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Seasonal Occurence and Distribution of Plant Parasitic Nematodes in Guava (*Psidium guajava* L.)

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Abstract

Guava cultivation in southern India is increasingly constrained by below-ground pests, particularly root-associated nematodes that contribute to decline and wilt syndromes. This investigation was undertaken to investigate the seasonal distribution and incidence of plant-parasitic nematodes (PPNs) associated with guavaand to understand ecological drivers of major nematode groups in orchards of the Eastern Dry Zone of Karnataka across three contrasting seasons. Morphological diagnosis confirmed the consistent predominance of *Meloidogyne enterolobii*, alongside spiral (*Helicotylenchus*), lesion (*Pratylenchus*), reniform (*Rotylenchus*), stunt (*Tylenchorhynchus*) and filiform (*Tylenchus*) nematode. The identity of *M. enterolobii* was validated through perineal patterns of females. Quantitative counts revealed peak densities during the monsoon, intermediate levels in summer and the lowest populations in winter. Reductions from monsoon to winter exceeded 45 per cent across most genera, highlighting the suppressive influence of low temperature and reduced soil moisture. Canonical Correspondence Analysis demonstrated that nematode groups were closely associated with seasonal shifts in edaphic factors, with *M. enterolobii* correlating strongly with elevated soil temperature and conductivity in summer and moisture in the rainy season. These findings underline the adaptability of RKN and its persistence across varied conditions, with important implications for disease management in perennial systems. The study underscores the need for integrated strategies that combine ecological monitoring, soil health management and eco-friendly control measures to mitigate nematode-driven guava decline in semi-arid zones.

Keywords : Edaphic factors, Plant-parasitic nematodes, Population dynamics, Seasonal distribution, Soil ecology

Guava (*Psidium guajava* L.) is one of the most widely cultivated fruit crops in tropical and subtropical regions and is valued for its high nutritional content, particularly vitamin C, dietary fibre and antioxidants (Angulo-López *et al*., 2021). Often referred to as the 'poor man's apple,' guava plays a significant role in human nutrition and food security due to its adaptability to diverse agroclimatic conditions and relatively low input requirements (Dinesh and Vasugi, 2010). In India, guava ranks fourth in area and production among fruit crops, with major cultivation hubs in Uttar Pradesh, Bihar, Maharashtra, Karnataka and Tamil Nadu. Karnataka, in particular, has seen a rapid expansion of guava cultivation in recent years, especially in districts like Kolar, Chikkaballapur and Bangalore Rural, owing to favourable soil and climatic conditions (NHB, 2023).

However, the profitability and sustainability of guava cultivation are increasingly threatened by a complex of biotic stresses, among which guava wilt has emerged as a major constraint. Guava wilt is now recognized as a pathobiome-driven disease complex, where interactions among multiple pathogens, including fungi and nematodes, contribute to disease development and progression (Ganeshan *et al*., 2019 and Gangaraj *et al*., 2022). Several studies have implicated *Fusarium oxysporum* and other fungal species in guava wilt; however, plant-parasitic nematodes (PPNs), particularly root-knot nematodes (*Meloidogyne* spp.)-play a crucial role in initiating or aggravating the disease by compromising root integrity and facilitating secondary infection (Trudgill & Blok, 2001 and Castillo & Vovlas, 2007).

PPNs are sub-microscopic, obligate parasites that feed on plant roots, causing direct damage and interfering with water and nutrient uptake. Among them, root-knot nematodes (*Meloidogyne* spp.) are the most economically important group globally, responsible for yield losses in a wide range of crops, including fruit trees (Sasser & Freckman, 1987 and Moens *et al*., 2009). *Meloidogyne enterolobii*, a highly aggressive and polyphagous species, has gained attention in recent years due to its rapid reproduction rate, ability to overcome host resistance and wide host range (Brito *et al*., 2004 and Kiewnick *et al*., 2009). It has been increasingly reported from guava orchards in India, often in association with wilt and decline symptoms (Khan *et al*., 2022).

Management of nematodes in perennial fruit crops like guava remains particularly challenging due to their soil-borne nature, wide host range and ability to persist through weed and alternate hosts (Chandana *et al*., 2025b). Chemical nematicides, though effective, are unsustainable in the long term due to environmental concerns, cost and potential resistance development (Chitwood, 2003 and Nicol *et al*., 2011). Cultural and biological methods are often constrained by the perennial crop system, where deep root systems and continuous host availability favour nematode persistence. Hence, effective management requires a deeper understanding of nematode community composition, their seasonal incidence and how they interact with soil physico-chemical properties to influence disease dynamics. Such ecological knowledge forms the foundation for developing integrated nematode management strategies tailored to specific production systems (Norton, 1978 and Sikora & Fernandez, 2005). Understanding the population dynamics of PPNs is therefore vital for developing region-specific and season-specific management strategies. Nematode activity and abundance are significantly influenced by environmental conditions, which vary with seasons and agroecological zones (Protand Van Gundy, 1981 and Norton & Niblack, 1991). Seasonal monitoring of nematode populations provides critical insight into their ecology, helping identify peak periods of infestation and target windows for control measures.

