Chapter 6
Management of Root-Knot Nematode in Different Crops Using Microorganisms

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Abstract Root-knot nematodes are severe pests that affect a wide variety of crops. These nematodes are controlled by various types of nematicides that have hazardous effects on the environment. Hence, identification of new approaches alternate to harmful chemical nematicides could be effective in controlling root knot nematodes. Conventional control measures use soil fumigants, but they have certain limitations. Being chemical in nature and cost-effective, they pose severe economic concerns. Besides, they have a broad-spectrum range by harming nontarget species. This raised a question regarding the biosafety of sustainable environment posed by hazardous chemicals. Application of plant-derived products is an effective eco-friendly approach to mitigate the infestations caused by nematodes in different crops.

6.1 Introduction

Root-knot nematodes are austere pests of various food and industrial crops and are globally distributed. They are polyphagous and have short life cycle, which allows them to multiply rapidly in numerous agroecosystems, ranging from vicious monocultures to subsistence crops. It is indeed an arduous task for the growers to avert crop losses due to root-knot nematode problems, susceptibility of the current crop varieties (Stirling 2006), and absence of control measures which are not economically effective. These nematodes are obligate plant parasites and invade live plants for their growth, development, and reproduction. They cause an annual global loss of around

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US$100 billion in agriculture. The damage caused by root-knot nematodes is not always apprehended because their ecological niche is present below the earth surface, which makes their management task hellacious. The plant parts such as roots, bulbs, and tubers present in the soil are usually attacked by plant parasitic nematodes, thus playing a key role in the interruption of nutrients and water uptake. The impairment of water and mineral transport pathways leads to the appearance of symptoms resembling water or nutrition deficiency like small, chlorotic, and less vigorous plants (Oka et al. 2000). The root tips are primarily invaded, and damage to plants is done by degradation of the cell wall followed by migration toward the vascular cylinder and formation of giant cells which are also known as "galls." The development of root galls siphons the nutrients and photosynthates of the plant. The root-knot nematode affects both young and mature plants. The infection process can be fatal for the young plants, whereas infected mature plants experience a considerable loss in the yield. The damages caused by root-knot nematode are as follows: stunt growth, loss of crop quality and yield, and a reduced resistance to several other stresses (e.g., drought, other diseases) (Borah et al. 2018; Kepenekci et al. 2018). They cause rigorous damage, resulting in significant yield losses in different crops like tomato, cotton, rice, carrot, pepper, potato, eggplant, watermelon, cucumber, ashwagandha etc. Root-knot nematode infection induces several biochemical changes such as alterations in the levels of amino acids and organic acids and reduced chlorophyll content in the plants (Saikia et al. 2013).

There are around 80 different infective species, but three (*Meloidogyne arenaria*, *M. incognita*, and *M. javanica*) of them are of utmost agronomic importance because they are the only ones responsible for at least 90% of the crop damage, which contributes to 5% of the global crop loss. These species are highly polyphagous as they infect more than 3000 plant species. Furthermore, their global distribution makes them eminently successful plant parasites (Castagnone-Sereno 2002).

The conventional control measures of root-knot nematode include use of soil fumigants. The use of these chemicals poses severe economic concerns due to their high cost. Moreover, the use of these chemical nematicides hinders sustainable environmental management by posing potential risks to nontarget microorganisms. Thus, the dire threats posed by chemical control measures have raised the concern for the development of nonchemical and eco-friendly management strategies for controlling root-knot nematode (Huang et al. 2016). Therefore, nonchemical and eco-friendly alternatives such as biological control are being sought.

6.2 Chemical Control of Root-Knot Nematodes

The chemical control of nematodes is mainly mediated by the use of soil fumigants. Farmers mainly relied on a broad-spectrum soil fumigant like methyl bromide (MeBr) against various soilborne diseases, weeds, and nematodes. However, the use of methyl bromide was banned in 2005 and it was completely phased out. Thus, farmers were left with only limited options against the root-knot nematodes. Pic-Clor

60 [1,3-dichloropropene plus chloropicrin (40:60, w/w)] (Agrian, Inc., Fresno, CA) was one of the main fumigants which was used as an alternative to methyl bromide for growing tomato in Florida (Castillo et al. 2017). Some nonfumigant nematicides are available also which are currently registered for use in a number of crops like tomatoes, peppers, and eggplants. Such nematicides, except Vydate, are usually applied on soil, which can also be applied foliarly. These compounds need to be applied in a uniform manner to the soil, so that the future rooting zone of the plant can be targeted, where the nematodes will come in contact, or they can be applied in the areas where they can be easily absorbed and taken up into the plant (Noling 2016).

