Use of different eco-friendly management approaches for controlling root-knot nematode (*Meloidogyne incognita* L.) in tomato (*Solanum lycopersicum* L.)

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Submission: 29 January 2020 Revised: 2 July 2021 Accepted: 12 August 2021

ABSTRACT

Root-knot nematodes are growing concerns for tomato growers because chemical nematicides are gradually disappearing and environmentally not sound. Alternative techniques based on organic soil amendments and other nematodes antagonistic (biological control agents) are needed to be solved the problem. This review analyzed the recent studies related to these techniques and their combinations and identified the most effective ones. Also, this analysis focused on a description of eco-friendly management techniques rather than chemical control. Several alternative techniques such as organic manure, plant products, organic wastes, antagonistic fungi, and bacteria are considered to control knot nematode (*Meloidogyne incognita*) in tomato production. The review analyzed the effect of each practice and interactions among the techniques. A remarkable variation was also found among the studies. Organic soil amendments enhance the activities of microorganisms that can significantly suppress root-knot nematode by the release of nematotoxic compounds. On the other hand, nematode antagonistic (nematophagous fungi, bacteria, etc.) also control root-knot nematode without any hazard to the environment. This study will help to find out the most effective, economical, eco-friendly management method for controlling nematode for encouraging tomato production.

Keywords: Biological control, *Meloidogyne*, organic amendments, root-knot nematode, solarization, tomato

Thai J. Agric. Sci. (2021) Vol. 54(1): 89−103

INTRODUCTION

Root-knot nematodes are microscopic plant-parasites from the genus *Meloidogyne* (Ghasemzadeh *et al.*, 2019; Miheret *et al.*, 2019; Yue *et al.*, 2019). They can exist in the soil under hot to short winter climatic conditions. Basically, *Meloidogyne* species are obligate endoparasites which are economically the most important groups of plant-parasitic nematodes in the world (Lambert and Bekal, 2002). More than 3,000 plant species of plants in worldwide are susceptible to root-knot nematodes and cause about 5% yield loss by *Meloidogyne* species every year (Abad *et al.*, 2003). There are more than 90 species of *Meloidogyne* have been described in several studies (Ghasemzadeh *et al.*, 2019; Miheret *et al.*, 2019; Yue *et al.*, 2019). Among these, three species of root-knot nematode such as *Meloidogyne incognita*, *M. javanica, M. arenaria* are the most damaging in all over the world (Hunt and Handoo, 2009). Among them, *M. incognita* is extensively widely distributed and economically important nematodes in tropical and subtropical regions. It can live in many soil types, while damage and yield losses in many crops were found severe in coarse-textured sandy soils (Van Gundy, 1985). Two-third of the root-knot nematodes in tropical countries were *M. incognita* (Sasser, 1979; Ghasemzadeh *et al.*, 2019; Miheret *et al.*, 2019). While, in South-Asia, including India, Bangladesh, and Nepal about 232 plant genera have been reported as hosts to *M. incognita* (Krishnappa, 1985).

Due to a short life cycle (6–8 weeks), *M. incognita* can easily survive in short duration crops. Second-stage juveniles can attack the plant and can easily enter through the root tip. After penetration into the root, they migrate intracellularly to the root apex and enter the vascular cylinder of the root where permanent feeding sites are developed. In these sites, the second-stage juveniles undergo three moults to develop into adults. They induce a redifferentiation process that leads to the formation of multinucleated feeding cells, named giant cells (Abad *et al.*, 2003). These giant cells are called gall. As a result, the root is damaged to the point where the plant is not able to absorb water and nutrients. For this reason, reduced shoot growth, decreased shoot-root ratio and nutrient deficiencies have occurred (Yamada and Takakura, 1975). Some specific symptoms such as chlorosis, growth stunting, yellowing, wilting, and premature death are observed due to nematode infestation and finally reduce yield. *M. incognita* infection also reduces the rate of photosynthesis in leaves. If it is infected in the seedling stage, few roots are produced and normally cause rapid death (Zeng *et al.*, 2014).