Despite the growing threat of nematode-induced wilt in guava, there is a lack of comprehensive data on the diversity and seasonal dynamics of PPNs in guava orchards across Karnataka. This study was therefore undertaken to address this gap by investigating five major guava-producing regions in the Eastern Dry Zone of Karnataka over three distinct seasons. The objectives were to identify the predominant PPN genera in the guava rhizosphere, assess their seasonal population trends and determine their relationship with soil physico-chemical properties. The results aim to contribute toward a deeper understanding of nematode ecology in guava systems and guide the formulation of integrated nematode management strategies.

MATERIAL AND METHODS

Study Area and Sampling Period

The study was carried out in the major guava-growing belts of southern Karnataka, India, focusing on five representative sites within the Eastern Dry Zone (Zone 5). The selected locations included Shivakote (13.13856°N, 77.51052°E) and Muthagdalli (13.22000°N, 77.55207°E) in Bengaluru Rural district, Talagvara (13.25195°N, 77.90945°E) and Orati Agrahara (13.25389°N, 77.94113°E) in Kolar district and Chintamani (13.31246°N, 78.07327°E) in Chikkaballapur district. These sites were chosen due to their prominence in guava cultivation and documented incidence of wilt. All orchards comprised mature guava plants aged 3-5 years, maintained under conventional management practices without pesticide application during the study.

Soil and root samples were collected across three distinct seasons over a one-year period (2023-2024): Monsoon (July), characterized by high soil moisture and moderate temperatures (24-27 °C) with rainfall exceeding 700 mm; Post-monsoon/Winter (November), with cooler temperatures (17-21 °C), lower soil moisture and reduced rainfall and Summer (April), marked by high temperatures (28-35 °C), low humidity and dry soil conditions. The study region is classified as semi-arid, with red sandy loam soils and a bimodal rainfall distribution typical of the Eastern Dry Zone of Karnataka.

Soil Sampling

Soil sampling was conducted during three seasons across five guava-growing locations. At each site, one orchard under active guava cultivation was selected for sampling. Within each orchard, five discrete rhizosphere sub-samples were collected from randomly chosen guava trees. Samples were taken from the root zone at a depth of 15-30 cm and at a distance of 30-50 cm from the main stem, targeting the zone of feeder roots where nematode activity is typically highest. Soil was collected using a hand auger and a soil corer with a 5-cm diameter opening, following the procedure described by Zhang *et al.* (2012).

The five sub-samples from each orchard were pooled, thoroughly mixed in a clean plastic tray and homogenized to form a single composite sample representing one replicate. This procedure was repeated across all selected orchards, resulting in three replicates of composite samples per location per season. Samples were immediately transferred to labelled polythene bags, kept under cool conditions during transport and stored at 4 °C in the Nematology Laboratory, AICRP (Nematodes), University of Agricultural Sciences, Bangalore. Nematode extraction and identification were carried out within 48 hours of collection to ensure sample integrity and accuracy of analysis.

Plant-Parasitic Nematode Extraction and Quantification

Soil samples were processed in the Nematology Laboratory, AICRP on Nematodes, University of Agricultural Sciences, Bangalore. Each composite sample was prepared by gently breaking soil clods and removing plant residues and stones, after which the soil was thoroughly homogenized. From the bulk sample, a 200 g sub-sample was taken for nematode isolation. Samples collected from each season (monsoon, summer and winter) were processed separately and nematode extraction was carried out following the same standardized protocol. The extraction procedure combined Cobb's sieving and decanting method with the modified Baermann funnel technique (Southey, 1986 and Hooper *et al.*, 2005). In this process, soil suspensions were passed through a graded sieve set to remove coarse particles and the nematode-containing fraction was concentrated by sedimentation and flotation. The concentrate was transferred to Baermann funnels lined with double-layered tissue paper and maintained at ambient temperature for 24 hours (Rawat and Kumar, 2023). Motile nematodes that migrated through the tissue into the collection tube were recovered and subsequently used for identification and enumeration.

Following extraction, nematode suspensions were allowed to settle and excess supernatant was carefully decanted to concentrate the sample. A 5 mL aliquot was drawn from the well-mixed suspension and examined under a compound microscope for enumeration. Population density of each plant-parasitic nematode genus was recorded and expressed as the number of individuals recovered per 200 g of soil (Chandana *et al.*, 2025a). Only live nematodes were considered for counts to ensure accuracy of population estimates. The seasonal reduction in nematode population densities was calculated using the formula:×100. Monsoon counts were considered as the baseline, as this season consistently recorded the highest nematode densities.

$$\text{Percent Reduction} = \frac{(\text{Monsoon Population - Seasonal Population})}{(\text{Monsoon Population})} \times 100$$

Morphological Identification

For permanent slide preparation, nematodes were first heat-killed by gentle warming and fixed in hot 4 per cent formaldehyde solution. Specimens were subsequently processed to anhydrous glycerin using the slow evaporation method described by De Grisse (1969). Morphological identification was carried out under a compound microscope (Leica DM1000), based on detailed diagnostic features including body shape, lip region configuration, stylet morphology, esophageal gland overlap, lateral field structure, tail shape and vulval position (for females). Identification was performed primarily to the genus level using standard taxonomic keys (Mai *et al.,* 1996). Special attention was given to *Meloidogyne* spp., owing to their recognized importance in the guava wilt complex. Second-stage juveniles (J2s) were examined for body length, stylet morphology and tail features, while females were analyzed for perineal pattern configuration. For species-level identification, perineal patterns of mature females were prepared following the method of Taylor and Netscher (1974).