6.3 Root-Knot Management in Vegetables and Horticulture

6.3.1 Root-Knot Nematode Management in Tomato

Tomato (*Lycopersicon esculentum*) has got a unique place among the most popular vegetables in the world. It suffers a great number of biotic stresses during its growth. The root-knot nematode is liable for inducing the most scourging and widespread stress among the many biotic stresses. These nematodes not only affect the crop yield in a direct manner but also make the plant more susceptible to bacterial and fungal attacks (Zhou et al. 2016). The management of root-knot nematodes in tomato includes various strategies like crop rotation, use of resistant cultivars, and treatment of soils with chemical nematicides. Plant's resistance toward root-knot nematodes is unstable and often results in decreased yields (Williamson and Robert 2009). They cause a considerable loss in annual yield of vegetables, which may range from about 10 to 30% depending on the severity of infection (Radwan et al. 2012). There are various control measures that can be employed for controlling root-knot nematodes, including conventional methods such as chemical control in infested areas. Use of such chemicals has potential adverse impacts on environment. Furthermore, their prolonged use has also made them inefficient, resulting in a total ban or restricted use, thus directing the acute need for safer and more effective alternatives (Zukerman and Esnard 1994). Biological control appears to be one of the most promising alternatives. The nematicidal activity of the biocontrol agents *Bacillus megaterium*, *Trichoderma album*, *Trichoderma harzianum*, and *Ascophyllum nodosum* against the root-knot nematode, *Meloidogyne incognita*, that infects tomato, was found to be comparatively much superior than the control. There was a substantial decline in the count of root galls which was observed much higher in case of oxamyl or carbofuran (Radwan et al. 2012). Actinomycetes can secrete a variety of antimicrobial substances that can alter the microbial variety and population of the root zone. *Streptomyces*, an important group of actinomycetes, are mainly reported for the secretion of insecticidal substances (Ruanpanun et al. 2010). Treatment of soil with actinomycetes strongly affects the culturable microorganisms present in the root zone of the plants, root knots, and root systems, along with marked changes in the population of nematodes. The disease index of plant is significantly reduced on treatment with

Streptomyces. A decrease of 37% in disease index has been reported in tomato when treated with *Streptomyces* sp. Furthermore, there was a sharp decline of 14% in the number of nematodes feeding on bacteria present in the root zone. The fresh weight of root and shoot also increased significantly. The culturable microflora of the root knots is also altered in a significant manner. Moreover, the populations of nematicidal bacteria as well as of plant growth-promoting rhizobacteria are greatly enhanced, whereas the numbers of plant pathogenic bacteria are sharply declined. The significant reduction in root-knot disease in tomato could be due the activation of systemic resistance and defensive mechanism in plant against nematode infection (Ma et al. 2017).

Arbuscular mycorrhiza is a highly infective species and greatly enhances the growth of plants. They reduce pathogenicity in the root system and induce tolerance in plants against disease. The preestablishment of arbuscular mycorrhizal fungi significantly reduces the reproduction of *Meloidogyne incognita*, which in turn reduces the disease severity in infected soil. The inoculation with AM can improves the growth of plants and also protects the plants against soilborne pathogens.. It also contributes toward increasing the nutrient uptake and also acts as a potential biocontrol agent improving plant growth by direct or indirect mechanisms, thus compensating the damages caused by root-knot nematodes (Sharma and Sharma 2017). The application of plant growth-promoting rhizobacteria (PGPR) belonging to *Pseudomonas* spp. and *Bacillus* spp. is also helpful in the efficient management of Root knot nematode (RKN) infestation in tomato. PGPR protects the plants by inducing systemic resistance against the pathogens. A diverse array of microbes having varied physiological requirements is advantageous than using a single biocontrol agent such as *Piriformospora indica*, an endophytic fungus, in combination with two plant growth-promoting rhizobacteria (*Bacillus pumilus* and *Pseudomonas fluorescens*) successfully suppress root-knot nematode infection (Varkey et al. 2018). Cyanobacteria (blue–green algae), a primitive group of organisms that contains at least 40 toxicogenic species, can be used as biocontrol agents. The endospores of the species of *Microcoleus* and *Oscillatoria* have been reported for their ability to kill nematodes. They inhibited the hatching of second-stage juveniles and also killed the hatched juveniles, and therefore, they can be used as potent biocontrol agents (Khan et al. 2007).