Whereas throughout the tropical and subtropical regions in the world, *M. incognita* is a major pest of vegetables including tomato, aubergine, okra, cucumber, melon, carrot, gourds, lettuce, and peppers. Among the vegetables which are susceptible to root-knot nematodes, tomato (*Solanum lycopersicum*) is one of the most important vegetable crops in the world, due to its wider uses such as salad or fast food and also a high level of pro-vitamin A and C, and economic value. Besides these, it is an excellent source of antioxidants which help to reduce risks of cancers and heart diseases, and prevent DNA damage (Giovannucci, 1999; Slavin and Lloyd, 2012). While, in field conditions, nematodes mainly *Meloidogyne* species hinder the growth and development, and final yield of tomatoes. Among the *Meloidogyne* species, *M. incognita* is known to cause high levels of economic loss in tomatoes worldwide (Lutuf, 2015; Seid *et al.*, 2015). Various studies reported that yield loss of tomato due to root-knot nematode *Meloidogyne incognita* on various tomato cultivars, ranges from 25–100% (Seid *et al.*, 2015). Sasser (1979) estimated vegetable crop losses due to *Meloidogyne* species, mainly *M. incognita and M. javanica*, were from 17–20%, while for tomato was 24–38%. Bhatti and Jain (1977) and Subramaniyan *et al.* (1990) found yield losses for tomato was 42–54% in India.

The focus on root-knot nematodes management strategies is highly pertinent to minimize vegetable (including tomato) scarcity problem as well as enhance nutritional security for increasing population (Ghasemzadeh *et al.*, 2019; Miheret *et al.*, 2019; Yue *et al.*, 2019). Annual vegetable yield loss caused by root-knot nematode is about 10% (Koenning *et al.*, 1999). The practices of controlling plant-parasitic nematodes have mainly depended on chemical nematicides, which showed the effective reduction of the nematode population (Akhtar and Malik, 2000) but considered as harmful to the human and environment (Wachira *et al*., 2009). There is growing concern to investigate the alternative management strategies of root-knot nematodes with less hazardous to the environment (Mashela *et al*., 2008). Many researchers have been reported the alternative management strategies such as prevention, crop rotation, cultural methods, physical control, resistant/tolerant variety, biological and chemical control (Oka *et al*., 2007).

For controlling root-knot nematodes cultural practice such as crop rotation is presently used but not so effective due to the wide host range. Application of organic amendments like crop residues, animal manure, green manure, and plant extract may help to reduce root-knot nematode (Naz *et al*., 2015a; 2015b). On the other hand, it can be beneficial for microorganisms that increase soil fertility in the soil through improve water retention, induce water infiltration, and enrich organic matter. Moreover, other best alternative strategies such as resistant varieties and the application of biological control agents help to control nematodes. Biological control of nematodes principally concerns microbial agents, i.e., management of plant diseases and pests with the help of living organisms. Therefore, root colonizing fungi such as mycorrhizae, trapping fungi, and rhizosphere bacteria can easily control nematodes through attack the second-stage juveniles of root-knot nematodes. Biological control agents are more effective when integrated with other control practices. They are simply the use of one or more organisms to reduce the population of harmful pests at a certain level (Nekouam, 2004). Biological control agents will not substitute nematicides but integrated with other control measures can play an important role for nematode control (Yue *et al*., 2019).

This review aims to compare the different management techniques for nematode control and to find out the most effective, economical, eco-friendly management method for controlling nematode in tomato production. Finally, this review aims to analyze and identify the eco-friendly techniques that can significantly suppress nematodes for sustainable tomato production. The first part of this review will cover the organic soil amendments while the other parts will cover the nematode antagonistic (biological control agents) that are effective for nematode control.