Soil Physico-Chemical Properties

To evaluate the role of abiotic factors in influencing nematode population dynamics, key soil physico-chemical parameters were assessed across all five study locations during the three seasons. From each site, approximately 500 g of field-moist soil was collected as a sub-sample from the composite bulk sample. The samples were air-dried at ambient room temperature, gently crushed and passed through a 2 mm sieve to ensure uniformity before analysis. Soil pH and electrical conductivity (EC) were determined in a 1:2.5 soil-to-distilled water suspension using a calibrated digital pH meter and EC meter, respectively, following the method of Jackson (1973). Organic carbon content was estimated by the Walkley and Black rapid titration method (Walkley and Black, 1934), which provides an index of soil organic matter levels known to influence nematode survival and activity. Soil temperature was measured directly in the field at the time of sampling, using a calibrated soil thermometer inserted at a depth of 15-20 cm in the rhizosphere zone, as described by Baver *et al*. (1972). All parameters were recorded concurrently with nematode sampling to enable correlation between soil conditions and seasonal nematode population fluctuations across locations.

Statistical Analysis

Mean nematode population density was calculated and expressed as the number of individuals per 200 g of soil for each nematode genus across seasons and locations. The data were subjected to one-way Analysis of Variance (ANOVA) to test for significant differences in nematode populations among seasons. All analyses were performed using R software. To evaluate the relationship between soil physico-chemical properties and nematode population dynamics, Canonical Correspondence Analysis (CCA) was conducted using the vegan package in R. Soil parameters (pH, electrical conductivity, organic carbon and soil temperature) were included as explanatory variables, while nematode genera served as response variables. Sampling locations and seasons were treated as categorical grouping factors. The CCA ordination biplots were used to visualize associations between nematode groups and soil parameters across monsoon, summer and winter seasons. Significance of the ordination axes and explanatory variables was tested using Monte Carlo permutation tests (999 permutations).

RESULTS AND DISCUSSION

Morphological Identification

Microscopic examination of the nematode community extracted from guava rhizosphere soils revealed the presence of diverse plant-parasitic nematode (PPN) genera across all five surveyed locations. The predominant and consistently occurring genera identified were *Meloidogyne* spp. (root-knot nematodes), *Helicotylenchus* spp. (spiral nematodes), *Pratylenchus* spp. (lesion nematodes), *Rotylenchus* spp. (reniform-like nematodes), *Tylenchorhynchus* spp. (stunt nematodes) and *Tylenchus* spp. In addition, occasional detection of other genera such as *Aphelenchoides* spp. and *Criconemoides* spp. were noted; however, these were excluded from the population density analysis due to their sporadic and inconsistent presence across locations.

Among the plant-parasitic nematodes, *Meloidogyne* spp. were the most abundant and widespread. Identification was confirmed based on observation of second-stage juveniles (J2), adult males and females. Species confirmation was made based on the characteristic perineal patterns of females (Plate 1). Microscopic examination of perineal patterns of females revealed the characteristic morphology of *Meloidogyne enterolobii*. The patterns were typically oval in shape with a high rounded dorsal arch. The striae were fine to coarse, generally smooth and curved around the tail region. Distinct and large phasmids were clearly visible on either side of the pattern, while lateral lines were poorly developed or absent. These features correspond closely with the descriptions of *M. enterolobii* provided by Karssen & van Hoenselaar (1998), Cetintas *et al*. (2007) and Yang *et al*. (2013), thereby confirming the species identity.

Morphological characterization of different life stages further supported the identification (Plate 2). The second-stage juveniles (J2s) were slender and vermiform, with a well-developed stylet, bearing distinct, rounded stylet knobs. The tail was elongated, tapering gradually with a finely rounded terminus and the hyaline tail portion was clearly differentiated. Males were vermiform and exhibited a robust stylet, with rounded knobs and well-developed head sclerotization. Females were pear-shaped, sedentary and retained a short, stout stylet with large, rounded basal knobs. These observations are consistent with earlier descriptions of *M. enterolobii* morphology (Rammah & Hirschmann, 1988 and Yang *et al*., 2013).