6.3.2 Root-Knot Nematode Management in Carrot

Carrot is one of the important root crops. It is among the main ten vegetables grown globally in subtropical and tropical areas. The roots of this plant find uses in a variety of food items including pickle, salad, and juice. Its seeds are also a good source of essential oils that are used for various purposes. Its roots are rich in a number of vitamins like vitamin B6, vitamin K, and provitamin A. This food crop finds an area of 1.59 million hectares under its cultivation across the world. It is grown in over 130 countries with an annual global production of 49.35 million tonnes. This crop is also cultivated in India under the area of 0.32 million hectares and the annual production is 0.49 million tonnes, thus making India a major producer of carrot (Nagachandrabose 2018). The major hurdle in the commercial cultivation of carrot is the root-knot nematode that parasitizes plant roots. This results in severe qualitative and quantitative loss of yield. The cultivation of carrot is provoked by six different varieties of root-knot nematodes, namely, *Meloidogyne incognita*, *Meloidogyne hapla*, *Meloidogyne javanica*, *Meloidogyne chitwoodi*, *Meloidogyne fallax*, and *Meloidogyne polycephannulata* (Charchar et al. 2009). In India, carrots are mainly affected by northern root-knot nematode, *M. hapla*, which is a sedentary endoparasitic nematode. Infection of nematodes followed by penetration of juveniles through growing root tips leads to the formation of various giant cells containing multiple nuclei in the vascular tissues. The activity of nematode further results in the formation of galls, digitation, hairiness, and compression in taproots, thereby resulting in the formation of defective and forked carrots. Low infestations usually deteriorate the quality of carrots by disfigurement (forking), whereas high infestations lead to the arrest of taproot formation. The root infection caused by *M. hapla* in carrots results in an overall 24–55% quantitative loss and 13–77% qualitative loss (Nagachandrabose 2018). Furthermore, the wounds created by the nematodes enable the easy entry of different kinds of soilborne pathogens particularly *Pectobacterium carotovorum*, the soft rot bacterium, and together these organisms result in the formation of a disease complex resulting in enormous crop loss (Sowmya et al. 2012).

Crop damages caused by root-knot nematode infection can be controlled by using biological control agents like fungus or bacteria that can antagonize the nematodes effectively. The application of biocontrol agents for controlling nematodes is gaining popularity among farmers. If the introduction of biocontrol agent leads to its establishment with nematode populations, the invasion may last for a long time, ranging from complete season to a period even greater than the required period (Jacobs et al. 2003).

Liquid formulations of various biocontrol agents exhibit more efficiency than the solid carriers such as talc- and peat-based formulations. These liquid formulations are advantageous in a number of ways than the solid formulations: they increase the viable cell count, reduce the risk of contamination, show more virulence, and have high shelf life. Moreover, the cells in liquid formulations maintain their dormancy, which become active again on application to the soil rhizosphere.

In a study by Nagachandrabose (2018), the field efficiency of liquid formulations of *Pseudomonas fluorescens*, *Trichoderma viride*, and *Purpureocillium lilacinum* was tested against the populations of nematode, *Meloidogyne hapla*. Seed treatment with *P. fluorescens* caused a paramount decline in the populations by around 68%, whereas treatment with *P. lilacinum* reduced the population by 64–67%. The treatment of plant with *P. fluorescens* and *P. lilacinum* increased 36% height of the plants. Furthermore, the plants were also reported to have comparatively higher leaf count and improved leaf size than the untreated plants. The plants experienced 28–36% increase in the number of leaves and 27–30% longer leaves were observed. Surprisingly, treatment with *P. fluorescens* resulted in 20–21% higher yield of root tuber, whereas treatment with *P. lilacinum* resulted in 19% higher yield.

