A Review On Seasonal Fluctuations Of Citrus Nematodes In Indian Agro-Ecosystems

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Abstract- *Citrus nematodes, particularly Tylenchulus semipenetrans, are major pests affecting citrus cultivation in India, leading to significant yield losses. This review examines the seasonal fluctuations of citrus nematode populations across different agroecological zones of India, highlighting the critical role of temperature, soil moisture, and root growth in shaping nematode activity. The study explores various monitoring and detection methods, including soil sampling, extraction techniques, and molecular tools, for accurate nematode population assessment. Integrated nematode management (INM) approaches, such as cultural practices, biological control, and the use of nematicides, are discussed in the context of their seasonal efficacy. Despite existing knowledge, challenges remain in the form of inconsistent data, the lack of region-specific IPM models, and limited awareness among farmers regarding nematode behavior. Future research should focus on regional studies, the development of localized IPM strategies, and increasing farmer education to enhance sustainable nematode management practices in Indian citrus orchards.*

Keywords- Citrus nematodes, Tylenchulus semipenetrans, seasonal fluctuations, integrated nematode management, biological control, nematicides, cultural practices, soil sampling, agroecological zones, rootstocks, nematode monitoring, crop rotation, sustainable agriculture, farmer awareness, India.

I. INTRODUCTION

Citrus fruits hold a significant place in India's horticultural sector, contributing substantially to the national fruit production and economy. Among various citrus fruits cultivated, sweet orange, mandarin, and lime are extensively grown across states like Maharashtra, Andhra Pradesh, Punjab, and Assam. India ranks among the top citrus-producing countries globally, with a considerable portion of the rural population relying on citrus cultivation for livelihood and income (National Horticulture Board, 2022).

The productivity and health of citrus orchards are increasingly threatened by several biotic stresses, among which plant-parasitic nematodes play a critical role. One of the most destructive nematodes affecting citrus is *Tylenchulus semipenetrans*, commonly known as the citrus nematode. This sedentary endoparasite attacks citrus roots, impairing nutrient and water uptake, which leads to stunted growth, yellowing of leaves, and reduced fruit yield and quality (Singh et al., 2019). Once established, these nematodes are difficult to eradicate and can persist in the soil for extended periods, making management challenging. The seasonal dynamics of *T. semipenetrans* is crucial for effective pest control and sustainable citrus production. The population density and activity of citrus nematodes are closely influenced by environmental factors such as soil temperature, moisture, and host plant phenology. Seasonal fluctuations significantly impact nematode reproduction and survival, which in turn affects the timing and severity of infestations (Patel & Patel, 2020). Therefore, timely monitoring and strategic nematode management practices aligned with seasonal variations can enhance control efficiency and minimize crop losses.

II. CITRUS NEMATODES: BIOLOGY AND ECOLOGY

Among the several nematodes affecting citrus crops, the most economically important species is *Tylenchulus semipenetrans Cobb*, commonly referred to as the citrus nematode. This nematode is a sedentary semi-endoparasite that primarily targets the root system of citrus plants, causing a slow decline in tree vigor, known as "citrus slow decline disease." Besides *T. semipenetrans*, other nematode species like *Meloidogyne spp.* (root-knot nematodes) and *Pratylenchus spp.* (lesion nematodes) can also occur in mixed populations, compounding the damage (Khan et al., 2021).

The life cycle of *T. semipenetrans* typically spans 6 to 8 weeks under favorable environmental conditions. It includes the egg, four juvenile stages (J1–J4), and adult male and female stages. The infective second-stage juveniles (J2) hatch from eggs in the soil and migrate toward the root zone, where females partially embed themselves in the cortical tissue of feeder roots. Males, in contrast, remain free-living in the soil and do not feed. The females excrete gelatinous egg masses that adhere to root surfaces, enabling the continuation of the life cycle (Singh et al., 2019). Their survival is enhanced by their ability to enter a quiescent state during unfavorable conditions such as drought or extreme temperatures.

