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Subhojit Chatterjee
M.Sc. Scholar, Department of Nematology, School of Crop Protection, College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya, India

Tania Roy
M.Sc. Scholar, Department of Nematology, School of Crop Protection, College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya, India

Raghubir Kumar Patidar
M.Sc. Scholar, Department of Nematology, School of Crop Protection, College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya, India

Corresponding Author:
Subhojit Chatterjee
M.Sc. Scholar, Department of Nematology, School of Crop Protection, College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya, India

Systematic literature review diversity & community analysis of plant parasitic nematodes associated with citrus crop

Subhojit Chatterjee, Tania Roy and Raghubir Kumar Patidar

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Abstract
Plant parasitic nematodes (PPNs) are among the most harmful biotic organisms affecting citrus crops globally, resulting to huge financial losses by lowering tree vigor and fruit quality. The diverse diversity and distribution of these nematodes are affected by many agroecological and edaphic characteristics. This review explores the present grasp of the community composition, species richness, and ecological characteristics of PPNs connected with citrus cultivation over diverse geographical regions, with particular emphasis on India and other semiarid to tropical ecosystems. The dominant genera in citrus rhizospheres are *Tylenchulus*, *Meloidogyne*, *Helicotylenchus*, *Pratylenchus*, and *Xiphinema*. *T. semipenetrans*, for instance, was found to be 70-100% common in studies conducted in India, Morocco, Egypt, and Korea. *Helicotylenchus* (45-75%), *Meloidogyne* (15-69%), *Pratylenchus* (27-47%), and *Xiphinema* (7-8%) were frequently found to follow. Common research techniques include morphologically identifying nematodes to genus or species, extracting the soil using a modified Baermann or sieve, and using composite soil samples from orchards (e.g., 1 kilogram per site in a zigzag pattern). Their populations are impacted by soil temperature, moisture, pH, organic matter, and management practices. Regional surveys have showed large variations in nematode diversity, which usually suggest environment gradients and soil physical properties. Soil texture and farming practices are also major factors determining nematode density and diversity. This study summarizes research results from several studies to show how PPNs' stability and abundance are influenced by environmental interactions and how they fit into larger soil food webs. Furthermore, in order to give a comprehensive picture of the ecological roles and pestiferous dynamics of nematode communities, both regional and temporal changes have been studied. It is essential to address PPN variety and community structure in order to create sustainable citrus pest management solutions. A better understanding of nematode ecology would limit the use of targeted control techniques, such as soil amendments, resistant cultivars, and biocontrol agents—all essential elements of integrated nematode management programs.

Keywords: Citrus orchards, diversity analysis, plant-parasitic nematodes, soil nematodes, soil factors

Introduction
In terrestrial ecosystems, soil nematodes are among the most common and significant creatures. They serve as major variables in nutrient cycling, decomposition processes, and soil food web dynamics (Mulder *et al*., 2003) [22]. Although the majority of nematodes contribute to soil health, a small percentage referred to as plant-parasitic nematodes (PPNs) are serious agricultural crop pests that cause large output losses globally. These nematodes lower productivity by penetrating plant roots, decreasing nutrient intake, and putting hosts at risk for secondary infections (Bakonyi *et al*., 2007; Cadet *et al*., 2004) [2, 3]. An essential fruit crop in tropical and subtropical regions, citrus plants are particularly vulnerable to nematode infestation, especially by *Tylenchulus semipenetrans*, often known as the citrus nematode. This species has a broad range and causes slow decline disease, significantly affecting tree vigor and fruit availability (Abu Habib *et al*., 2020; Sorribas *et al*., 2008) [1, 32]. It is commonly found in citrus orchards, frequently co-occurring with species like *Helicotylenchus*, *Meloidogyne*, and *Pratylenchus*, according to surveys conducted in India, Iran, Egypt, and Spain (Mahanta *et al*., 2017; Kumar & Das, 2019) [14, 16]. Citrus plants are constantly strained by these nematodes, which makes management difficult under typical cultivation techniques. Physical and chemical properties of the soil, including pH, texture,