Helicotylenchus spp. were readily distinguished by their tightly coiled spiral or arc-shaped body when relaxed. They possessed a strong, well-developed stylet with distinct basal knobs and a conical head. A ventral projection was often visible near the tail terminus, and the vulva was located in a median position (Plate 2J). Head sclerotization was prominent. *Pratylenchus* spp. were identified by their rounded head, short and robust stylet with rounded

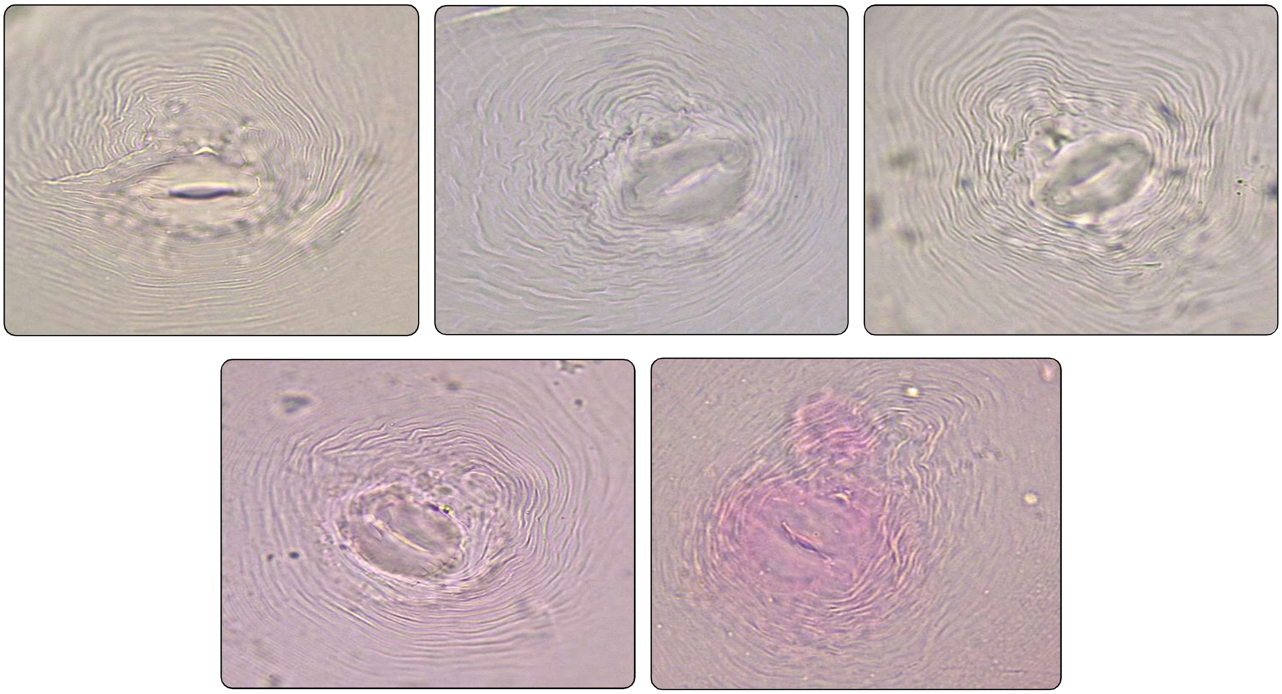

Plate 1 : Perineal patterns of *Meloidogyne enterolobii* isolates identified from five representative sites under study

