Citrus Plant Nematodes: Diversity, Impact, And Management Strategies: A Review

Pooja A. Katare
Dr. Babasaheb Ambedkar Marathwada University,
Chhatrapati Sambhajinagar

Abstract- *Citrus cultivation is a vital component of global horticulture, yet it faces persistent threats from plant-parasitic nematodes (PPNs) that compromise root health, reduce yield, and affect fruit quality. This review explores the diversity of nematodes associated with citrus crops, including key genera such as Tylenchulus, Meloidogyne, and Pratylenchus, and highlights their pathogenic impact on plant growth and orchard productivity. The mechanisms of nematode-citrus interaction, including life cycles, infection behavior, and interactions with soil microbiota, are discussed to provide a foundational understanding of nematode ecology. Furthermore, the review presents current diagnostic approaches, from traditional soil and root analysis to advanced molecular techniques. A comprehensive overview of management strategies is provided, covering cultural practices, chemical and biological controls, host resistance, and integrated nematode management (INM). The paper concludes by addressing key challenges and future perspectives, emphasizing the need for farmer education, sustainable control methods, technological innovation, and supportive policy frameworks. Together, these insights contribute to the development of holistic and environmentally sound strategies for effective nematode management in citrus production systems.*

Keywords- Citrus nematodes; plant-parasitic nematodes; Tylenchulus semipenetrans; root damage; nematode management; biological control; molecular diagnostics; resistant rootstocks; integrated nematode management (INM); sustainable agriculture

I. INTRODUCTION

Citrus is one of the most economically significant fruit crops cultivated globally, with major production hubs in tropical and subtropical regions. However, citrus production is increasingly threatened by a variety of biotic stressors, among which plant-parasitic nematodes represent a significant but often overlooked component. These microscopic roundworms can inflict severe damage on citrus roots, leading to reduced vigor, nutrient uptake, and ultimately, yield losses (Duncan, 2009). The root-knot nematodes (*Meloidogyne* spp.), citrus nematode (*Tylenchulussemipenetrans*), and lesion nematodes (*Pratylenchus* spp.) are among the most prominent groups affecting citrus orchards worldwide (Verdejo-Lucas & McKenry, 2004).

The diversity of nematode species associated with citrus varies by region and is influenced by soil type, climatic conditions, and agricultural practices (Noling, 2019). Their impact can range from subtle, long-term yield declines to severe stunting and tree mortality under heavy infestations. In many cases, symptoms are non-specific, making diagnosis and management more difficult. Moreover, nematodes often act synergistically with other pathogens, such as fungi and bacteria, compounding the damage and complicating control measures (Sharma & Sharma, 2015).

Given the challenges associated with chemical nematicides, such as environmental concerns and regulatory restrictions, integrated pest management (IPM) strategies are increasingly emphasized. These include biological control agents, resistant rootstocks, organic amendments, and cultural practices aimed at reducing nematode populations and improving plant health (Timper, 2011).

II. DIVERSITY OF NEMATODES IN CITRUS

Citrus crops are host to a wide array of plant-parasitic nematodes (PPNs), with their diversity influenced by regional environmental conditions, soil types, and management practices. Among the nematodes associated with citrus, the most commonly reported and economically significant species belong to the genera *Tylenchulus*, *Meloidogyne*, *Pratylenchus*, *Radopholus*, and *Hemicriconemoides* (Verdejo-Lucas & McKenry, 2004; Noling, 2019).

The citrus nematode, *Tylenchulussemipenetrans*, is considered the most prevalent species globally, often forming chronic infestations that result in slow decline of citrus trees. It is semi-endoparasitic, with females partially embedded in root tissue, and is particularly difficult to eradicate once established (Verdejo-Lucas & McKenry, 2004). This species exists in several biotypes, with varying host ranges and adaptability to rootstocks, making its management complex (Duncan, 2009).
Root-knot nematodes (*Meloidogyne* spp.), particularly *M. incognita*, *M. javanica*, and *M. arenaria*, are also widely reported in citrus orchards. They induce gall formation on

roots, impairing water and nutrient uptake. While more common in sandy soils and warm climates, their distribution is expanding due to changing agricultural practices and climate conditions (Cohn & Duncan, 2014).