organic matter, and moisture, have a major impact on the range and population dynamics of nematodes (Griffiths *et al*., 2003; Salahi Ardakini *et al*., 2014) [11, 29]. Nematode activity and survival are further regulated by climatic parameters, including temperature and precipitation patterns (Bakonyi *et al*., 2007; Liu *et al*., 2009) [2, 15]. Nematode assemblages for several crops, such as sugarcane (Gade & Hiware, 2017) [9], saffron (Mokrini *et al*., 2019) [19], vegetables (Sahu *et al*., 2011) [28], and ornamentals (Rashid *et al*., 2014) [26], exhibit notable heterogeneity among agroecosystems, driven by crop type and soil quality, according to studies on these crops. The ecological interactions of nematodes under shifting soil conditions and farming systems remain poorly understood despite a plethora of research. For sustainable nematode management, thorough evaluations that incorporate diversity indicators, correlations between soil components, and comparative crop analysis are required. Therefore, the current investigation systematically synthesizes results on nematode diversity in citrus orchards and draws contrasts with other valuable crops. The impact of environmental and soil factors on nematode distribution is also evaluated, and possible approaches to integrated nematode control in various agricultural systems are discussed.

Materials and Methodology

The PRISMA method is used in this Systematic literature review. A keyword search was conducted in three databases i.e. Google Scholar (GS), Science Direct (SD), MDPI to gather the relevant articles. Then all the findings were further screened for eligibility and exclusion. The review process entails several stages, including identification, screening, eligibility, and data abstraction and analysis. (Moher *et al.*, 2009).

Search Strategy and Selection of Literatures

Database Search

A comprehensive literature search was conducted across three databases to identify relevant research articles. We performed an electronic literature search to identify pertinent peer-reviewed articles written in English, without a limitation on publication year (2004-2021). The search was conducted using three databases Google Scholar, Science Direct and MDPI encompassing titles, abstracts, and keywords. The search strategy was tailored to each database.

Keywords and Search Terms

The keywords and search terms used to capture relevant studies were: “Plant Parasitic Nematodes”, “Diversity analysis”, “Soil nematodes”, “Citrus orchards”, “Management”, “different types”. Combinations and variations of these terms were used to refine the search and ensure comprehensive coverage.

Search Strategy

The search strategy involved using Boolean operators (AND, OR) to combine keywords and apply filters for language (English). Example search strings include: ("Plant Parasitic Nematodes" AND " Soil nematodes" AND " Citrus orchards " AND " Diversity analysis" AND “Management” AND “Different types”).

Study Identification

The initial literature search included 217 scientific articles related to this topic. After screening out papers, 137 papers were found relevant to this topic. Among them 80 papers have been screened out from 2004 to 2021. Later the articles were screened out on the basis of keywords like ‘Diversity analysis’ ‘Nematodes’ ‘Citrus Orchards’. Total 34 papers were chosen for writing this systematic literature review.

A majority of the papers were categorized into the area of nematode management and population dynamics, botanicals, biopesticides. Only 34 papers in the final categories were empirical.

Inclusion and Exclusion Criteria

To ensure the selection of relevant and high-quality studies, the following criteria were applied:

Inclusion Criteria

1. Only open-access articles are selected relevant to objectives set.
2. Peer-reviewed original research articles published in English.
3. Articles published from 2004-2021

Exclusion Criteria

1. Articles with irrelevant titles and abstracts.
2. Articles research objectives are not related to “Plant Parasitic Nematodes”, and “Diversity analysis”.
3. Non-peer-reviewed book chapters, News items, Editorial materials are excluded
4. Studies lacking sufficient data or methodological rigor.

Data Extraction and Analysis

Data Extraction

Relevant data were extracted from the selected studies using a standardized extraction form developed in Excel. The form included the following fields:

- **Study Identification:** Authors, year of publication, title, journal.
- **Study Location:** Country/region.
- **Study Design:** Methodology, sample size, data sources, and analysis techniques.
- **Key Findings and Conclusions:** Summarized insights and implications from the study.

Data extraction was performed independently by all the reviewers to ensure accuracy and consistency. Discrepancies were resolved through discussion among the reviewers.

Qualitative Synthesis

A qualitative synthesis of the information based on siderophore usage in plant health improvement. This involved summarizing the findings on mechanisms of Biorationals and its impact over plants, adaptation strategies, and identifying causes and unique feature from different studies.

Results

The initial literature search included 217 scientific articles related to this topic. After screening out papers, 137 papers were found relevant to this topic. Among them 80 papers have been screened out from 2004 to 2021. Later the articles were screened out on the basis of keywords like ‘Diversity analysis’ ‘Nematodes’ ‘Citrus Orchards’. Total 34 papers were chosen for writing this systematic literature review.

