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ROOT-KNOT NEMATODE MANAGEMENT IN VEGETABLE CROPS: A REVIEW

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ABSTRACT

In order to preserve the quantity and quality of food and fibre supplied by growers worldwide, plant parasitic nematodes must be controlled. It is impossible to completely eradicate nematodes; instead, the objective is to control their population and bring their numbers down below which is harmful. Planting resistant crop types, alternating crops, fallowing the land, flooding, plugging, rouging, adding soil nutrients, nematode-suppressive plants, biocontrol techniques and using insecticides and soil solarization are examples of conventional management techniques. This publication reviews and discusses management approaches related to nematode control.

Key words : Root-knot Nematode, Vegetables crops, Integrated Pest Management, Phyto-Parasitic organism.

Introduction

Phyto-parasitic nematodes are serious limitations worldwide, causing significant agricultural damage. Nematodes are soft-bodied creatures also known as round worms, eel worms or thread worms. The Greek word "Nema," which means "thread," is the source of the word "Nematode." It belongs to the extraordinarily diverse and common phylum "Nematoda". These organisms can be spotted in freshwater, saltwater and terrestrial habitats. They are both free-living and parasitic on both plants and animals, including mankind. Plant parasitic nematodes are minute, ranging in size from 0.5 to 2.0 mm and typically attack the root system, stems, foliage and flower of plants. They have all the organs found in higher organisms but lack the respiratory and circulatory systems. The root knot infection was initially described by Berkeley (1855) in cucumbers cultivated in glasshouses in England, and he called this worm "vibrios". Barber (1901) identified the root knot nematode for the first time from a tea plantation in Kerala, and this is thought to be the first instance of a plant parasitic nematode being recorded from India. Later, Ayyar (1926) and numerous others documented root knot nematode infestation on a variety of vegetables. Almost all of the important crops, including vegetables, fruits, flower plants, pulses, cereals, plantation crops, cash crops and even weeds are susceptible of being attacked by root knot nematodes. Even though there are over 90 different Meloidogyne species, only four of them, *Meloidogyne arenaria* (Neal) Chitwood, *Meloidogyne javanica* (Treub) Chitwood and *Meloidogyne incognita* (Kofoid and White) *Chitwood* which are thermophilspecies and *Meloidogyne hapla* Chitwood, which is a cryophil species are of particular economic significance to the production of vegetables since they have widespread distribution and widest host range (Moens *et al*., 2009). For vegetables, an average yield loss of 10% is typically mentioned (Barker and Koenning, 1998, Koenning *et al*., 1999, Regnault-Roger *et al*., 2002). Yield losses of more than 30% were documented in three highly vulnerable vegetable crops such as egg plant, tomato and melon (Sikora and Fernandez, 2005). The objective of this review is to evaluate alternative cropping strategies and pinpoint strategies and combos of strategies that work well for sustainable agricultural systems.

Ecological influence on existence

Nematode behaviour in the soil environment is substantially controlled by biotic and abiotic variables. However, other factors like antagonistic flora and fauna, the physical and chemical constitution of soil affect the nematode behaviour and their impact on host plant. Soil and temperature are the primary determinants in the soil ecosystem which are discussed as follows:

Temperature : Three well-known species of the root knot nematode *i.e.*, *M. incognita*, *M. arenaria* and *M. javanica*, often require a greater temperature for reproduction and long-term survival than *M. hapla*. In order to thrive and develop, former species need a temperature of 25–30°C. However, *M. hapla* is the most common species of root knot nematode in temperate and sub-temperate zones where the temperature is between 0°C and 15°C or higher (Hunt and Handoo, 2009). Maximum populations of nematodes and extensive damage to vegetable crops are typically seen in India's northern plains in the months of September- October and March- April. The life cycle can last for up to 28 to 30 days at its ideal temperature, but it can last for up to 50 days during the winter.

Soil : Root knot nematodes are more prevalent in sandy and sandy loam soils which contain 50% or more sand. When the particle diameter to juvenile length ratio is 1:3 then infectious juvenile movement and root penetration gets easier. Although root knot nematodes live in a wide range of soils, clayey soils are less vulnerable to their damage. Regarding vertical distribution, pathogenic juveniles tend to be more prevalent up to a 20 cm layer of soil at field level.