Lesion nematodes (*Pratylenchus* spp.), such as *P. coffeae* and *P. penetrans*, are migratory endoparasites that cause necrotic lesions on citrus roots. These lesions can act as entry points for secondary pathogens, exacerbating plant stress and yield loss (Sharma & Sharma, 2015). In some tropical regions, burrowing nematodes (*Radopholussimilis*) also pose a threat, particularly in intercropping systems involving banana or ginger (Bridge et al., 2005).

The diversity of nematode fauna is often underestimated due to limitations in traditional diagnostic methods. Advances in molecular diagnostics and soil metagenomics have begun to reveal greater species richness and cryptic diversity in citrus rhizospheres, suggesting the need for more refined surveillance and classification efforts (Jones et al., 2013).

Understanding the diversity of nematodes associated with citrus is crucial for designing targeted and sustainable management programs, especially as many of these nematodes co-occur and interact in complex ways that influence disease dynamics and crop performance.

III. IMPACT ON CITRUS CROPS

Nematodes inflict considerable damage on citrus crops primarily through their parasitic activity on the root systems. The citrus nematode (*Tylenchulussemipenetrans*), for example, feeds on cortical tissues of feeder roots, leading to significant structural damage, reduced root mass, and impaired nutrient and water uptake (Verdejo-Lucas & McKenry, 2004). Similar effects are caused by *Meloidogyne* spp., which induce root galls and disrupt vascular function, further limiting nutrient translocation (Duncan, 2009).

Affected citrus trees commonly exhibit above-ground symptoms such as chlorosis, stunted growth, leaf drop, and poor canopy development. In severe cases, premature fruit drop and poor fruit set are also observed, contributing to substantial yield losses (Cohn & Duncan, 2014). Because the symptoms of nematode infestation often resemble those caused by nutrient deficiencies or other root-related disorders, the damage is frequently underdiagnosed or misattributed (Sharma & Sharma, 2015).

Over time, chronic nematode infestations reduce tree vigor and lifespan, particularly in mature orchards. This decline affects both the quantity and quality of fruit production, diminishing juice content, fruit size, and overall marketability (Noling, 2019). The long-term economic consequences are considerable, as growers face lower yields, increased replanting costs, and greater dependency on soil treatments and inputs to maintain productivity.

In regions where nematode pressure is high, economic losses can be particularly severe. It is estimated that global annual losses due to plant-parasitic nematodes exceed $100 billion, with citrus accounting for a notable share of this figure (Jones et al., 2013). These losses are compounded by the increasing limitations on chemical nematicides and the need for sustainable, long-term management solutions.

IV. NEMATODE-CITRUS INTERACTION

The interaction between plant-parasitic nematodes and citrus plants is complex, involving several stages of host invasion, feeding, and long-term effects on plant physiology and soil ecology. Understanding the biology of these interactions is critical for effective management.

4.1 Life Cycle of Nematodes in Citrus Roots

Nematodes such as *Tylenchulussemipenetrans* and *Meloidogyne* spp. have well-adapted life cycles suited to parasitizing citrus roots. The life cycle of *T. semipenetrans* typically lasts 6–8 weeks and includes egg, four juvenile stages (J1–J4), and adult stages (Verdejo-Lucas & McKenry, 2004). Juveniles invade feeder roots and develop into sedentary females that embed their anterior into the root cortex while leaving the posterior outside to lay eggs.

Root-knot nematodes (*Meloidogyne* spp.) follow a similar pattern: second-stage juveniles (J2), the infective stage, penetrate the root tips, migrate intercellularly, and establish feeding sites by inducing giant cells in the vascular tissue (Duncan, 2009). The development of these specialized cells facilitates continuous nutrient extraction from the host plant.