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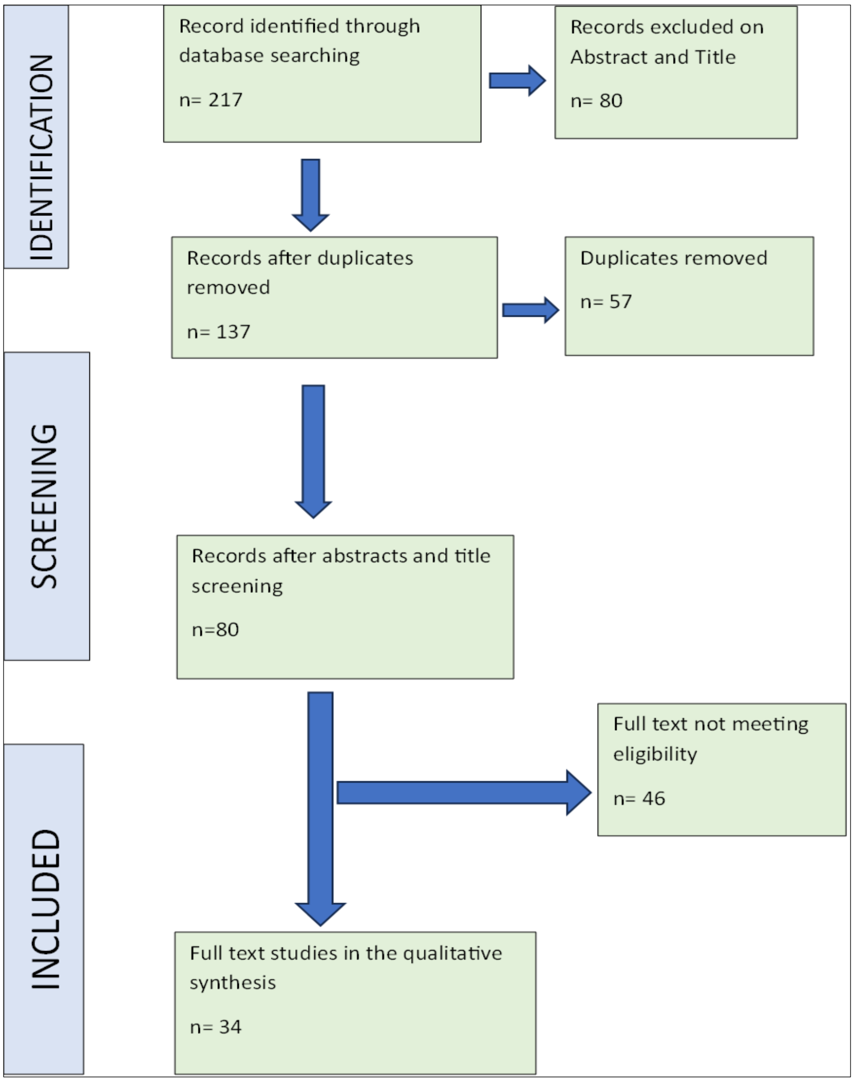
PRISMA Diagram



Distribution and Economic Importance of Plant Parasitic Nematodes in Citrus

Citrus, a fruit crop of global importance, is susceptible to a number of plant parasitic nematodes (PPNs), which drastically lower fruit quality and productivity. Citrus decline and poor orchard sustainability are caused by PPN infestation in India, where citrus is one of the most important horticulture crops (DAC&FW, 2017; Meena *et al*., 2018) [6, 18]. The most common and economically detrimental species is the citrus nematode, *Tylenchulus semipenetrans*, which infests almost all of the main citrus-growing regions (Duncan, 2009; Khan *et al*., 2010) [8, 13]. A wide variety of nematodes, such as *Helicotylenchus*, *Pratylenchus*, *Meloidogyne*, and *Hoplolaimus* species, have been found to inhabit citrus orchards, according to extensive surveys conducted in India and abroad (Gade and Hiware, 2017; Mahanta *et al*., 2017; Mokbel *et al*., 2006) [9, 16, 21]. Research has shown how they can lead to root rot, growth retardation, leaf yellowing, and heightened vulnerability to secondary infections. These PPNs exacerbate yield losses by weakening host plants through direct and indirect harm. Nematode populations have demonstrated variability in Assam, Jammu & Kashmir, Maharashtra, and Egypt as a result of host cultivars, environmental variables, and soil physicochemical characteristics (Abu Habib *et al*., 2020; Mahanta *et al*., 2018; Zalpuri *et al*., 2013) [1, 16, 34]. Abu Habib *et al*. (2020) discovered that T. semipenetrans was the predominant species in Egypt, exhibiting significant cultivar-specific variation in susceptibility.