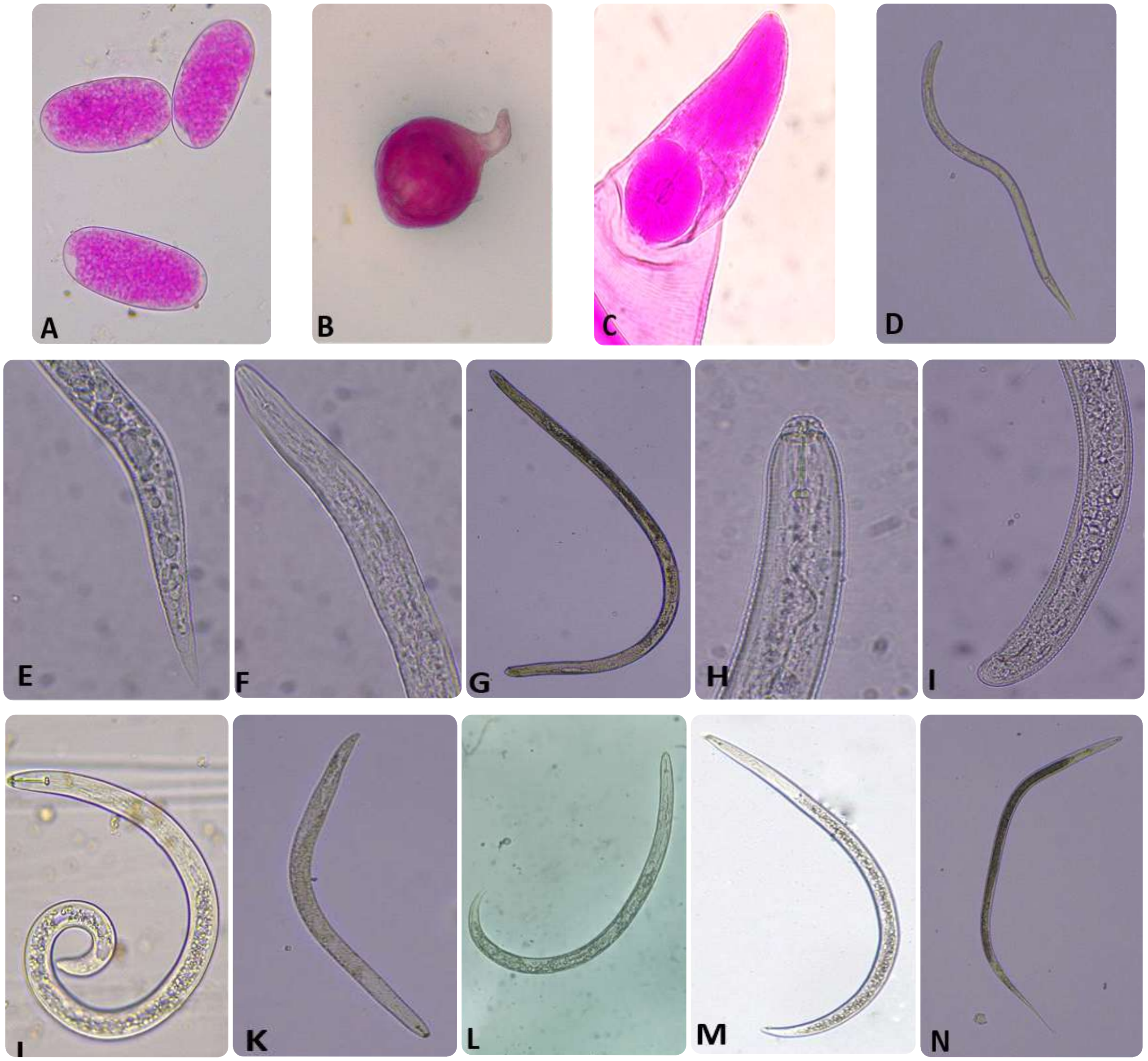

Plate 2 : Morphological characters of plant-parasitic nematodes recovered from five representative sites. Eggs (A), female (B), anterior part of female showing stylet and median bulb (C), second stage juvenile (D-F), male (G-I) of *Meloidogyne enterolobii*; (J) *Helicotylenchus*, (K) *Pratylenchus*, (L) *Rotylenchus*, (M) *Tylenchorynchus* and (N) *Tylenchus*

basal knobs and slender, cylindrical bodies. The tail was conoid to rounded, often terminating in a narrow-rounded region (Plate 2K). *Rotylenchus* spp. typically assumed a relaxed C-shape upon heat-killing. These nematodes exhibited a moderately developed stylet with rounded knobs and a tail that narrowed gradually, terminating in a slightly curved or pointed tip (Plate 2L). *Tylenchorhynchus* spp. showed a well-developed stylet with prominent basal knobs and a cephalic region that was slightly offset from the body. The lip region showed moderate sclerotization. Tail morphology varied among individuals, ranging from bluntly rounded conoid to cylindrical or clavate forms with smooth terminations, typical of stunt nematodes (Plate 2M). *Tylenchus* spp. were identified by their distinctively long, filiform tail tapering to a fine point. Their slender bodies and delicate stylets were visible under high magnification (Plate 2N).

Seasonal Nematode Population Dynamics

Quantitative analysis of nematode populations revealed notable seasonal fluctuations in the density of all six major plant-parasitic nematode genera across the five guava-growing locations. The population dynamics exhibited a clear pattern influenced by both seasonal changes and site-specific conditions.Among all the genera, *M. enterolobii* exhibited the highest population densities in every location and season, confirming its dominance in guava rhizospheres, followed by *Helicotylenchus* (Fig. 1). The peak population of *M. enterolobii* was observed during the monsoon season, particularly at Muthagdalli and Orati Agrahara, where average counts exceeded 450 individuals per 200 cc of soil.

Helicotylenchus was the second most prevalent genus, with moderately high populations across seasons and peaks recorded during summer at Shivakote and Muthagdalli. *Pratylenchus* exhibited higher densities in monsoon and summer with marked reductions in winter, the highest counts being observed at Muthagdalli and Shivakote. *Rotylenchus* and *Tylenchorhynchus* also showed peak populations during monsoon followed by gradual declines, with Shivakote recording the highest densities, particularly for *Tylenchorhynchus*. *Tylenchus*, though comparatively lower in density, followed the same seasonal pattern. Overall, nematode populations were consistently highest during monsoon, intermediate in summer and lowest in winter across all locations.

A marked seasonal variation was observed in nematode populations across all locations, with reductions consistently greater from monsoon to winter than from monsoon to summer (Table 1). Root-knot nematodes (RKN) showed reductions ranging from 17.95 to 24.39 per cent in summer and 43.59 to 51.22 per cent in winter. Similar trends were noted for spiral, lesion, reniform, stunt and *Tylenchus* spp., where winter reductions were nearly double those in summer. Among locations, Shivakote and Muthagdalli recorded relatively higher reductions for most genera, particularly lesion and stunt nematodes, which showed winter declines