4.2 Mechanism of Infection and Feeding Behavior

Nematodes use a stylet, a needle-like feeding apparatus, to puncture root cells and secrete effectors that manipulate plant cellular functions. In the case of *Meloidogyne* spp., effectors reprogram plant gene expression to form multinucleate giant cells, which serve as nutrient sinks (Jones et al., 2013). *T. semipenetrans* feeds more superficially on cortical cells and forms nurse cells that support long-term feeding.

These interactions not only deprive plants of nutrients but also trigger localized and systemic changes in root physiology, leading to compromised growth and secondary susceptibility to other pathogens (Sharma & Sharma, 2015).

4.3 Interaction with Soil Microbiota and Other Pathogens

Nematode infestations significantly influence the structure and function of the rhizosphere microbiome. Their feeding activity alters root exudation patterns, which in turn affect microbial colonization. These changes can promote opportunistic soil pathogens, particularly fungi such as *Fusarium*, *Phytophthora*, and *Rhizoctonia* (Bridge et al., 2005).

Synergistic interactions between nematodes and soilborne fungi are well-documented. For example, root lesions caused by *Pratylenchus* spp. provide entry points for fungal pathogens, intensifying root rot and decline syndromes (Timper, 2011). Conversely, some beneficial microbes such as mycorrhizal fungi and nematode-antagonistic bacteria may suppress nematode activity and improve plant resilience.

The tripartite interaction among nematodes, citrus plants, and soil biota highlights the need for integrated management approaches that consider the entire soil-plant-pathogen ecosystem.

V. DIAGNOSIS AND DETECTION

Accurate diagnosis and detection of plant-parasitic nematodes (PPNs) in citrus orchards are essential for effective management and timely intervention. Since symptoms caused by nematodes often mimic those of nutrient deficiencies or other root pathogens, laboratory confirmation is necessary to identify the presence and species of nematodes.

5.1 Soil Sampling and Root Examination

The most common approach to nematode detection involves systematic soil and root sampling. Soil samples are typically collected from the rhizosphere, especially near feeder roots, where nematode populations are concentrated. Root examination under a dissecting microscope can reveal visible signs of nematode infestation, such as root galls (from *Meloidogyne* spp.) or necrotic lesions (from *Pratylenchus* spp.) (Noling, 2019). Extraction techniques like Baermann funnels, centrifugal flotation, and sieving are used to isolate nematodes from soil and root samples for further analysis (Coyne et al., 2007).

5.2 Morphological and Molecular Identification Techniques

Traditionally, nematodes are identified based on morphological characteristics using light microscopy. Key features include the shape of the stylet, esophageal glands, tail, and reproductive structures. However, morphological identification requires expert taxonomic knowledge and is time-consuming, particularly for juvenile stages or cryptic species (Jones et al., 2013).

Molecular techniques offer a more precise and efficient method for nematode identification. Polymerase chain reaction (PCR)-based assays targeting ribosomal DNA regions (e.g., ITS, D2-D3 of 28S rDNA) have become widely used for distinguishing closely related nematode species (Powers et al., 2011).

5.3 Use of DNA-Based Tools for Accurate Nematode Detection

Recent advancements in DNA-based diagnostic tools have revolutionized nematology. Techniques such as quantitative PCR (qPCR), loop-mediated isothermal amplification (LAMP), and high-throughput sequencing (HTS) allow for rapid, sensitive, and species-specific detection of nematodes in complex soil samples (Subbotin et al., 2021). These tools enable early detection even before symptoms become visible, enhancing the chances of timely intervention.
Furthermore, DNA barcoding and metagenomic approaches are increasingly being employed to profile nematode communities in citrus soils, uncovering cryptic diversity and aiding in risk assessment for new or emerging threats (Jones et al., 2013).

VI. MANAGEMENT STRATEGIES

Managing nematode infestations in citrus requires a multifaceted approach due to the complexity of nematode-host-environment interactions. Effective control involves integrating cultural, chemical, biological, and genetic strategies, tailored to specific orchard conditions.