Diversity and Composition of Nematode Communities

In citrus orchards, the taxonomic and functional variety of soil nematode communities is essential. The presence of several taxa, including *Xiphinema*, *Radopholus*, *Rotylenchulus*, and *Tylenchulus*, indicates niche partitioning and adaptability to different soil types (Kumar and Das, 2019; Rashid *et al*., 2014) [14, 26]. According to surveys conducted in India's citrus-growing regions, Tylenchulus semipenetrans is commonly mixed with other nematodes to create complex communities that affect the dynamics of illness (Pathak and Chandra, 2011; Sahu *et al*., 2011) [25, 28]. Based on soil samples from various areas, such as Rajoun (J&K), Durg (Chhattisgarh), and Tinsukia (Assam), community analysis revealed significant variations in species richness and abundance, which were impacted by cropping practices and soil moisture (Mahanta *et al*., 2018; Rashid *et al*., 2014; Sahu *et al*., 2011) [16, 26, 28]. Seasonal variations in nematode density were also identified, with peak numbers related with warm and moist conditions suitable to worm activity (Sen *et al*., 2008) [30]. Soil nematode communities in Brazil and the Amazonian savanna vary greatly based on land-use structures, suggesting that nematode diversity and trophic structure are influenced by agricultural activities (Huang and Cares, 2006) [12]. Comparable results have been observed in Morocco and New Caledonia, where diversity indices have been connected to soil amendments and land management (Grandison *et al*., 2009; Mokrini *et al*., 2019) [10, 19].

Environmental and Soil Factors Shaping Nematode Communities

In citrus ecosystems, research has shown a strong correlation between the physicochemical characteristics of the soil and the structure of nematode communities (Bakonyi *et al*., 2007; Cadet *et al*., 2004) [2, 3]. In sandy loam soils with moderate moisture content and a slightly acidic pH, for example, *T. semipenetrans* exhibits high population densities (Salahi Ardakini *et al*., 2014; Sorribas *et al*., 2008) [29, 32]. Both biotic and abiotic soil variables had an impact on nematode assemblages, according to pot studies done in India by Griffiths *et al*. (2003) [11]. According to Liu *et al.* (2009) [15], irrigation practices have a major impact on nematode dynamics in semi-arid grasslands, as they showed that water availability is a critical regulator of microbial and nematode activity. Nematode population changes in agroecosystems have also been caused by nutrient depletion, soil degradation, and unsustainable agricultural practices (Mulder *et al*., 2003) [22]. It is well known that nematode trophic groups can be changed by organic farming, cover crops, and the application of organic amendments, which can increase ecosystem resilience and diversity (Nisa *et al*., 2021) [23].

Methodologies for Nematode Identification and Quantification

Standard methods for nematode isolation and identification include Cobb's sieve and decanting technique (Cobb, 1918), Baermann funnel method, and centrifugal flotation. Quantitative extraction from rhizosphere soils and taxonomic identification using morphometric criteria under a microscope are frequently used in population surveys (Southey, 1986) [33]. Diversity indices including Shannon-Weiner, Simpson's dominance, and evenness measures are frequently used in ecological research to evaluate the organization of nematode communities (Norton, 1978) [24]. To investigate environmental connections and nematode assemblage patterns, multivariate techniques such as cluster analysis, principal component analysis (PCA), and canonical correspondence analysis (CCA) are used (Kumar and Das, 2019; Matute *et al*., 2013) [14, 17]. In order to identify nematode hotspots and investigate the connections between soil zones and nematode infestations, GIS and spatial mapping have also developed (Monfort *et al*., 2007) [20]. These tactics are essential for managing citrus crop nematodes at specific sites.