Mechanism of infestation

The majority of PPN species possess a needle-like protruding oral structure known as a stylet, which serves to puncture the host plant tissues. They release specific enzymes into these tissues, facilitating the partial breakdown of plant cells, which are then readily absorbed into the nematode's digestive system (Grymaszewska *et al*., 2014).

Numerous PPNs undergo a life cycle consisting of three main stages: eggs, larvae and adults. They deposit a considerable quantity of eggs, either internally within their bodies or in masses attached to their bodies. After embryogenesis within the eggs, the initial stage juveniles (J1) undergo moulting to become the second stage infective juveniles (J2). These J2 individuals hatch from the eggs and infiltrate the root tissues to initiate infection. The affected root sections exhibit abnormalities, such as the presence of root-knot nematode females in galls or the development of pathological nodes on roots, resulting from injuries inflicted by the nematode stylets or spears penetrating the root surface. Nevertheless, some juveniles can survive without hosts for several months by utilizing stored reserves, namely glycogen and glycolipids. These J2 individuals are non-feeding and must locate a suitable host and establish a feeding site before depleting their reserves. J2 individuals are particularly drawn to and penetrate the region of the root located just above the root tip, which approximately corresponds to the elongation zone (Wang *et al*., 2009).

In their natural habitat, RKN J2 probably react to various sensory cues, detecting potential hosts from afar through volatile compounds (scent) and on a more localized level, through water-soluble chemical signals (Curtis *et al*., 2009). When they locate a host, they enter through the root tips and consume epidermal cells. Second-stage juveniles employ both physical and enzymatic methods to breach the host. Using a stylet, they harm the plant cell wall and subsequently release cellulolytic and pectolytic enzymes to fully digest it. These nematode enzymes also stimulate an excessive conversion of tryptophan into indole acetic acid, causing the pericycle cells to enlarge and merge into multinucleate giant cells. Furthermore, the cortical parenchymatous tissue surrounding the giant cells experiences significant multiplication, resulting in the formation of small swellings or galls on the roots. Some of these galls merge to form larger multiple galls. The giant cells, which arise from repeated nuclear divisions in this area, serve as permanent feeding sites for the sedentary J2 stage. Here, they go through the third and fourth stage moults to ultimately develop into reproductive male and female adults (Price *et al*., 2021).

Given favourable circumstances, eggs will hatch into larvae that can complete their life cycle in a span of 5 to 8 weeks (Anderson, 2000). The temperature range of 22 to 27°C is considered ideal for PPNs to successfully complete their life cycle (Duan *et al.*, 2009).

Root-knot nematodes adopt a plant parasitic lifestyle primarily because of the high prevalence of genes within their genomes that degrade plant cell walls. Dealing with the damage inflicted by *Meloidogyne* species proves challenging due to their brief life cycle and wide range of potential hosts, as documented by De Waele & Elsen in 2007. Because of their short life spans, these organisms rapidly propagate and infect nearby crop plants in a matter of days. Root-knot nematodes also form complex plant diseases by interacting with other pathogens such as *Fusarium* wilt, *Rhizoctonia solani* and *Thielaviopsis*

Table 1: Some examples of Nematode Suppressive Plants (NSPs) used in vegetable cultivation.

Nematode species	Susceptible plants	Resistant plants
Meloidogynae javanica	Cabbage, Okra, Beans, Carrot, Potato, Egg Plant, Onion, Tomato	Sweet Potato, Coastal Bermudagrass, Pepper, Strawberry
Meloidogynae incognita	Tomato, Potato, Carrot, Cucumber, Cabbage	Sorghum, Some Millets, Strawberry, Peanut, Bahia grass, Johnsongrass
Meloidogynae hapla	Sweet Potato, Eggplants, Lima Beans, Cucumber, Lettuce, Potato, Snap Bean	Watermelon, Corn, Bahia grass, Okra, Coastal Bermudagrass, Cotton
Meloidogynae arenaria	Potato, Eggplant, Pepper, Cabbage, Carrot, Onion	Sweet Potato, Bahia grass, Sudan grass, Coastal Bermudagrass.

basicola (Manzanilla and Starr's, 2009). *Meloidogyne incognita* employs a defence mechanism similar to that of plant pathogenic bacteria, secreting calreticulin, which assists in sequestering free calcium ions and thereby restricting calcium ion influx (Jaouannet *et al.*, 2013).