6.1 Cultural Practices

Cultural methods play a foundational role in nematode suppression by modifying the environment to reduce nematode populations and prevent their spread.

- **Crop Rotation with Non-host Plants:** While citrus is a perennial crop, intercropping and rotational strategies during replanting phases with non-host crops such as grasses or marigold (*Tagetes* spp.) can significantly reduce nematode populations in soil (Noling, 2019).

- **Use of Nematode-Free Planting Material:** Certified nematode-free seedlings and rootstocks prevent the introduction of nematodes into new orchards. Sanitation practices during propagation and transplantation are crucial (Verdejo-Lucas & McKenry, 2004).
- **Organic Amendments and Green Manuring:** Incorporating organic materials such as compost, neem cake, and green manures enhances soil health and fosters antagonistic microbial communities that suppress nematode activity (Akhtar & Malik, 2000).

6.2 Chemical Control

- **Application of Nematicides:** Synthetic nematicides like fenamiphos, oxamyl, and fosthiazate have shown efficacy against *Tylenchulussemipenetrans* and *Meloidogyne* spp. (Duncan, 2009). These compounds reduce nematode populations and improve root health.
- **Limitations:** Chemical nematicides face growing restrictions due to environmental contamination, human health concerns, and the potential development of nematode resistance. Moreover, they are often cost-prohibitive for small-scale farmers and require careful application (Jones et al., 2013).

6.3 Biological Control

Biological control harnesses natural enemies of nematodes to reduce their populations sustainably.

- **Nematophagous Fungi:** Species such as *Paecilomyces lilacinus* (now *Purpureocilliumlilacinum*) parasitize nematode eggs and juveniles, disrupting their life cycle (Kiewnick& Sikora, 2006).
- **Nematode-Trapping Fungi and Predatory Nematodes:** Fungi like *Arthrobotrys* spp. form specialized traps to capture and kill nematodes. Predatory nematodes such as *Mononchus* spp. also contribute to natural nematode suppression (Timper, 2011).
- **Role of Biofertilizers and Beneficial Microbes:** Rhizobacteria like *Pseudomonas fluorescens* and *Bacillus subtilis* produce nematicidal compounds and promote plant defense mechanisms, contributing to integrated biological suppression (Hallmann et al., 2009).

6.4 Host Resistance

- **Development and Use of Resistant Rootstocks:** Resistant or tolerant citrus rootstocks, such as *Poncirus trifoliata* hybrids, have been developed to limit nematode feeding and reproduction. These are particularly effective against *T. semipenetrans* (Verdejo-Lucas & McKenry, 2004).
- **Breeding Programs and Genetic Engineering Efforts:** Conventional breeding is complemented by molecular techniques to develop nematode-resistant varieties. Genetic engineering and CRISPR-based gene editing hold future promise in introducing durable resistance traits (Ali et al., 2020).

6.5 Integrated Nematode Management (INM)

- **Combining Cultural, Chemical, and Biological Methods:** INM emphasizes the synergistic use of diverse control strategies for sustainable nematode suppression. For example, combining resistant rootstocks, organic amendments, and biocontrol agents can effectively reduce nematode populations while enhancing soil health (Stirling et al., 2011).
- **Site-Specific and Sustainable Approach:** INM considers site-specific factors such as nematode species present, soil type, crop age, and economic thresholds, ensuring that interventions are both ecologically sound and cost-effective (Noling, 2019).

VII. CHALLENGES AND FUTURE PERSPECTIVES

Despite the advancements in nematology and citrus production practices, several challenges hinder the effective management of plant-parasitic nematodes (PPNs). Addressing these challenges through innovation, policy, and education will be key to sustainable citrus cultivation.