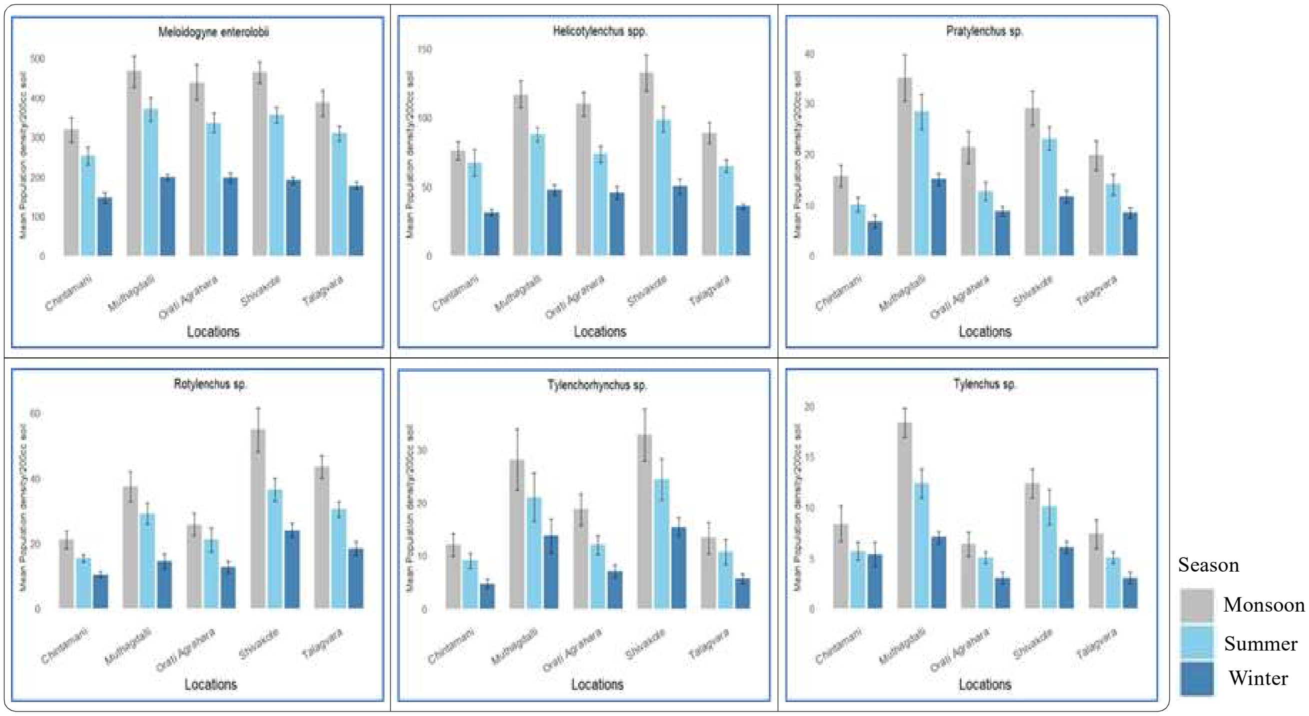

Fig. 1 : Seasonal variation in the mean population densities of six plant-parasitic nematode groups across five guava-growing locations in Karnataka. Error bars represent standard errors of the mean

Table 1

Percent reduction in nematode population from monsoon to winter and summer

Locations	RKN		Spiral N		Lesion N		Reniform N		Stunt N		Tylenchus	
	W (%)*	S (%)*	W (%)*	S (%)*	W (%)*	S (%)*	W (%)*	S (%)*	W (%)*	S (%)*	W (%)*	S (%)*
Chintamani, Chikkaballapur	43.75	18.75	45.45	18.18	50.00	25.00	50.00	33.33	60.00	20.00	53.33	33.33
Muthagdalli, Bengaluru Rural	51.22	24.39	42.31	15.38	58.33	33.33	50.00	25.00	57.14	28.57	50.00	25.00
Orati Agrahara, Kolar	43.59	17.95	41.67	16.67	55.56	22.22	42.86	28.57	50.00	33.33	46.67	33.33
Shivakote, Bengaluru Rural	46.67	20.00	35.71	14.29	50.00	20.00	50.00	30.00	50.00	25.00	50.00	25.00
Talagvara, Kolar	50.00	22.50	39.13	13.04	50.00	25.00	55.56	33.33	50.00	16.67	46.67	33.33

*S (%): Percent reduction in nematode population from monsoon to summer, W (%): Percent reduction in nematode population from monsoon to winter

exceeding 55 per cent. Overall, nematode populations followed the seasonal order of abundance: Monsoon > Summer > Winter, indicating that winter conditions were least favourable for their survival.

Relationship between Soil Physico-Chemical properties and Nematode Population

Soil physico-chemical parameters exhibited clear seasonal variation across locations (Table 2). Soil pH was generally acidic to near neutral during monsoon (5.38-6.01), increasing to neutral or slightly alkaline values in summer (5.89-7.32) and winter (6.21-7.44). Electrical conductivity (EC) remained low across all sites and seasons, ranging from 0.11 to 0.29 dS/m, with slightly higher values in summer and winter compared to monsoon. Organic carbon (OC) content showed moderate seasonal variation, with values ranging from 0.36 to 0.64 per cent and was consistently higher in summer. Soil moisture content was highest during monsoon (42-56%) and declined markedly in winter (14-25%). In contrast, soil temperature peaked in summer (27-29 °C) and dropped to its lowest in winter (16-20 °C). These seasonal shifts highlight the influence of rainfall and climatic conditions on soil properties across guava-growing regions.