MANAGEMENT APPROACHES FOR CONTROLLING ROOT-KNOT NEMATODE

Soil Solarization

Soil solarization offers an alternative management method to control nematodes (Viaene *et al*., 2013). This method has been widely used to reduce the population of root-knot nematodes (Tisserat, 2006). In this method, plastic film is used to cover the soil for at least 2 weeks and it enhanced soil temperature by 2–15°C. Therefore, it helps to reduce the egg of the nematode (Ralmi *et al*., 2016). The study of Fiume (1994) in a greenhouse found that the root-knot nematode *Meloidogyne incognita* on tomatoes was controlled effectively by soil solarization in combination with using of resistant variety.

An investigation related to soil solarization was applied in consecutive three years on a soil infested by the root-knot nematode *Meloidogyne javanica* to observe the effect of soil solarization in nematode infestation on tomato and melon. Results of the observation showed that single solarization significantly improved the yield of melon by 116%, by reducing the nematode infestation and root gall index by >99% and >98%, respectively. While two- and three-year solarized soil gave the maximum yield than non-solarized soil. In the case of tomatoes, the yields were 284% for two-year solarized soil and 263% for three-year solarized soil. While for melon, the yields were 162% and 368% for two- and three-year solarized soil, respectively. Similarly, two and three years of solarization almost completely reduced the infestation of the *M. javanica* nematode in tomatoes (Candido *et al*., 2008). Similarly, Carson and Otoo (1996) also found that root-knot nematodes of tomato were reduced, due to soil solarization that ultimately helps to improve the growth, development, and final yield of tomatoes. During solarization, mean soil temperatures were increased, ranged from 44–53ºC at 5 cm depth and from 36–46ºC at 10 cm depth as a result of successive increases in the period of solarization. Results of the study found that soil root-knot nematodes (*Meloidogyne* spp.) were significantly reduced by the longer period of solarization through reducing the root-galling incidence in tomatoes. In addition, Al-Rehiayani and Bellal (2009) showed that soil solarization using polyethylene sheets during hot summer months in Al-Qassim (Saudi Arabia) was effective in reducing populations of *H. avenae* in wheat.

Management through Organic Amendments

Different research studies have evaluated to control of plant-parasitic nematodes by an application of organic amendments on the soil. Organic amendments are polysemic. It covers different sources and products including organic manure, plant products, organic wastes, etc. Amendment with animal waste products such as poultry refuse (poultry manure) and goat manure has also been observed to reduce nematodes. It also stimulates a huge number of organisms in the soil food web. In addition, it also increases the number of predators and parasites of plant-parasitic nematodes (Akhtar and Malik, 2000; Ferris and Matute, 2003)

Pakeerathan *et al.* (2009a) reported that goat manure at 800 kg ha^{-1} can help to control nematode in tomato crops. Microelements such as potassium (1.9%) and phosphorus (0.7%) are rich in goat manure. These two elements increase the healthy root system which also can suppress the nematode infection. Biomass is a key factor for the better yield of tomato crops. The highest biomass was observed from goat manure than other manures (Pakeerathan *et al.*, 2009a). Biomass also affects on C: N ratio. Soil amendments with a low C: N ratio helps to control root-knot nematode (Oka, 2010).

Poultry refuse was found as another eco-friendly effective compound to control nematodes. For instance, poultry refuse at 5 t ha^{-1} was reported to control nematode effectively (Faruk *et al.*, 2011). Again, the application of a composition of poultry refuses at 3 t ha^{-1} and Furadan (carbofuran) at 20 kg ha^{-1} showed higher performance than sole poultry refuse. But Furadan should be avoided due to its hazardous effect on the environment and human health. In tomatoes, root growth, shoot growth, and yield also differed when poultry refuse was applied at different rates. Applications of poultry refuse at 3 t ha^{-1} were found less effective than that at 5 t ha^{-1}. However, the highest root growth, shoot growth, and yield of tomato were observed from at 5 t ha^{-1} poultry refuse (Faruk *et al.*, 2011).