Host range of Root Knot Nematode

The root-knot nematodes (*Meloidogyne* spp.) are one of the top 10 PPN taxa globally (Jones *et al.*, 2013). Previous research found that the genus *Meloidogyne* contains approximately 98 species (Jones *et al.*, 2013) with a host range of over 3000 plant species from various plant families, causing serious output losses, particularly in tropical and subtropical agriculture (Sikora and Fernandez, 2005).

Symptom of Root Knot Nematode Infestation

The most common and distinctive sign of *Meloidogyne* infection is the development of galls in the structures of the roots.The species present, the overall number of nematodes in the tissues, the host plant, and the plant's age all influence the size and appearance of the galls. The symptoms of *M. hapla* on vegetables are distinct from those of the majority of other species in that they only result in small, approximately spherical galls with abundant root branching coming from the galled tissue, creating a "bearded root" system. When there is a serious infestation, the normal root system is reduced to a few numbers of heavily galled roots and a completely disorganized vascular system. In essence, rootlets do not exist. The essential functions of the roots such as transport and absorb water and nutrients are severely hampered. Broad-leaved plants undergo slower plant growth and may have chlorotic leaves (Mitkowsk *et al.*, 2003; Anwar *et al.*, 2007). Galls induced by nematode is far different from rhizobium nodules. Bacterial nodules are side appendages like structure and spongy in nature but nematode induced galls are hard and cause swelling in roots and cannot be easily detachable from roots (Costa *et al.*, 2020).

Management of root knot nematode in vegetable crops

A. Physical/cultural control

1) **Sanitation :** Sanitation is essential for avoiding primary infections (introduction into a manufacturing site) and avoiding secondary infections (spreading within the manufacturing site). Activities performed by humans, such as the conveyance of diseased plant material, soil, plant waste, and irrigation water, can serve as transmission networks within infected and uncontaminated regions and facilitate the spread of infection *Meloidogyne* spp. (Collange *et al.*, 2011). Hugo and Malan (2010) evaluated numerous cases of nematode dispersion in particularly *Meloidogyne* spp.through irrigation water and highlighted the difficulty in regulating the problem. Cleaning all of the farming equipment and implements at the farm levels might help to avoid carrying nematode with the soil. The water from irrigation systems can also be a nematodes transmission origin or a method of disseminating it inside the field.

2) **Soil solarization :** It is possible to utilize solarization to temporarily lower nematode numbers in the top 12 inches of soil, enabling the growth of shallow-rooted yearly crops and assisting new woody plants in establishing themselves before worm populations rise. Moisten the land and then wrap it with a transparent plastic sheet [100-gauge Linear Low-Density Polyethylene (LLDPE)] for efficient solarization. During the warmest period of the summer, keep the covering affixed for 4 to 6 weeks. When soil temperatures are higher than 125°F for a period of thirty minutes or 130°F for five minutes, the root knot nematodes and their eggs perish. In colder coastal regions, during summer, temperatures frequently stay below 80°F, solarization is less successful. When used in conjunction with thermal treatment, solarization repeated over a period of two or more years may be more effective against root-

knot nematodes (*Meloidogyne* spp.) or heat-resistant weed species (Rubin and Benjamin, 1983; Stapleton and DeVay, 1995). Candido *et al.*, (2008) reported that the *M. javanica* nematode infestation in tomato was entirely controlled by two- and three-year solarization treatments and the nematode effect in melon and tomato was decreased by 86% and 79%, respectivelyin green house. Oka *et al*, (2007) found that nematode densities in the soil and plant galling indices for tomato and pepper plants were both decreased by soil solarization alone. Root-knot nematode management in organic farms may be achieved by combining soil solarization with organic inputs.

3) **Crop Rotation and Fallowing :** Crop rotation entails cultivating a crop, which is not an ideal host of the nematode in concern before planting a crop that is vulnerable. The resistant or non-host crop will lead to a decrease in nematode populations in the soil, allowing the succeeding host crop to develop a strong root system. Since, several nematodes, including root-knot, reniform and burrowing nematodes, have extremely broad host ranges, caution must be adopted while choosing the rotation crop. Crop rotation can be effectively utilized with fallowing and green manuring processes. Fallowing is the process of temporarily leaving the land barren. Root knot nematode populations can be successfully reduced by fallowing for one year with the objective to effectively grow a sensitive annual crop. Even more nematode populations will be reduced by two years of fallow land. Kratochvil *et al*. (2004) the management strategy that produced the best RKN suppression when regularly rotated with the sensitive host crops was sorghum Sudan grass.