Canonical Correspondence Analysis (CCA) revealed clear seasonal variation in the relationships between soil physico-chemical parameters and plant-parasitic nematode communities across locations (Fig. 2). During the monsoon (July), nematode genera such as *Tylenchorhynchus*, *Meloidogyne* and *Pratylenchus* showed moderate associations with soil moisture and pH, indicating that these parameters were key drivers of nematode distribution during this period. Locations including Chintamani and Orati Agrahara were positioned closer to soil temperature and pH vectors, suggesting their influence on nematode assemblages.

In summer (April), soil temperature and moisture exerted greater influence on nematode distribution, with sites such as Muthagalli and Shivakote showing closer alignment with these variables. Nematode genera remained clustered near the ordination center, indicating a more uniform distribution across sites under high-temperature conditions. During winter (November), the ordination displayed weaker associations between nematode populations and soil variables, reflecting a general decline in nematode activity during cooler months. Soil temperature and pH retained some influence, particularly at Talagvara and Shivakote, whereas Chintamani and Orati Agrahara were positioned further from key environmental gradients. Overall, CCA indicated that soil moisture and pH were the dominant factors

TABLE 2

Soil physico-chemical properties recorded across five representative locations during monsoon, summer and winter

Location	Monsoon					Winter					Summer				
	pH	EC dS/m	OC (%)	Moisture (%)	Temperature (%)	pH	EC dS/m	OC (%)	Moisture (%)	Temperature (%)	pH	EC dS/m	OC (%)	Moisture (%)	Temperature (%)
Chintamani, Chikkaballapur	5.38	0.13	0.42	53.00	25.00	6.98	0.21	0.52	24.00	17.00	6.88	0.18	0.56	42.00	28.00
Muthagdalli, Bengaluru Rural	5.54	0.25	0.39	48.00	26.00	6.72	0.25	0.54	18.00	16.00	6.12	0.28	0.58	38.00	28.00
Orati Agrahara, Kolar	6.01	0.19	0.51	39.00	25.00	7.44	0.29	0.59	14.00	18.00	7.32	0.24	0.64	22.00	27.00
Shivakote, Bengaluru Rural	5.89	0.11	0.47	56.00	25.00	6.21	0.21	0.54	20.00	17.00	5.89	0.14	0.50	36.00	28.00
Talagvara, Kolar	5.94	0.13	0.36	45.00	26.00	6.60	0.19	0.52	19.00	20.00	6.74	0.16	0.48	25.00	29.00

shaping nematode communities during the monsoon, temperature and moisture were more influential in summer and winter conditions were associated with reduced nematode activity and weaker environmental associations.

Correlation between *Meloidogyne* Population and Soil Moisture and Temperature

Since soil moisture and temperature are key environmental factors influencing nematode population dynamics, their relationship with *Meloidogyne* population density was analysed across three seasons (monsoon, summer and winter) in guava orchards. The results revealed a strong association between these soil physical parameters and the abundance of *Meloidogyne* second-stage juveniles (J2) (Fig. 3 and 4).

A clear seasonal trend was observed in the interaction between soil moisture and *Meloidogyne* population (Fig. 3). During the monsoon season (July), when soil moisture levels were relatively high (45-55%), the *Meloidogyne* J2 population also peaked, often exceeding 400 J2 per 200 cc of soil. In contrast, during the summer season (April), although moisture content declined to intermediate levels (25-35%), moderate nematode populations were still recorded, ranging between 250 and 350 J2 per 200 cc of soil. The lowest populations were recorded in the winter season (November), coinciding with the lowest soil moisture levels (15-25%), where J2 densities dropped below 200 per 200 cc of soil. This pattern suggests a positive correlation between soil moisture and nematode activity, with optimal population build-up occurring under higher moisture conditions typical of the monsoon period.

Similarly, soil temperature exhibited a significant relationship with *Meloidogyne* J2 density across seasons (Fig. 4). Population levels were highest when soil temperatures ranged between 24-26 °C during the monsoon, conditions that are conducive for nematode development and survival. As soil temperature increased to 28-30 °C during the summer months, nematode populations showed a slight decline, possibly due to suboptimal thermal