Bacillus subtilis is a widely used bacterium which has been commercialized as a potent biocontrol agent against a number of diseases and infectious nematodes parasitizing an extensive range of plants. In addition to its ability to form spores, it possesses numerous characteristics which strongly enhance its survival in rhizosphere. It exhibits various modes of action like competition, antibiosis, and induction of systemic resistance, and it also exhibits various traits of plant growth promotion. The success of any biocontrol agent strongly depends on its delivery mechanism into the field.

B. subtilis produces different types of antimicrobial compounds like subtillin, bacillin, bacitracin, bacillomycin, and subtenolin (Killani et al. 2011). In addition, it is also reported to produce various volatile compounds such as 2-nonanone, 2-undecanone, benzene acetaldehyde, dimethyl disulfide, and decanal, which show nematicidal activity; these compounds exert antagonistic activity toward the egg hatching of root-knot nematode and its second-stage juveniles (Huang et al. 2010). The seed treatment together with soil application of *B. subtilis*-enriched vermicompost increased the yield of carrot to 28.8%, decreased the total nematode population by 69.3%, and decreased the disease incidence by 70.2% (Rao et al. 2017). There are various natural enemies of nematodes, and fungus *Pochonia chlamydosporia* is one among them. This fungus parasitizes the eggs and the exposed females of the root-knot nematodes, so it can tremendously manage the root-knot nematodes. Moreover, it produces a large amount of resistant structures called chlamydospores, which allows its survival during adverse conditions. The incorporation of *Pochonia chlamydosporia* into the soil increased the total weight of taproots by approximately 55% in a study by Bontempo et al. (2014).

Aspergillus is another most effective biocontrol agent. They inhibit the hatching of nematode eggs and also promote enzymatic degradation by disintegrating chitin and vitelline layers of the nematode eggshell, which in turn leads to the disintegration of egg contents. The effect of this species is mainly exogenous. The coinoculation of *P. lilacinus* with *A. niger* significantly reduces nematode multiplication and also improves plant growth more compared to the inoculation of single organism due to the combined mechanisms of action of both organisms (Nesha and Siddiqui 2017).

6.3.3 Root-Knot Nematode Management in Chili

Chili (*Capsicum annuum*) is one of the important commercial crops grown worldwide and is a rich source of proteins, vitamin, ascorbic acid, and other nutrients. It belongs to the family Solanaceae and grows well in hot regions of the world. Several crop losses caused by plant parasitic nematode have been reported in chili (Khan et al. 2012). Chili crops infested with root-knot nematode *Meloidogyne incognita* appears to be stunted in growth, produces less flowers, and gives less yield. *Pseudo-*

monas fluorescens has proved its efficacy as a biocontrol agent for nematode management; in addition, compared to pesticides, it has also provided a prolonged resistance against nematode attack. The root-knot nematode infects the plant roots, when it becomes second-stage juveniles, and establishes a feeding site within the pericycles and vascular tissues of the plant cells and forms giant cells. Galls are formed due to hyperplasia of root cells around giant cells. Root-knot nematode destroys the root system, which creates competition for food and nutrition among the developing nematodes within the root system. During infection, root-knot nematode induces cell enlargement accompanied by nuclear division without cytokinesis. It results in the formation of multinucleate giant cells which confer resistance to root-knot nematode, characterized by hypersensitive reactions. The juveniles surrounded by necrotic cells fail to develop and die, which prevent nematode penetration and migration at early infection stages.

In a study of disease management in chili pepper infected with the root-knot nematode *Meloidogyne incognita*, Moon et al. (2010) reported 39 chili pepper cultivars/lines, out of which 6 were found to be resistant and 33 susceptible. The resistant cultivars/lines showed enhanced resistance against gall formation as compared to susceptible lines. These results revealed that disease resistance in chili pepper may be related to post-inflectional defense mechanisms.

Nowadays, plant products and their derivatives are also gaining importance in the management of plant parasitic nematodes and have increased the awareness of environmental hazards associated with nematicidal chemicals. Several indigenous plants and plants parts have been identified as promising sources of biopesticides. Plant products such as terpenoid, triterpenoid, limonoid, flavanoid, azadirachtins, meliantriol, salannin, nimbin, and nimbidin can be explored for their nematicidal potential. The neem-based formulations used in dressing and seedling bare root dip showed a significant decrease in the population of *M. incognita* and an increase in the yield of green chili.