In terms of soil and root interaction, citrus nematodes prefer sandy to loamy soils that facilitate easier movement and root penetration. Once inside the root cortex, the female induces the formation of a specialized feeding site, resulting in necrosis, reduced water uptake, and nutrient imbalance. These infected roots often show the presence of soil particles adhering to gelatinous egg masses, a characteristic diagnostic symptom. Infestation is typically confined to the feeder roots, which are crucial for nutrient absorption. As the nematode population increases, the damage accumulates seasonally, leading to observable above-ground symptoms such as chlorosis, reduced canopy growth, and diminished fruit yield (Jain & Prasad, 2020).

III. INDIAN AGROECOSYSTEMS AND CITRUS CULTIVATION

India's diverse agroecosystems offer suitable conditions for the cultivation of a wide range of horticultural crops, with citrus fruits occupying a prominent position. Citrus is grown across several states, each representing different agroclimatic zones. Major citrus-producing regions in India include Maharashtra (Nagpur orange, acid lime), Andhra Pradesh (sweet orange), Punjab (kinnow), and Assam (mandarin). These states contribute significantly to the country's total citrus output, with Maharashtra leading in area and production due to favorable soil and climate conditions (NHB, 2022).

The agroclimatic conditions across these regions vary significantly with the seasons, influencing citrus growth and nematode activity. Summers (March to June) are typically hot and dry, with temperatures ranging from 30°C to over 45°C in central and western India. The monsoon season (June to September) brings substantial rainfall, particularly in the northeastern and coastal states like Assam and Andhra Pradesh. Winters (November to February) are generally cool and dry, especially in northern states like Punjab, which provides an ideal environment for kinnow cultivation. These seasonal shifts affect soil moisture, root growth, and microbial activity, which in turn impact the population dynamics of plant-parasitic nematodes like *Tylenchulus semipenetrans* (Sharma & Prasad, 2021).

Citrus in India is commonly cultivated on a variety of soils, including sandy loam, clay loam, and black cotton soils, depending on the region. Sandy loam soils are generally preferred for citrus as they facilitate better drainage and root aeration. However, these soils are also more conducive to nematode movement and penetration due to their loose structure. Irrigation practices vary, with regions like Maharashtra and Andhra Pradesh adopting drip or basin irrigation to optimize water use in semi-arid areas, while flood irrigation is still practiced in some traditional orchards. Poor irrigation management, especially in heavy soils, can lead to waterlogging or drought stress, both of which can indirectly influence nematode population growth and plant susceptibility (Patel et al., 2020).

IV. SEASONAL FLUCTUATIONS OF NEMATODES

The population dynamics of citrus nematodes, particularly *Tylenchulus semipenetrans*, exhibit marked seasonal fluctuations influenced by climatic factors and host plant phenology. Studies across different citrus-growing regions in India have consistently shown that nematode populations tend to rise during periods of moderate temperature and increased soil moisture—conditions that favor nematode reproduction and activity.

In Maharashtra, root sampling conducted in Nagpur orange orchards revealed that nematode populations typically begin to rise during the late monsoon (September) and peak in the post-monsoon period (October–November), when soil moisture remains high and temperatures are moderate (Kale et al., 2020). A similar pattern was observed in Punjab and Haryana, where kinnow orchards showed elevated nematode counts in winter months (December–January), which was attributed to cooler temperatures and moist soil conditions resulting from winter irrigation and dew formation (Sharma & Singh, 2021).

Temperature plays a crucial role in influencing nematode life cycles. Optimal temperature for *T. semipenetrans* development ranges between 25°C and 30°C. Temperatures above 35°C, as seen in peak summer months, tend to suppress nematode activity and can induce dormancy or mortality, especially in the absence of adequate moisture. Conversely, low winter temperatures in northern India can slow down nematode metabolism and reproduction, leading to reduced population densities (Meena et al., 2019).

Soil moisture and humidity further regulate nematode movement and root penetration. High soil moisture following monsoon rains enhances nematode migration toward root zones, increasing the likelihood of infestation. Excessive water, however, can lead to anaerobic soil conditions, which may be detrimental to nematode survival. Root sampling studies from Andhra Pradesh and Assam showed population surges in October and November, correlating with the recovery of root growth post-monsoon, providing fresh feeding sites for nematodes (Reddy & Rao, 2018).