Radwan *et al.* (2011) tested different types of oil cakes and observed their potentiality against root-knot nematodes. The different dosages of oil cake varied from 5–50 g kg^{-1} soil significantly reduced the number of galls. Application of higher dose (50 g kg^{-1}) oil cake showed adverse effect than that of lower (5–20 g kg^{-1}). The rate of 50 g sesame cake kg^{-1} soil reduces galling of tomato compared to a similar rate of soybean, flax, and cotton or flax cake. On the other hand, the effective control of second-stage juveniles depended on the application rate of oil cake. The rate of 50 g olive cake kg^{-1} soil acts as most effective compared to other rates (Radwan *et al.*, 2011). Sesame, flax, and cotton cakes significantly increase the shoot length of tomatoes. Sesame meal releases methyl isothiocyanates which have the nematicidal effect that might help to control nematodes (Lear, 1956).

Management through Green Manures

The application of green manures can play a vital role to control nematodes. Naz *et al.* (2013; 2015a; 2015b) tested different dose of green manure of *Fumaria parviflora* (Fumariaceae) along with different application date to control nematodes on tomato. They observed that using green manure of Fumaria at 30 g fresh material kg^{-1} soil before 15 days planting significantly reduced the nematode population in tomato plants. Ferraz and de Freitas (2004) reported that some green manures had a positive impact to control root-knot nematodes. They found that some green manures produced anthelmintic compounds which might be helpful to reduce root-knot nematodes. Pakeerathan *et al.* (2009b) observed that green leaf manures from *Thespesia populnea*, *Calotropis gigantia, Azadiracta indica* (neem), *Gliricidia maculate*, and *Glycosmis pentaphylla* applied at 25 t ha^{-1} improved the plant growth, as well as yield of tomato through effectively controlled of root-knot nematodes. Among the leaf green manures, *Gliricidia maculata* was significantly effective as compared to others.

Management through Plant Products

Seed powders of plant species are environmentally sound and have some nematicidal effects which can control nematodes. Radwan *et al.* (2012a) compared the effects of dried seed powder produced from different plant species such as *Ammi majus, Matricaria chamomilla, Ricinus communis,* *Brassica alba, B.oleracea, Peganum harmala, Solanum nigrum, Raphanus sativus, and Eucalyptus* sp. All plant seed powders contain nematotoxic compounds. The seed powders of the tested plants were incorporated into the soil at the rate of 5 g kg^{-1}. They observed that *M. Chamomilla* performed better and reduced root-knot nematodes effectively compared to other dried seed powders. In terms of shoot length, *Brassica oleracea* was significantly more effective than other seed powders. The dried seeds of *B. oleracea* reduced the number of juveniles in the soil (92.3%) compared to *M. chamomilla* (90.5%), *R. communis* (81.1%), and *B. alba* (79.1%) (Radwan *et al.*, 2012a). Oka (2010) observed that dried seeds or their byproducts provided toxic substances (allelochemicals) which help to control root-knot nematodes.

Root extracts of some medicinal plants were found more effective to control many species of nematode (Haroon *et al.*, 2009). Among them, *Calendula officinalis, Ambrosia maritima,* and *Origanum vulgare* significantly reduced the hatching of eggs and mortality of different species of nematode include root-knots of tomato as compared to the chemical control. In addition, Ngala *et al.* (2015) potentially used the brassicaceous crops for controlling the potato cyst nematode (*Globodera pallida*).