4) **Intercropping :** Nematode populations are also decreased by intercropping of crops with plants that are either poor nematode hosts or hostile to the nematodes. Farmers observe lower arthropod and nematode pest occurrence on sunhemp (*Crotalaria juncea*) and spider plant (*Cleome gynandra*) compared to exotic ones. According to the observation above, these vegetables have natural pest-repelling and hostile qualities. These plants also keep non-edible weeds in check in fertile soils (Wang *et al.*, 2003).

5) **Nematode Suppressive Plants :** Farmers and gardeners frequently use chemical nematicides to control nematode infestations. On the other hand, they might be harmful to both the environment and people's health. Nematode suppressive plants (NSPs) provide a sustainable alternative for controlling nematode populations. Trap crops or biofumigant crops, commonly referred to as nematode suppressive plants have certain properties that aid in nematode population reduction or limit the damage that nematodes can cause to vulnerable plants. These plants have a variety of functions that can interfere with nematode reproduction, disrupt nematode life cycles, or prevent nematodes from attacking plant roots. A few plants, which also serve as trap crops, stop nematodes from developing or creating offspring after they penetrate the roots. Additionally, some of these plants' roots could not be a viable source of food for nematodes, which would starve them out and reduce their population. Some NSPs have developed specialised structures or systems to trap and eliminate nematodes. These plants have altered roots or other underground parts that are capable of entangling, ensnaring, or digesting nematodes. Venus flytraps (*Dionaea muscipula*) and bladderworts (*Utricularia* spp.) are examples of nematode-trapping plants.

B. Chemical Control

1) **Soil amendments :** High nematicidal activity and even the avoidance of phytotoxicity on crops were very acceptable characteristics of organic amendments with C: N ratios between 12 and 20. Neem (leaf, seeds kernel, seed powdered substances, seed extracts, oil, saw dust and oilcake) is a plant product that has been widely utilized to combat root knot nematodes as well as other significant plant parasitic nematodes. For example, Neem releases chemical substances like Salanin, Azadirachtin, Nimbin, Thionemone and other flavonoids that have nematocidal effects. The use of compost made from garden waste produced inconsistent results; McSorley and Gallaher (1995) reported no change in nematode density, while Chellemi (2006) reported a considerable inhibitory impact. Most people agree that oilcakes are effective for managing nematodes. In their multiple experiments, Akhtar and Malik (2000) discovered that neem (*A. indica*) oil cake can be particularly effective—even at low dosages—against root-knot nematodes.

2) **Application of Nanoparticles :** According to Narayanan and Park (2014), there is growing interest in the manufacturing of metal nanoparticles using environmentally friendly techniques and their use in biological fields. *In vitro* and *in vivo* studies on tomato

Table 2 : List of different host range of root-knot nematode.

Species	Hosts	References
	A. Vegetable crops	
M. incognita, *M. mayaguensis*	Cabbage, Okra	Abu-Gharbieh (1982b) Rodriguez *et al.* (2003)
M. javanica *M. incognita* *M. mayaguensis*	Common bean	Karajeh and Al-Ameiri (2010) Karajeh (2004) Abu-Gharbieh (1982b)
M. javanica	Cowpea	Abu-Gharbieh (1982b)
M. incognita, M. javanica *M. mayaguensis*	Eggplant	Abu-Gharbieh (1982b) Rodriguez *et al.* (2003)
M. incognita *M. mayaguensis*	Garlic	Abu-Gharbieh (1982b) Rodriguez *et al.* (2003)
M. javanica	Faba bean	Abu-Gharbieh (1987)
M. incognita, M.mayaguensis	Pepper	Abu-Gharbieh (1982b)
M. incognita *M. javanica*	Squash	Yousef and Jacob (1994) Karajeh (2004)
M. javanica	Peas	Karajeh (2004)
M. arenaria race 2 *M. incognita race 1* *M. javanica*	Tomato	Karajeh (2004) Karajeh (2004) Mamluk *et al.* (1984)
M. javanica	Watermelon	Abu-Gharbieh (1982b)
	B. Fruit Crops	
M. javanica	Cavendish Banana, Peach	Yousef and Jacob (1994)
M. incognita race 1	Date palm	Rubeya (1999)
M. incognita race 1	Grapevine	Karajeh, (2004)
M. incognita	Pomegranate	Hashim (1983a)
M. javanica, *M. mayaguensis*	Guava	Yousef and Jacob (1994) Rodriguez *et al.* (2003)
M. javanica	White mulberry	Karajeh (2004)
M. incognita, M. javanica	Olive	Hashim (1979)
	C. Plantation crops	
M. incognita	Blackpepper	Ravindra *et al.* (2014)
M. mayaguensis	Coffee, Tobacco	Rodriguez *et al.* (2003)
M. incognita, M. javanica	Cardamom	Eapen (1992)