Population density trends over the year often follow a bell-shaped curve, with a gradual rise from late summer, peaking in post-monsoon, and declining during the dry and extreme cold months. This trend has important implications for timing of control measures, such as nematicide application or bio-agent introduction, which are most effective when nematode populations are actively feeding and reproducing.

V. HOST-PLANT INTERACTIONS AND YIELD IMPACT

Citrus nematodes, especially *Tylenchulus semipenetrans*, have a profound impact on citrus plant health and productivity, and these effects are closely linked to seasonal fluctuations in nematode activity. The parasitic interaction between *T. semipenetrans* and citrus roots is primarily localized in the feeder roots, where the nematodes establish semi-endoparasitic relationships. This interaction disrupts the plant's physiological functions, particularly nutrient and water uptake, resulting in a gradual decline in tree vigor.

During the active growth periods of nematodes—typically post-monsoon and in cooler months—root systems are more vulnerable. These seasons coincide with renewed root flushing, which provides fresh root tips, ideal for nematode invasion. The feeding activity of female nematodes within the cortex tissue leads to localized necrosis, collapse of cortical cells, and eventual rotting of feeder roots (Jain et al., 2019). Over time, this chronic root damage affects the overall health of the tree and its ability to absorb nutrients, particularly nitrogen and potassium, which are vital for fruit development and quality.

The symptoms of citrus nematode infestation become more visible during periods of peak activity. Affected trees exhibit yellowing of leaves (chlorosis), leaf drop, reduced canopy growth, and poor flowering. Fruit size and juice content are often reduced, and in severe infestations, yield losses of up to 30–40% have been reported (Kumar & Sharma, 2020). The impact on fruit quality includes uneven ripening, lower sugar content, and premature fruit drop, which significantly reduces market value.

Seasonal assessments of root damage, conducted through root sampling in different citrus-growing regions, have shown that nematode-induced damage is most severe during October to December and again during February to March in irrigated systems. In these months, feeder roots show browning, poor branching, and are often encrusted with soil particles due to gelatinous egg masses. In contrast, during peak summer (April to June), root samples tend to show lower nematode populations, and symptoms may be less evident, although underlying damage persists (Yadav et al., 2021).

These seasonal trends highlight the importance of timely monitoring and integrated management strategies, especially during vulnerable growth stages of citrus plants. Delayed intervention can result in irreversible root damage and cumulative yield losses over successive seasons.

VI. NEMATODE MONITORING AND DETECTION METHODS

Effective monitoring of nematode populations is critical for managing citrus nematode infestations, especially given their seasonal fluctuations and subterranean habitat. Accurate detection and timely quantification of nematodes enable early intervention, reducing yield losses and improving the efficacy of control strategies.

6.1 Soil and Root Sampling Techniques across Seasons

Seasonal sampling plays a vital role in assessing nematode populations, as density varies significantly throughout the year. Soil and feeder root samples are typically collected during periods of active root growth and moderate temperatures—usually in post-monsoon (October–November) and late winter (February–March). These are the seasons when nematode populations are highest and root infections are most evident (Singh et al., 2020).

Soil is generally sampled from the root zone at depths of 15–30 cm using augers or trowels. Multiple subsamples are taken around the drip line of the tree and then composited to provide a representative sample. Roots are also collected from the same area for nematode extraction and direct observation of symptoms such as root necrosis or gelatinous egg masses.

6.2 Extraction and Quantification Methods

Once collected, nematodes are extracted from both soil and root samples using established methods. For soil samples, the Baermann funnel technique is widely used, especially for detecting motile stages like second-stage juveniles (J2s). This method relies on the nematodes' active movement out of the soil into water under gravity (Khan et al., 2018). However, it may be less effective for inactive or embedded nematodes.

Centrifugal flotation, using sugar or magnesium sulfate solutions, is another widely used technique that improves recovery efficiency by separating nematodes from soil particles based on density differences. This method is particularly useful for quantifying population density, often expressed as the number of nematodes per 100 cc of soil or per gram of root tissue (Patel & Kumar, 2021).

For root samples, staining techniques such as acid fuchsin staining are used to visualize nematodes embedded within the root cortex under a microscope. This allows for direct observation of nematode developmental stages and assessment of internal damage.