Sivakumar and Gunasekara (2011) observed that neem seed oil formulations can reduce nematode populations. The oil formulation at 0.2% concentrations was used for seed treatment and seedling root tip and was found effective to control root-knot nematodes. Ahmad *et al.* (2010) assumed that green chopped leaves of four test plants (*Lantana camara, Ficus virens, Kigelia pinnata, and Ficus bengalensis*) were significantly effective to control root-knot nematodes. Application of *Lantana camara* was found not only for controlling root-knot nematodes but also showed a positive effect on plant height, fresh and dry weight, number of fruits per plant, and fruit yield. This might be due to the release of organic additives from the chopped leaves to the soil, improved soil fertility and soil biological activity as well as increased crop performance. Qamar *et al.* (2005) also shown that pentacyclic triterpenoids from *Lantana camara* have nematicidal effects on root-knot nematodes.

Abo-Elyousar *et al.* (2010) observed that fresh leaf extracts of neem (*Azadirachta indica*), garlic (*Allium sativum*), and African marigold (*Tagetes erecta*) decreased the nematode population in the tomato field. They also showed that garlic performed better than the other two leaf extracts in terms of nematode control and fruit yield. The antimicrobial substance allicin produced from garlic has nematicidal effects which can suppress soil nematode as well as reduce plant disease.

Taye *et al.* (2013) also observed that extracts from different plant species, i.e., bakar tree, bitter leaf, parthenium, lantana, Mexican marigold, Mexican tea, neem, and pyrethrum can reduce the formation of galls, and number of eggs/egg-mass and can reduce the nematode population. Mexican marigold, parthenium, bitter leaf, and Mexican tea at 5% were also effective to control root-knot nematodes. Plant extracts can play a role to interfere in a biochemical reaction inside the nematode such as denaturing and degrading of proteins, inhibition of enzymes, and interfering with the electron flow in the respiratory chain or with ADP phosphorylation (Singh and Devi, 2012).

Management through Organic Wastes

Several studies found that organic wastes can significantly suppress root-knot nematode on tomato crops. Hassan *et al.* (2010) tested three types of organic wastes namely refuse dump, rice husk, and sawdust at the rate of 15, 30, and 45 t ha^{-1}. They found that refuse dump (at 30 t ha^{-1}) significantly reduced the nematode population in tomato plants as well as produced the highest tomato yield rather than other wastes. Refuse dump also reduced the C: N ratio rather than other wastes. The lower C: N ratio may help to lower the nematode population in the soil.

Aslam and Saifullah (2013) reported that oyster mushroom spent compost was more effective to reduce the egg hatching and killing juveniles of root-knot nematodes. It might be due to good sources of nutrients like nitrogen, phosphorus, and potassium which improve the organic matter of the soil. This organic matter releases some organic compounds such as acetic acid, propionic, and butyric acid that may be toxic to nematodes. D'addabbo *et al.* (2011) observed that olive pomace-based composts significantly reduced nematode infestation and gall formation on tomato plants. On the other hand, olive waste compost performed positively in tomato growth when it was combined with sheep wool wastes.

Biological Control

Biological control of nematodes principally concerns the exploitation of microbial agents, as chemical control of nematodes is often considered economically and environmentally unacceptable (Mokrini *et al.*, 2017; Kim *et al.*, 2018; Xiang *et al.*, 2018). Therefore, the development of microbial antagonists for controlling nematodes might be one of the most important alternatives under changing climate (Riley *et al.*, 2010). A range of microorganisms has been investigated as potential biological control agents (BCAs) such as *Pochonium chlamydosporium, Trichoderma longibrachiatum*, and *Purpureocillium lilacinus* (Zhang *et al.*, 2014; Mokrini *et al.*, 2017). In addition, some bacteria have been shown to offer potential as biocontrol agents. For example, a bacterium similar to *Pasteuria* spp. was able to parasitise *H. avenae* and was shown to prevent 38–56% of the juveniles from invading roots (Davies *et al.*, 1990). While *Azotobacter chroococcum* reduced cyst formation by 48% (Bansal *et al.*, 1999). The main controlling mechanisms against nematodes by BCAs are antagonism (antibiosis, competition for nutrients or space and suppression) and induced resistance (systemic acquired resistance) (Xiang *et al.*, 2018; Kumar and Dara, 2021). The present review only takes biological control as well as living organisms that have been applied to the soil, which are described in detail in the following subheads:

Control through nematophagous fungi

According to their nematophagous characteristic, different types of fungi have been identified. Some nematophagous fungi are obligate parasites, facultative parasites, egg parasites, and toxin producers. Among them, *Arthrobotrys dactyloides*, *Arthrobotrys superba, Arthrobotrys oligospora*, and *Monacrosporium gephyropagum* are the most frequently used as nematode-trapping fungi (Zhang *et al.*, 2020). Poveda *et al.* (2020) reported that the genus *Trichoderma*, mycorrhizal and endophytic fungi are the main groups of filamentous fungi used as BCAs against nematodes as resistance inducers. They induce resistance both directly and indirectly. They work against plant-parasitic nematodes directly by parasitism, antibiosis, and paralysis and by the production of lytic enzymes. The indirect mechanisms are space and resource-competition, providing higher nutrient and water uptake to the plant, or modifying the root morphology, and/or rhizosphere interactions, which constitutes an advantage for the plant growth. *Acremonium strictum* and *Aspergillus terreus* have toxic effects on nematode (Singh and Mathur, 2010). The authors also reported that the talc formulation of both fungi has a significant effect on the suppression of *M. incognita*. Simultaneously they have no adverse effect in terms of pathogenicity. The combined application of *A. striatum* and *A. terreus* has not only the highest suppression capacity of *M. incognita* on tomato plants but also showed the highest recovery percentage of plant growth (Singh and Mathur, 2010). Ashoub *et al.* (2009) observed that some fungi have toxic effects on nematodes such as *Trichoderma* spp., *Aspergillus* spp. and *Rhizoctonia* spp. *Trichoderma viride* showed the highest toxicity against *M. incognita*. In an *in vivo* study, *Fusarium* spp. showed toxic effects to control of *M. incognita.* Other *Aspergillus* species such as *Aspergillus tamarii* had no significant effect on the suppression of nematodes (Ashoub *et al.*, 2009).

Liu *et al.* (2011) reported that dual inoculation with arbuscular mycorrhizal fungi *Glomus versitorme* and *Glomus mosseae*, and plant growth-promoting rhizobacteria *Bacillus polymyxa* and *Bacillus* spp. had a positive impact on controlling *M. incognita* of tomato plants. Fan *et al.* (2020) reported that *T. citrinoviride* Snef1910 significantly inhibited egg hatching of *M. incognita* with the hatching inhibition percentages of 90.27, 77.50, and 67.06% at 48, 72, and 96 h after the treatment, respectively. They also observed that the metabolites of the fungus significantly decreased the numbers of root galls, second-stage juveniles, and nematode egg masses, and density of second-stage juveniles population of the nematode in soil and significantly promoted the growth of tomato plants. Several studies have found that they do not interfere with each other (Dwivedi *et al.*, 2009). Plant height, stem diameter, number of nodes, and dry weight of the tops and roots were significantly higher when *G. mosseae* was used with *Bacillus* spp. compared to other single inoculations. Application of vermicompost + *Glomus aggregatum* + *Bacillus coagulans* had a positive effect to reduce root-knot index, nematode reproduction rate, and number of gall formation on tomato plants (Serfoji *et al.*, 2010). Elsen *et al.* (2008) showed that arbuscular mycorrhizal fungus has strong induction of systemic resistance in plants towards nematodes while Shreenivasa *et al.* (2007) reported that plant growth-promoting rhizobacteria directly affect the plant metabolism (enhance plant enzyme activity and improve root development). Arbuscular mycorrhizal fungi may also interfere with the production of root diffusates or produce nematoxic compounds (Viaene *et al.*, 2006).