Host-Nematode Interaction and Disease Complexes

With citrus hosts, plant parasitic nematodes establish complex relationships and frequently collaborate with bacterial and fungal pathogens to create disease complexes. Phytophthora spp. and T. semipenetrans have a well-established association that causes increased root degradation and citrus decline (Duncan, 2009; Reddy and Agarwal, 2010) [8, 27]. The ability to breed citrus rootstocks resistant to nematodes was shown by Cameron *et al*. (1969) [4], and this technique has been widely used in rootstock development projects all over the world. Physical root characteristics, biochemical deterrents, and genetic factors are frequently associated with resistance. Nematode resistance has been assessed in a number of Indian citrus varieties, with varying degrees of success. Khasi Mandarin and sweet orange are extremely vulnerable, whereas cultivars such as Rangpur lime and Poncirus trifoliata exhibit only moderate resistance (Mahanta *et al*., 2018; Singh *et al*., 2016) [16, 31]. Nematode reproduction and penetration are influenced by the secondary metabolite profile and root exudate composition of citrus roots (Zalpuri *et al*., 2013) [34].

Integrated Management Approaches

Citrus plant parasitic nematodes must be managed using a multifaceted strategy that incorporates chemical, biological, and cultural methods. Crop rotation, deep ploughing, and solarization are efficient cultural methods that lower nematode loads by disrupting life cycles (Duncan, 2009; Khan *et al*., 2010) [8, 13]. Potential for reducing PPN populations in field settings has been suggested via biological management employing predatory nematodes and nematode-trapping fungi (*Paecilomyces lilacinus, Pochonia chlamydosporia*) (Meena *et al*., 2018) [18]. Neem cake, castor cake, and mustard oil cake are examples of botanicals that have been used to reduce nematode populations and improve soil health. Chemical nematicides, however advantageous, have recently been prohibited due to environmental concerns. Site-specific application and reduced-dose treatments utilizing nematicides like fenamiphos and oxamyl are being investigated within precision agriculture frameworks (Monfort *et al*., 2007) [20]. Host resistance is a feasible and long-term strategy, and screening of rootstocks for nematode resistance is an important study domain. To identify resistance genes and create nematode-resistant cultivars, modern technologies like as transcriptome profiling, QTL mapping, and genetic markers are being used (Cameron *et al*., 1969; Duncan, 2009) [4, 8]

Future Perspectives and Research Gaps

There are still a number of constraints in our understanding of PPN dynamics in citrus despite tremendous progress. The ecological relationships between nematode succession and soil microbiota require long-term research. There is a pressing need to standardize diversity evaluation techniques and link community structure to functional effects on citrus health and productivity. Additionally, studies should look into how the dynamics of nematode populations are affected by climate change, particularly in light of changing temperature and precipitation patterns. In order to identify new nematode risks, routine surveillance should use molecular diagnostics and next-generation sequencing methods. Furthermore, regional nematode distribution atlases and nematode forecasting models are important for proactive management and policymaking (Khan *et al*., 2010) [13]. Sustainable citrus farming will be supported by investments in integrated management training, nematode diagnostic facilities, and farmer awareness.

Conclusion

Plant parasitic nematodes (PPNs) pose significant risks to citrus production worldwide, especially in regions like India where various agro-ecological zones nurture abundant nematode communities. The citrus nematode *Tylenchulus semipenetrans* remains the most economically devastating, typically co-existing with other genera like *Helicotylenchus, Meloidogyne, Pratylenchus*, and *Xiphinema*. These nematodes not only inflict direct harm to root systems but also operate synergistically with other infections, increasing citrus decline and lowering output. This review has shown how nematode diversity and abundance are regulated by several soil variables such as temperature, pH, moisture, texture, and organic content. A clear geographical heterogeneity exists in nematode populations, influenced by soil management approaches, host cultivar vulnerability, and environmental variables. The use of nematodes as markers of soil quality and ecosystem disturbance further highlights their ecological value. Integrated nematode management strategies—combining cultural techniques, resistant rootstocks, biological control agents, and precision chemical application—are necessary for sustained citrus production. Advances in molecular diagnostics, GIS-based mapping, and nematode community analysis give potential methods for targeted control and early detection. Moving forward, additional interdisciplinary and long-term investigations are needed to untangle the ecological roles of nematode communities and their interactions with the broader soil microbiome. Investment in farmer education, nematode surveillance infrastructure, and the creation of nematode-resistant citrus varieties will be vital to offset the impacts of PPNs and secure citrus productivity in the face of evolving agricultural and climate problems.

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Author Contributions

Tania Roy helped in experimentation, data analysis, and manuscript drafting. Raghubir Kumar Patidar helped in conceptualization, resources, manuscript editing and revision.

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