6.3 Microscopic and Molecular Identification Tools

Traditional identification is based on morphological features observed under a compound microscope, including the shape of the stylet, tail, and esophageal glands. However, these techniques require expertise and are often time-consuming.

To complement morphological methods, molecular tools such as PCR (Polymerase Chain Reaction) have been developed for precise and rapid identification of *T. semipenetrans*. DNA is extracted from individual nematodes, and species-specific primers are used to amplify genetic markers like ITS (Internal Transcribed Spacer) regions or COI (Cytochrome Oxidase I) genes (Gupta et al., 2019). These molecular techniques enhance accuracy, especially in distinguishing closely related nematode species or when mixed populations are present.

VII. INTEGRATED NEMATODE MANAGEMENT APPROACHES

Managing citrus nematodes effectively requires a combination of strategies tailored to seasonal population dynamics and agroecological conditions. Integrated Nematode Management (INM) focuses on reducing nematode pressure sustainably by combining cultural, biological, chemical, and genetic approaches.

7.1 Cultural Practices Based on Seasonal Knowledge

Cultural practices are foundational in nematode management and become more effective when aligned with seasonal nematode activity. Practices such as crop rotation with non-host crops (e.g., cereals or legumes) can help suppress nematode populations during off-seasons. Fallowing the land during the hot summer months (April–June) can lead to nematode desiccation, especially in light soils. Orchard sanitation, including removal of infected feeder roots and debris, reduces inoculum sources and should be prioritized during pruning cycles, typically done post-harvest in winter or early spring (Sharma & Khan, 2019).

7.2 Biological Control Agents and Seasonal Efficacy

Biological control has emerged as a promising alternative to chemical nematicides. Fungal biocontrol agents like *Paecilomyces lilacinus* and *Purpureocillium lilacinum*, and bacterial strains such as *Bacillus subtilis* and *Pseudomonas fluorescens*, have shown effectiveness in suppressing citrus nematodes. Their application is most successful during the post-monsoon period (October–November), when soil moisture supports microbial activity and root flushing allows better colonization of rhizosphere zones (Patel et al., 2021). These microbes not only parasitize eggs and juveniles of nematodes but also enhance plant resistance mechanisms.

7.3 Use of Nematicides – Timing for Maximum Efficacy

Chemical nematicides, although used sparingly due to environmental concerns, remain essential in high-infestation scenarios. The timing of application is critical for maximum impact. Nematicides such as carbofuran, phorate, or newer low-toxicity options like fluopyram are most effective when applied during the early post-monsoon season, when nematode populations are active and in contact with young roots (Kumar & Verma, 2020). Split applications—once in October and again in February—can help manage recurring population surges.

Proper soil moisture at the time of application ensures even distribution of the chemical and improves nematicidal activity. However, repeated use should be avoided to prevent resistance development and non-target effects.

7.4 Resistant Rootstocks and Varietal Trials

The use of resistant or tolerant rootstocks is a long-term, eco-friendly strategy gaining importance in citrus breeding programs. Trials conducted in Maharashtra and Andhra Pradesh has identified certain rootstocks like *Poncirus trifoliata*, *Carrizo citrange*, and *Rangpur lime* as moderately resistant to *T. semipenetrans* (Yadav et al., 2022). These rootstocks support healthy tree growth under nematode pressure and reduce the reliance on chemical control.

Field trials of different citrus varieties grafted onto resistant rootstocks are being conducted under different agroclimatic conditions to evaluate yield stability and nematode resistance across seasons. Such trials also help in selecting combinations best suited for integrated nematode management under Indian conditions.

VIII. CHALLENGES AND RESEARCH GAPS

Despite progress in understanding citrus nematode biology and management, several challenges continue to impede the development of comprehensive and regionally effective control strategies in Indian agroecosystems.

8.1 Inconsistent Data across Agro ecological Zones

A major challenge lays in the fragmented and inconsistent data on citrus nematode population dynamics across diverse agro ecological zones of India. Most existing studies are localized and conducted over short durations, making it difficult to generalize findings across different climatic conditions and soil types. For example, while nematode peaks are well documented in Maharashtra and Punjab, comparable long-term data from northeastern states like Assam or from southern citrus belts like Tamil Nadu are scarce or outdated (Sharma et al., 2020). This limits the ability to develop national or zonal forecasting systems for nematode outbreaks.