Dallemole-Giaretta *et al.* (2011) compared the effect of cover crops and *Pochonia chlamydosporia* for controlling *Meloidogyne javanica* on tomato crops. They also found that Surinam grass, pearl millet, and black oat could reduce gall and egg of *M. javnica* more than 90% while *P. chlamydosporia* + Surinam grass could significantly reduce by 72%. Their findings also explained that these grasses were the poor host for different root-knot nematodes (Carneiro *et al.*, 2007) and *M. ethiopica* (Lima *et al.*, 2009). Nematophagous fungi like predaceous, nematode-trapping, and nematode-destroying fungi demand significant applied interests in agriculture (de Freitas Soares *et al.*, 2018) due to their amazing abilities to capture nematodes and reduce the population size of plant-parasitic nematodes (Zhang *et al.*, 2020).

Control by antagonistic bacteria

Most bacteria interfere with nematode behavior, feeding, or reproduction through producing antibiotics, enzymes, or toxins. Several findings were found that many products such as volatile fatty acid and nitrogenous substances are produced by bacteria during the decomposition of organic materials that might influence nematode populations (Lee *et al.*, 2014; Cho *et al.*, 2015). Xiang *et al.* (2018) reported that fifteen species of *Bacillus* have been identified for *M. incognita* management. Several bacteria species such as *Pseudomonas fluorescens, Paecillomyces lilacinus, Pichia guilliermondii, Aztobacter* spp. etc., are antagonistic bacteria. Anwar-ul-Haq *et al.* (2011) reported that *P. fluorescens* had the most significant positive effect on controlling root-knot nematode on tomato crops. On the other hand, *Azotobacter* spp. was least effective in terms of *M. incognita* on tomato crops. Application of *P. fluorescens* had no negative impact on root and shoot length of tomato as well as plant growth and yield of tomato. *Pseudomonas* spp. had antagonistic activity against plant pathogens (Weller *et al.*, 2002). *Bacillus firmus* also provided better results against root-knot nematode *M. incognita*. It is available as a trade product in some countries (Terefe *et al.*, 2009). They also reported that the application of different doses of *Bacillus firmus* had a different effect on gall formation and phytotoxicity.

Chinheya *et al.* (2017) collected 70 *Bacillus* isolates from the root-zone of crops and a goat pasture and found that five out of 70 isolates, caused mortality at second-stage juvenile greater than 50% under *in vitro* conditions after 24 h. While three isolates (BC27, BC29, and BC31) which were isolated from the root-zone of a goat pasture, caused mortality at second-stage juvenile greater than 80% at 10^8 spores mL^{-1} at the same condition and same time, while, isolate BC27 caused 100% mortality at second-stage juvenile after 3 h. Seeds of soybean treated with isolates BC27 and BC29 caused a reduction in root-knot galling and egg mass as compared with the control treatment. Similarly, Zhou *et al.* (2016) also isolated 19 bacterial strains from the rhizosphere soils and plant tissues in Yunnan province of China to find out the strains that are suitable to use as a bio-controlling agent against root-knot nematode of tomato *Meloidogyne incognita*. Among the isolated strains, *Bacillus methylotrophicus* strain R2–2 and *Lysobacter antibioticus* strain 13–6 showed the maximum antagonistic action against the root-knot nematode of tomato *Meloidogyne* *incognita* in both conditions of laboratory plate and greenhouse pot experiments. *B. methylotrophicus*, *L. antibioticus,* and *B. methylotrophicus* are used as a biocontrol agent for the first time against a plant-parasitic nematode for suppressing disease caused by root-knot nematodes *Meloidogyne incognita*.