7.1 Need for Awareness and Farmer Education

A significant challenge in managing nematodes in citrus is the limited awareness among farmers regarding the presence and impact of nematodes. Since symptoms often resemble those of nutrient deficiencies or fungal infections, nematodes are frequently misdiagnosed or overlooked (Noling, 2019). Training programs, field demonstrations, and extension services are essential to improve farmer capacity for early detection and adoption of integrated nematode management (INM) practices (Coyne et al., 2007).

7.2 Development of Eco-Friendly, Cost-Effective Management Tools

There is a pressing need for the development and dissemination of environmentally sustainable and economically viable control methods. Many current options, such as chemical nematicides, are either too costly for smallholder farmers or carry ecological and health risks. Research should focus on enhancing the efficacy of biocontrol agents, botanical extracts, and soil health–improving amendments that can be locally produced and adopted (Timper, 2011; Akhtar & Malik, 2000).

7.3 Advancements in Molecular Diagnostics and Precision Agriculture

Technological innovations such as molecular diagnostics and precision agriculture are transforming nematode detection and management. DNA-based diagnostics, including real-time PCR and next-generation sequencing, enable early, accurate identification of nematode species before symptom development (Subbotin et al., 2021). Combined with remote sensing and GIS-based mapping, these tools offer precision in nematode surveillance and targeted intervention, reducing the need for blanket treatments (Jones et al., 2013).

7.4 Policy Support for Nematode Surveillance and Research

Strong institutional and policy support is vital for nematode management to become a national agricultural priority. This includes funding for nematology research, surveillance programs, diagnostic laboratories, and capacity-building initiatives. Integrating nematode monitoring into national pest management frameworks and promoting public–private partnerships will enhance the scalability and effectiveness of control programs (Nicol et al., 2011).

VIII. CONCLUSION

Plant-parasitic nematodes pose a significant threat to citrus cultivation worldwide, with their ability to damage root systems, reduce nutrient uptake, and cause substantial economic losses. The diversity of nematode species associated with citrus, such as Tylenchulussemipenetrans, Meloidogyne spp., and Pratylenchus spp., necessitates an in-depth understanding of their biology, host interactions, and environmental dynamics.Although traditional detection and control methods have provided some relief, modern agriculture demands more precise, eco-friendly, and sustainable solutions. The integration of molecular diagnostic tools, biological control agents, resistant rootstocks, and cultural practices into an Integrated Nematode Management (INM) framework represents the most promising path forward. However, success hinges on farmer education, access to reliable diagnostics, and strong policy support for nematode research and management programs.Future efforts must focus on bridging knowledge gaps, enhancing farmer participation, and promoting interdisciplinary research. With a collaborative and innovative approach, it is possible to mitigate the nematode burden on citrus crops and ensure the long-term productivity and sustainability of citrus orchards globally.

IX. RECOMMENDATIONS

- **Enhance Farmer Awareness and Training:**Strengthen extension services to educate farmers on nematode identification, symptoms, and management strategies. Demonstrations, field schools, and local workshops should be implemented to bridge the knowledge gap.
- **Promote Use of Molecular Diagnostics:**Encourage the adoption of DNA-based diagnostic tools for early and accurate detection of nematodes. Investment in local diagnostic labs and training of personnel will support widespread and cost-effective monitoring.
- **Develop and Disseminate Eco-Friendly Management Tools:**Support research and field validation of biological control agents, organic amendments, and resistant rootstocks. These methods should be made accessible, especially to smallholder farmers, through subsidies or local production initiatives.
- **Encourage Integrated Nematode Management (INM):**Promote INM as a standard practice by integrating cultural, chemical (where appropriate), biological, and genetic strategies tailored to site-specific conditions.
- **Support Policy and Research Initiatives:**Governments and agricultural institutions should allocate funding and develop policies focused on nematode surveillance, research, and sustainable management programs. Public–private partnerships can help drive innovation and dissemination.
- **Foster International Collaboration:**Facilitate collaboration among global nematologists, research centers, and citrus-producing countries to share knowledge, data, and technologies for nematode control in citrus systems.

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