6.3.4 Root-Knot Nematode Management in Banana

Banana (*Musa* sp.) is one of the chief economic tropical fruit crops grown worldwide and is rich in carbohydrates, proteins, minerals, and vitamins. It grows in a wide variety of soils. A total of 132 species of nematodes belonging to 54 genera are associated with rhizosphere of banana. Although crop yield is affected by a number of crop pests, the productivity of banana orchards is highly limited due to root-knot nematode infestation (Eissa et al. 2005). Infestation of plant roots by the pests results in toppling, reduces plant longevity, increases crop cycle duration, and results in yield losses. *Meloidogyne* spp. are the predominant nematode agents in bananas with an occurrence of about 76% (Mokbel et al. 2006). The management of root-knot nematodes by using hazardous chemicals is not a useful practice because these are highly prone to the humans and the environment. Thus, alternative control strategies such as biocontrol agents are needed. The biological, chemical, and physical properties of soil are also improved with the amendments of organic and biological products. During the decomposition of these organic amendments, some volatile compounds such as formic, propionic, and butyric acids and phenols are released, which proved to be toxic to nematodes. Biocontrol agents such as *Penicillium* spp., *Glomus fasciculatum*, *Bacillus subtilis*, *Trichoderma viride*, and *Paecilomyces lilacinus* also showed effective nematicidal activities against *M. incognita* (Esnard et al. 1998). *P. lilacinus*-treated plants showed significant reduction in root galls index and eggs per egg mass in soil but showed an increase in the number of leaves, root length, shoot length, and height of plant. Recent studies have reported that alga is also an effective biocontrol agent in treating plants affected by root-knot nematodes. Few algae such as *Ulva lactuca*, *Jania rubens*, *Sargassum vulgare*, and *Laurencia obtusa* can be successively used for controlling root-knot nematode and for promoting plant growth.

El-Nagdi et al. (2015) studied the biological control of root-knot nematode and *Fusarium* root rot fungus in banana by using two commercial biocontrol agent products (CBAP)— Fornem x5® (contains *Rhodotorula pustula*, *S. marcescens*, *Serratia entomophila*, *P. putida*, and *P. fluorescens*) and Micronema® (contains *Azotobacter* sp., *Pseudomonas* sp., *Bacillus thuringiensis*, *Serratia* sp., and *Bacillus circulans*)—compared to chemical nematicide Nemacur® against *Meloidogyne incognita* and *Fusarium* root rot (*Fusarium solani*) fungus. Micronema® and Fornem x5® significantly reduced the numbers of nematode parameters after 2, 4, and 6 months of treatment. The highest reduction of juveniles in stage three (J2), stage two (J3), eggs and females in roots were achieved by application of Fornem x5® followed by Micronema® at 30 ml/plant after 6 months. Results showed that the treatments increased the frequency of *Aspergillus* spp. and *Penicillium* spp., while they decreased the frequency of *Fusarium* spp., moderately inhibitory effect on *Fusarium* root rot was obtained by CBAP. Yield parameters were increased with Micronema® and Fornem x5® at 30 ml/plant as compared to Nemacur® and untreated control.

6.4 Root-Knot Nematode Management in Agricultural Crops

6.4.1 Root-Knot Nematode Management in Sugarcane

Sugarcane is a very popular sugar crop and is also a regenerative energy crop. The soils which are not suitable for conventional agricultural crops are used for sugarcane plantation. This crop has occupied a significant area under cultivation in more than 80 countries across the globe. The crop is mainly grown for fiber, crude sugar, and bioethanol production (Chirchir et al. 2008). This crop is susceptible to a number of threats including nematode diseases, which affect its production significantly and also cause austere economic losses globally (Stirling et al. 2001). The susceptibility of current varieties of sugarcane toward the attack of root-knot nematode makes it a very challenging problem for the farmers as the preclusion of crop losses resulting from nematode infections appears to be a strenuous exercise (Stirling 2006) due to the absence of control measures which are economically effective. The nematodes are responsible for approximately 20% reduction in the production. In addition to the presence of nematodes also poses a threat to the cultivation of new crops thus making the process of growing new crops an uneconomical operation in infested areas (Morgado et al. 2015).