8.2 Lack of Region-Specific IPM Models

Another critical gap is the lack of integrated pest management (IPM) models tailored to specific regions and citrus varieties. Current management recommendations are often broad-based and fail to account for seasonal variability in nematode activity, soil health, irrigation schedules, and varietal susceptibility. Without localized IPM protocols that integrate cultural, biological, and chemical approaches with seasonal timing, the adoption and success of nematode management remains suboptimal (Rao & Gupta, 2021).

8.3 Limited Awareness among Farmers

Farmer-level awareness of citrus nematodes and their seasonal behavior is significantly limited, especially in small and marginal citrus holdings. Nematode symptoms often mimic nutrient deficiency or drought stress, leading to misdiagnosis and inappropriate treatment. Many farmers are unfamiliar with proper soil sampling methods, nematode identification techniques, or the importance of post-monsoon interventions. This knowledge gap severely restricts the implementation of preventive and timely management strategies (Kumar & Sinha, 2022).

These challenges underline the urgent need for region-wise nematode surveillance, farmer education campaigns, and the development of seasonally synchronized IPM models that can be adopted at scale.

IX. RECOMMENDATIONS FOR FARMERS, RESEARCHERS, AND EXTENSION WORKERS

1. For Farmers:
   - Timely Sampling and Monitoring: Farmers should adopt regular soil and root sampling, especially during peak nematode activity periods (post-monsoon and late winter). This will help identify nematode infestations early and enable proactive management.
   - Cultural Practices: Encourage the use of crop rotation with non-host plants, orchard sanitation, and fallowing practices during the off-season. These methods can help reduce nematode populations between citrus planting cycles.
   - Nematicide Application: If chemical nematicides are used, application should be scheduled based on seasonal trends—typically in post-monsoon periods when nematodes are most active.
2. For Researchers:
   - Long-Term Studies: Researchers must conduct long-term studies across different regions to create comprehensive databases on seasonal nematode trends and their relationship to climatic variables. This will enable the development of region-specific pest management models.
   - Biological Control Development: Further research into biological control agents that are effective in specific climates and soil types is needed. Studies on microbial and fungal antagonists to nematodes should be expanded, especially for sustainable pest management.
3. For Extension Workers:
   - Farmer Education: Extension services should focus on educating farmers about the seasonal dynamics of nematodes, providing them with practical, region-specific recommendations. Training on nematode identification, soil sampling techniques, and interpreting seasonal trends will enhance the adoption of integrated pest management strategies.
   - Field Demonstrations: Organizing field trials and demonstration plots can help show the benefits of integrated nematode management, including cultural practices, biological controls, and

resistant rootstocks, thus increasing farmer engagement and confidence.

X. CONCLUSION

Citrus nematodes, particularly *Tylenchulus semipenetrans*, pose a significant threat to the health and productivity of citrus orchards in India. Understanding their seasonal fluctuations is crucial for developing effective management strategies that can mitigate their impact. As this review highlights, nematode populations tend to peak during the post-monsoon and early winter months, coinciding with periods of active root growth. This seasonal activity provides critical windows for intervention and informs the timing of cultural, biological, and chemical control measures.

Despite significant advancements in nematode biology, monitoring techniques, and management practices, challenges persist. Data inconsistency across agroecological zones, the absence of region-specific Integrated Pest Management (IPM) models, and limited farmer awareness hinder the widespread adoption of effective control strategies. Moreover, while biological and cultural control measures show promise, their effectiveness is highly dependent on local environmental conditions and timely application.

To address these challenges, future research should focus on long-term, region-specific studies that provide consistent data on nematode population dynamics across diverse climatic zones. Additionally, developing tailored IPM models that incorporate seasonal timing, resistance rootstocks, and biologically active agents can significantly improve nematode management outcomes. Finally, increasing farmer awareness through training programs and extension services is crucial to enhance the adoption of sustainable practices and early detection methods.

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