IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Root-Knot Nematodes (*Meloidogyne spp.*): Biology, Plant-Nematode Interactions, and Eco-Friendly Management Strategies

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Abstract

Root-knot nematodes (*Meloidogyne spp.*) are among the most destructive plant-parasitic nematodes, causing significant economic losses in global agriculture. These obligatory parasites attack a wide range of crops, leading to the formation of characteristic galls or root-knots that disrupt nutrient and water uptake. This article reviews the biology of root-knot nematodes, their interaction with host plants, and eco-friendly management strategies that align with sustainable agriculture practices. Emphasis is placed on biological control, resistant crop varieties, and integrated nematode management approaches.

Keywords: *Meloidogyne*, destructive, disrupt, sustainable agriculture.

1. Introduction

Root-knot nematodes (*Meloidogyne spp.*) are globally distributed soil-dwelling pests with a wide host range, including vegetables, cereals, and horticultural crops. RKNs are distributed globally, infecting more than 2,000 plant species and reducing global crop yields by about 5%, mainly through root-knot gall formation and nutritional deprivation (Sasser, 1977).One of the three plant-parasitic nematode genera with the greatest economic impact on field and horticulture crops are Meloidogyne spp. (Sasser & Freckman, 1987). The impact of these nematodes is exacerbated by their adaptability to diverse environmental conditions and their ability to establish in protected cultivation systems such as greenhouses. Effective management of root-knot nematodes is critical for maintaining agricultural productivity and environmental sustainability.

2. Biology of Root-Knot Nematodes

Root-knot nematodes have a complex life cycle comprising six stages: egg, four juvenile stages (J1 to J4), and adult. The infective stage, second-stage juvenile (J2), emerges from the egg and migrates toward host roots. Upon penetrating the root tissue, J2 initiates the formation of feeding sites, known as giant cells, by inducing cellular hypertrophy and hyperplasia. J2's, are attracted by plant roots (Curtis *et al.*, 2009), to reach the vascular cylinder of the host plant by piercing through growing tip and moving through intercellular spaces (Caillaud *et al.*, 2008). These giant cells serve as nutrient sinks, supporting the nematode's development into sedentary adult females, which produce eggs within gelatinous matrices on or inside the roots.Key species, such as *Meloidogyne incognita*, *M. javanica*, and *M. arenaria*, are responsible for substantial yield losses worldwide.Meloidogyne incognita, M. hapla, M. javanica and M. arenariaare the four commonly found species which comprise up to 95 percentage of all RKN (Dong et al., 2012).

Table 1. Life stages duration in RKN (*M. incognita*) on noni (*Morindacitrifolia*).

Life stage	Duration (Days)
Second stage juvenile (J2)	1-5
Third stage juvenile (J3)	6-8
Fourth stage juvenile (J4)	9-12
Adult male	23
Adult female	27
Total life cycle	25-30

(Source: Kavitha *et al.*, 2011)

3. Plant-Nematode Interactions

The interaction between *Meloidogyne spp.* and their host plants involves a sophisticated interplay of mechanical and biochemical mechanisms.

- **Host Penetration and Migration**: Nematodes use their stylet to pierce root tissues, secreting cell wall-degrading enzymes (e.g., cellulases and pectinases) to facilitate entry and migration.Plant cell wall performance and integrity during the nematode infection is suggested to play an essential role in intense cross talk between the sensing and signalling of defective cell walls and the control of innate immune response against plant-parasitic nematodes (Wieczorek & Seifert, 2012).

- **Feeding Site Formation**: Through effector proteins delivered into plant cells, nematodes manipulate host gene expression and cellular metabolism to create giant cells.

- **Host Response**: Plants recognize nematode invasion via pattern recognition receptors (PRRs), triggering basal defenses such as reactive oxygen species (ROS) production. However, nematodes often suppress these responses through effector-mediated signaling interference.

4. Eco-Friendly Management Strategies

4.1. Cultural Practices

- . **Crop Rotation**: Alternating susceptible crops with non-host species reduces nematode populations. Cropping system helps in minimizing inoculum level of root knot nematodes (Khan et al. 2010). For example, cereals can disrupt the life cycle of root-knot nematodes in vegetable systems.

- **Soil Solarization**: Covering soil with transparent polyethylene sheets during hot months raises soil temperatures, killing nematode eggs and juveniles.

4.2. Biological Control

- **Nematophagous Fungi**: Fungi such as *Paecilomyces lilacinus* and *Pochoniachlamydosporia* parasitize nematode eggs and juveniles, reducing their populations. Francisco et al.2021

Bacterial Antagonists: Beneficial bacteria like *Bacillus subtilis* and *Pseudomonas fluorescens* enhance plant defense and inhibit nematode activity through antibiosis and induced systemic resistance (ISR).

- **Endophytic Fungi**: Fungi such as *Trichoderma spp.* establish symbiotic relationships with plants, improving plant health and nematode resistance.

4.3. Resistant Varieties

The use of resistant or tolerant cultivars is a cornerstone of nematode management. Genetic resistance in crops such as tomatoes (e.g., Mi-1 gene) and cowpeas effectively limits nematode infection and reproduction Williamson et al. (1998).

4.4. Organic Amendments

Incorporating organic materials like neem cake, mustard meal, and compost into soil promotes microbial antagonists of nematodes and enhances soil health. Moosavi et al.(2022) identified that soil amendment with organic matters is more potential for control phytonematodes.

4.5. Botanical Nematicides

Gahukar et al. 2011b used Plant-derived compounds such as azadirachtin (from neem) and saponins have shown nematicidal properties with minimal environmental impact.

4.6. Integrated Nematode Management (INM)

Combining multiple strategies, including crop rotation, resistant varieties, biological control agents, and organic amendments, provides sustainable and effective nematode management. Sikora et al. (2023).

5. Challenges and Future Directions

- **Climate Change**: Changing environmental conditions may expand the geographical range of *Meloidogyne spp.*, necessitating adaptable management approaches.
- **Biotechnology**: Advances in gene editing and RNA interference (RNAi) offer opportunities for developing nematode-resistant crops. Banerjee. et al. (2017).
- **Policy Support**: Promoting eco-friendly practices requires policy-level incentives and farmer training programs to ensure widespread adoption.

6. Conclusion

Root-knot nematodes are a persistent challenge to agriculture, but eco-friendly management strategies offer sustainable solutions. By leveraging biological control, resistant cultivars, and integrated approaches, it is possible to mitigate the impact of these pests while preserving environmental health. Continued research into plant-nematode interactions and innovative control methods is crucial for enhancing global food security.

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