The yields of sugarcane affected with nematodes are significantly increased when treated with functional biofertilizers as compared to chemical fertilizers. There is a significant decrease in the population of plant parasites along with an increase in the number of beneficial nematodes. The yield of sugarcane is increased by comparatively high number of bacterivore and a reduced population of plant parasites (Zhang et al. 2017).

The introduction of spore-forming bacterium *B. subtilis* in the soils has been reported to cause a reduction in the number of plant parasitic nematodes. Furthermore, its ability to form spores ensures its survival over long periods. Moreover, suppression of nematodes by treating with *B. subtilis* is found to be equivalent to the use of conventional chemical control measures (Morgado et al. 2015).

When alternative methods of nematode control are taken into consideration, *Pasteuria penetrans* also proves to be an effective biocontrol agent that is commendable for investigation. Its host specificity toward the root-knot nematode can be explored for a significant reduction in the populations of root-knot nematode. The elevated number of endospores can even lead to the elimination of 99% of the nematode population (Bhuiyan et al. 2018). The rigorousness of root galls and the amount of nematode eggs can be knocked down by amplifying the concentration of endospores. Thus, the perpetual sustentation of altitudinous concentration of endospores in the vicinity of roots can strikingly reduce the infections induced by root-knot nematode, a dire pest of sugarcane.

An integrated use of nematophagous fungi along with the application of arbuscular mycorrhizal fungi also proves to be an effective biocontrol measure. Arbuscular mycorrhizal fungi like *Glomus mosseae* and *Glomus fasciculatum* have the potential to act as effective biocontrol agents when used with nematophagous fungi like *Arthrobotrys oligospora*, *Pochonia chlamydosporia*, and *Paecilomyces lilacinus*. A maximum reduction of 47% in the population of *M. javanica* has been reported with the integrated use of *G. fasciculatum* and *P. lilacinus*. This combination proved to be very effective in increasing the shoot weight of the plant (Sankaranarayanan and Hari 2013). The plant parasitic root-knot nematode can also be controlled by amendments of organic matter in the soil. The organic amendments of filter mud and sugarcane bagasse can significantly lower the numbers of parasitic nematodes (Chirchir et al. 2008).

6.4.2 Root-Knot Nematode Management in Rice

Rice is the most important staple crop consumed globally, which finds an area of 162 mha under annual cultivation with an overall global production of 464 mmt annually. Rice crop is very much susceptible to the attack of root-knot nematodes and is infected by *Meloidogyne triticoryzae*, *M. arenaria*, *M. incognita*, *M. graminicola*, *M. oryzae,* and *M. javanica*. The primary pest that attacks rice is *M. graminicola*, which poses an extensive threat to the cultivation of rice particularly in Southeast Asia where around 90% of the global rice is cultivated as well as consumed (Khan et al. 2014). Rice undergoes attack by nematodes in nursery as well as in the main field, which results in considerable loss of crop yield. This nematode causes an annual yield loss of around 16–32% in upland and rainfed rice in India (Haque et al. 2018). The chemical control of root-knot nematode proves to be much effective, and organophosphates are the widely used pesticides for nematode control. Although chemical treatment is very effective, the persistence of saturated conditions in rice fields due to irrigation leads to the percolation of pesticides from the root zones, which further results in the persistence of root-knot nematode (Khan et al. 2014). The use of biocontrol agents proves to be the best alternative for root-knot nematode management in rice.

There are a number of biocontrol agents such as *Pseudomonas putida*, *Trichoderma harzianum*, *P. fluorescens*, *Purpureocillium lilacinum*, and *Bacillus subtilis*, which provide better and effective control of root-knot disease. *P. putida* is found to be much effective than *P. fluorescens* and *P. lilacinum*, and *T. harzianum* effectively suppresses the nematode as an endophyte (Haque et al. 2018). Biological control employing different endophytic microorganisms is found to be highly effective in mitigating endoparasites which complete their life cycle inside the host. Various endophytes are capable of targeting various life stages of the parasitic nematodes by delaying development, reducing penetration, and diminishing reproductive capacity. *Bacillus megaterium*, a bacterial endophyte, is capable of reducing the attraction and penetration of rice roots by *M. graminicola* and also of diminishing the rate of hatching of nematode eggs. The inoculation of rice roots with *Fusarium* isolates and *Trichoderma* species has been found to decrease the severity of infection. These fungal isolates have also been found to decrease the severity of root galling by 29–42% and increase root weight by 33% (Le et al. 2009).