have demonstrated the toxicity of three different types of nanoparticles, including silicon oxide, silver and titanium oxide, to *M. incognita* (Ardakani, 2013). In addition, lipid, glycogen and mucopolysaccharides are all impacted by ZnO NPs, which have an opposite effect on nematodes' cuticle and hypodermis (Siddiqui *et al.*, 2018). The management of root-knot nematodes may also be improved by using gold nanoparticles (Thakur *et al.*, 2018; Hu *et al.*, 2018).

3) **Application of Nematicides :** Chemical control employs various combinations of inorganic compounds to either eliminate or hinder the growth of RKN. Nematicides containing active chemicals such as methyl bromide, whose usage has been outlawed in some countries due to its impact on non-target creatures (UNEP, 2006). Nematicidal treatments prevent nematode development and egg

hatching by preventing nematode penetration into the host as well as by having nematicidal effects on worms themselves. According to Jones *et al*. (2017), fluensulfone and fluopyram have significant potential for controlling root knot nematode in lima beans. Fluensulfone is provided as a contact nematicide and is labelled for applications on the cucumber, melon, pumpkin, tomato, ladyfinger, brinjal and pepper (Kearn *et al*., 2014; Oka *et al*., 2009).

C. Biological control

In order to decrease nematode density, the primary goal of biological management is to enhance the natural predators of nematode in the soil. The first line of defence for root towards pathogen attack is provided by microorganisms that can proliferate in the rhizosphere, making them perfect for use as biological controls (Weller, 2001). Endophytic fungus such as *Trichoderma* spp. are widely known for secreting huge amounts of poisonous compounds, such as gliotoxins, that possess antifungal properties. They survive inside plant tissue without spreading disease. In addition to their competition for resources and space, Trichoderma spp.'s antagonistic activity is linked to direct mycoparasitism (Sharon *et al*., 2001; Afzal *et al*., 2013). As a result, *Trichoderma* spp., which are mycoparasites, have been regarded as effective biological control agents for foliar and soil-borne diseases as well as numerous kinds of plant-parasitic nematode (Kowsari *et al*., 2014). *Trichoderma* species like *T. harzianum*, *T. asperelloides* and *T. hamatum* can be developed for use as potent biocontrol agents because they have demonstrated nematocidal capability over root-knot nematode species (Sharon *et al*., 2001; Sayed *et al*., 2019). *Trichoderma* spp. is being tested more and more for their ability to combat root-knot nematodes on a variety of crops, including okra, tomatoes, mung beans, cucumber, capsicum, and sugar beets (Meyer *et al*., 2001).

D. Nematode resistant varieties and rootstocks

Using vegetable cultivars with nematode-resistant rootstocks is one of the greatest strategies to manage nematodes. The development of nematode-resistant plant cultivars is important because they offer a powerful and environmentally friendly alternative to chemical nematicides. Sujatha *et al*. (2017) reported that Hisar Lalit, HN 2, PNR 7, IIHR 2614 and IIHR 2868 are resistant varieties of tomato. Akhter *et al.* (2018) reported that Mahy 80, Das *et al*. (2022) reported that Noagramand Nayak (2015) Pusa Kranti, Kantabaingan are some of the resistant varieties of brinjal. Ravishankar (2007) concluded that Surajmukhi, Pant chilli-4 are some of the resistant varieties of chilli.

Conclusion

The consequences on alternative prevention approaches, such as soil management, fertilisation, biological control, sanitation, fertiliser and heat-based strategies are reviewed in this paper along with the conclusions and debates surrounding them. The majority of these alternate methods have an adverse effect on other soil functions and only partially reduce nematode infestations. Firstly, enhancing the existing understanding of pests control, which depends on outside assistance to regulate the number of pests. This approach relies on the discovery of novel nematodes, ideally derived from natural sources or sources of inspiration (crop isolates; biological management). The second approach, which entails creating farming methods with intrinsic qualities that keep the parasitic nematode abundance under an acceptable level of tolerable damage, is likely more promising despite being more involved.

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