The culture filtrates of some endophytic *Bacillus* sp., *Methylobacterium* sp., and *Pseudomonas* sp. isolates significantly reduced the number of adult females, egg masses, eggs/egg mass, and soil and root population of *M. incognita* (Vetrivelkalai, 2019). Mahgoob *et al.* (2010) reported that application of three combined bacterial strains *Paenibacillus polymyxa* UBF 15, *Bacillus megaterium* UBF 10, and *B. circulance* UBF 20 significantly suppressed the numbers of galls/root, egg masses/root, hatched juveniles/root, and females/root by 70, 74.2, 66.6 and 70.3%, respectively. This finding was supported by Anastasiadis *et al.* (2008). They also found that application of *Paecilomyces lilacinus* and *Bacillus firms* either singly or together had a positive effect to control of root-knot nematode. This might be due to the production of toxins from plant growth-promoting bacteria (Siddiqui and Mahmood, 1999). Moslehi *et al.* (2021) reported that endophytic bacteria like, *Bacillus wiedmannii*, *Pseudoxanthomonas mexicana*, *Pseudomonas thivervalensis, Serratia liquefaciens, Pseudomonas chlororaphis,* and *P. fluorescens* were good candidates for the management of root-knot nematodes.

Biocontrol organisms have shown varied results. Application of *Pseudomonas fluorescens*, *P. lilacinus*, and *P. guilliermondi* significantly reduced nematode on tomato crops (Hashem and Abo-Elyousr, 2011). Among all the biocontrol organisms, *Pseudomonas fluorescens* showed the highest positive impact to reduce the number of second-stage juvenile nematodes by 45%. This might be due to the production of growth-promoting substances such as auxins and gibberellins by *P. fluorescens* (Ramamoorthy and Samiyappan, 2001). This *P. fluorescens* also enhanced the plant growth which has a positive effect on tomato crops (Hashem and Abo-Elyousr, 2011). Radwan *et al.* (2012b) tested different biocontrol organisms such as *Bacillus megaterium, Trichoderma album, Trichoderma harzianum, and Ascophyllum nodosum* to control nematode on tomato crops. Among the organisms, the application of *Bacillus megaterium* at 10 g kg^{-1} soil had a significant positive effect to reduce the number of roots galling (89.20%) on tomato crops.

CONCLUSIONS

This review covers the findings of eco-friendly management techniques including organic manure, plant products, organic wastes, and biological control methods. Most of the techniques were involved in controlling nematode infestations as well as improve the soil status. In the future, two directions for controlling root-knot nematode can be considered. Firstly, by improving the current conception of controlling nematode through new nematicidal products, preferably from the natural origin such as plant extracts biological control, etc. Secondly by organic soil amendments can enhance the soil microbial populations as well as reduce the root-knot nematodes. The majority of studies have focused on the different types of organic amendments as controlling of root-knot nematode due to their large host range. Different soil amendments have nematicidal activity because they can release toxic compounds such as organic acid, phenolic compounds, ammonia, etc., which act to control root-knot nematode. The application of oilseed cakes, such as neem reduced the nematode populations. Organic wastes such as coffee husk and oil palm debris also effectively reduced the nematode population. Applications of poultry manure, animal manure also created toxic compounds which significantly controlled the nematode population and would be an additional benefit for soil fertility management. In the future, improving the design of cropping systems that maintain the nematode population under a threshold level should be considered as well as the mineral fertilizer which may be toxic to the nematode. For commercial agriculture, production economics also should be considered because of the uprising price of pesticides (nematicides) and synthetic fertilizers. In addition, it is also harmful to beneficial organisms as well as the environment. For this reason, the use of organic amendments, nematophagous fungi, and antagonistic bacteria is a beneficial tool for effective control of root-knot nematodes throughout the whole vegetation period. More research is needed to identify the locally effective available amendments and to estimate the impact of biological control of nematode as well as environmental preservation.

ACKNOWLEDGEMENTS

This is an academic course work "Host parasite interaction" of the first author (M.M.R. Sarker) during his MSc in Organic Agriculture, the Farming Systems Ecology (FSE) Group of Wageningen University, The Netherlands. Therefore, financial support for the study was provided by the first author's fellowship.

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