins, protecting the host plant from fungal pathogens (Sharan et al. 2015; Ahmed and Lee 2015).

Silver nanoparticles are one of the widely studied antifungal agents. But there are scanty reports against *Pythium* spp. causing soft-rot in ginger. Kasprowicz et al. (2010) studied antifungal efficacy of silver nanoparticles against *F. culmorum*, a plant pathogenic fungus. Oh et al. (2006) observed the total inhibition of phytopathogenic fungi, namely, *P. ultimum*, *R. solani*, *M. grisea*, *Colletotrichum gloeosporioides*, and *Botrytis cinerea*, by silica-silver nanoparticles at 10 ppm concentration. Inhibition of *R. solani*, *B. cinerea*, *A. alternata*, *M. phaseolina*, *Sclerotinia sclerotiorum*, and *C. lunata* by silver nanoparticles at 15 mg was reported by Krishnaraj et al. (2012). Silver nanoparticles cause damage to the fungal hyphae, conidial germination, decrease fungal growth, and interfere with microbial absorption (Woo et al. 2009; Jo et al. 2009). In vitro antifungal activity of zinc nanoparticles showing 77% mycelia inhibition in *F. oxysporum* and *P. expansum*, at concentration of 12 mg/L was shown by Ramy and Osama (2013). Parizi et al. (2014) reported antifungal activity of magnesium nanoparticles against tomato wilt causing *F. oxysporum* f. sp. lycopersici.

16.5 Conclusion

Ginger is a cash crop cultivated around the globe for its various novel properties which mainly include culinary and medicinal properties. This crop is susceptible to the attack of various microbes including most important *Pythium* and *Fusarium*, and there is a huge economic loss owing to diseases caused by these fungi. Various physical and chemical methods are in practice since long for the effective control of soft-rot disease of ginger. Unfortunately, the fungal pathogens have developed resistance to the fungicides, and therefore, the management of these pathogenic fungi seems difficult. Moreover, there are increasing concerns of toxicity of these fungicides to humans and environment. Hence, now the biological methods or biocontrol methods are being used for the management of this disease as these methods are eco-friendly and economically viable. A variety of microbes especially bacteria and fungi found to have promising activity against different pathogenic fungi. The members of genus *Trichoderma* such as *T. viride*, *T. aureoviride*, *T. virens*, and *T. hamatum* have been reported as potential biocontrol agents. Among the bacteria and actinomycetes, fluorescent pseudomonads, *Bacillus* spp., and *Streptomyces* have demonstrated their potential against *Pythium* spp. In addition, extract of different plants also showed high potential against *Pythium* spp. Although several efforts have been made for biological control of *Pythium* spp., a little success has been achieved. In future, there is huge possibility of use of nanotechnology-based methods to control soft-rot disease.

Acknowledgement MR is thankful to University Grants Commission, New Delhi for award of BSR faculty fellowship.

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