There are various biocontrol agents which have been reported to control the infections of plant parasitic nematodes. Chitinolytic microorganisms—for instance, the plant-growth-promoting rhizobacterium, *Pseudomonas fluorescens*, and the egg parasitic fungus, *Paecilomyces lilacinus*—seem to be the ideal agents for controlling rice nematodes due to their enhanced survival under clay soils which are meant for cultivation of irrigated rice. The talc-based formulations of *Paecilomyces lilacinus* and *Pseudomonas fluorescens* have been reported to produce comparable results with nematicide carbofuran application (Seenivasan 2011).

Dactylaria brochopaga is also supposed to be an effective biocontrol agent of root-knot nematode. In a study by Kumar and Singh (2008), it was observed that the application of *D. brochopaga* at 1% significantly reduced the parasitic nematode population and number of galls. The application of spore suspension of *D. brochopaga* also significantly controlled the disease along with significant upsurge in shoot and root weight.

6.4.3 Root-Knot Nematode Management in Chickpea

Chickpea (*Cicer arietinum* L.), a pulse crop, is a chief source of vitamins, minerals, and nutritional protein. It is widely used as a source of protein. Parasitic nematodes cause a great loss to chickpea, estimated to 13.7% loss in its production globally with an approximate total of 7620 hg/ha yield. It is more prone to be attacked by numerous ectoparasitic and endoparasitic nematodes like *M. javanica*, *Helicotylenchus* spp. (Ali and Sharma 2002), *Heterodera swarupi*, *Meloidogyne incognita*, and *Pratylenchus thornei*; therefore, management of chickpea is very complex. A few reports in India stated that root-knot nematodes reduce the yield of chickpea from 17 to 60% depending on the soil types and nematode inoculum density, and this has been reported in many states of India (Khan and Siddiqui 2005). *Meloidogyne* sp. is one of the most common root-knot nematodes in both tropical and subtropical regions where it has highly reduced the crop production and caused extensive economic loss globally (Sikora and Fernandez 2005).

Nematode alters plants metabolic processes such as nitrogen fixation and nodule formation, which ultimately affect the total yield of plant. To combat this problem, nematicides are currently being used to control nematode population. But this is not an effective practice; as nematicides are toxic, they may accumulate in plant, which may cause environmental pollution and there is reduction in amount stratosphere layer (Wheeler et al. 1979). Therefore, a substitute for nematode management is urgently required. Substances that occur naturally may also possess nematicidal activity. Yadav et al. (2006) reported that oil cakes are an important organic substitute in the management of root-knot nematodes that affect the yield of chickpea.

Rehman et al. (2012) studied the effect of *M. incognita*, a root-knot nematode, in reducing the yield of chickpea. They observed that application of chickpea with high concentration of *M. azedarach* leaf extracts showed reduction of *M. incognita* infection as compared to other doses. Chickpea plants were inoculated with second-stage juveniles of *M. incognita*, and a highest reduction in plant growth was observed with a reduction in root and shoot length (cm), total chlorophyll content, nitrate reductase activity, fresh weight (g), dry weight (g), and flower number per pods as root-knot index increased. A significant reduction in infection was observed in chickpea plants (control) inoculated with lesser concentration of leaf extract of *M. azedarach*. This study supports the use of organic substitutes in the control management of nematodes as an effective approach to manage environmental pollution. This study was supported by Mojumder and Mittal (2000); the results showed that chickpea transplanted with neem seedlings showed significant reduction in *M. incognita* infection. Therefore, these studies provide evidence that the infestation of *Meloidogyne* spp. may be reduced by the use of organic compounds obtained from plant in view of eco-friendly environment to avoid expensive and hazardous chemical nematicides for eco-friendly environment.

6.5 Conclusion

Root-knot nematodes are serious threat to global food industries and other industrial sectors. They cause reduction in crop yield due to the formation of galls that siphon the photosynthetic machinery of plants. Application of soil fumigants as a control measure of root-knot nematode poses severe economic concerns and also raises a question on the sustainable management of agroecosystems. To cope with this, best alternatives such as organic substitutes of microbial origin possessing nematicidal activity are to be opted for root-knot nematode management.

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