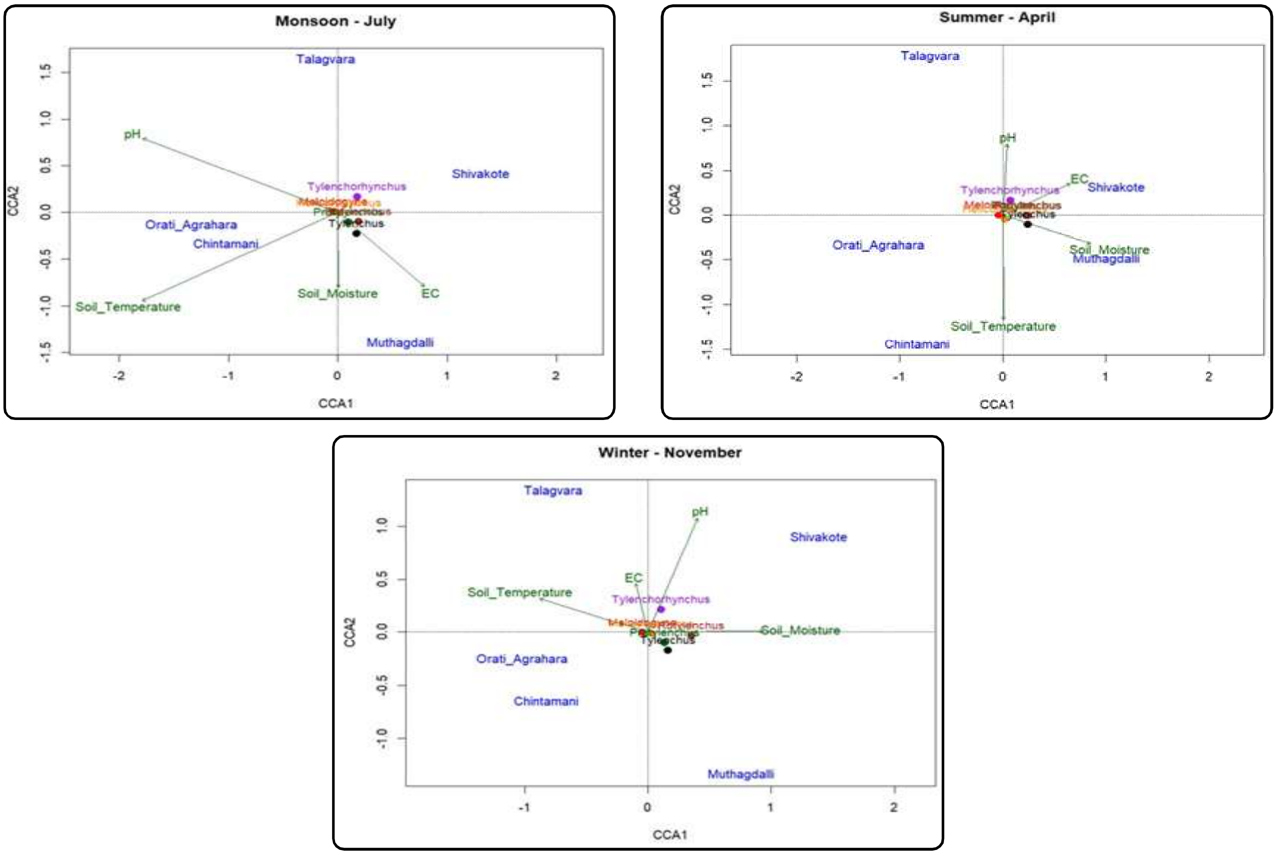

Fig. 2 : Canonical Correspondence Analysis (CCA) ordination biplots showing the relationship between soil physico-chemical parameters and nematode populations across five study locations during monsoon (July), summer (April), and winter (November). Arrows represent soil parameters, locations are shown in blue, and nematode genera in different colours

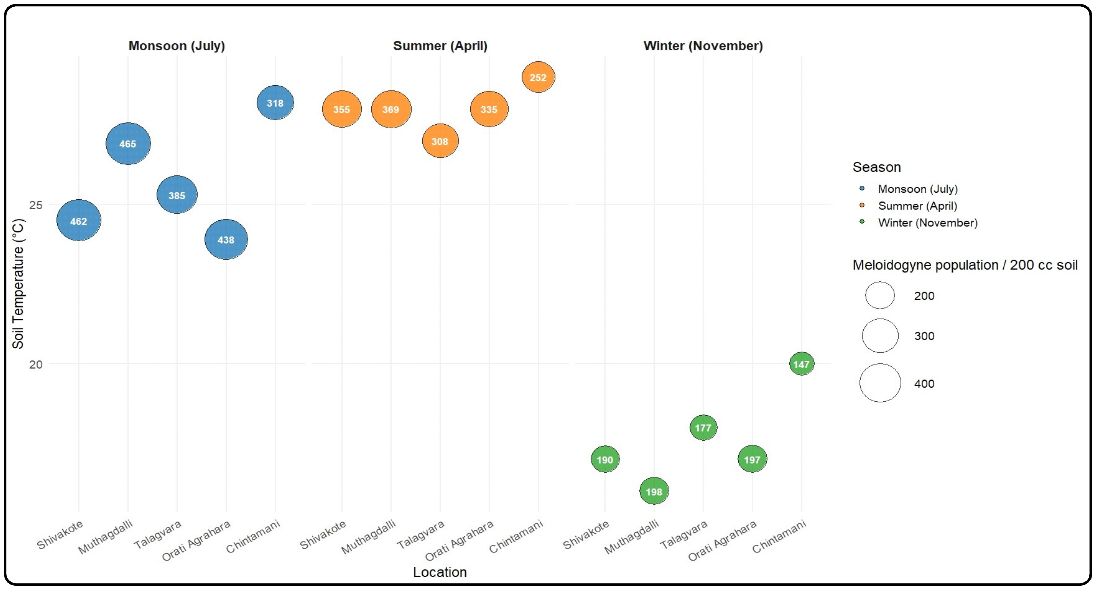

Fig. 3 : Bubble plot illustrating the relationship between soil moisture content and the population density of *Meloidogyne* juveniles in soil across three different seasons

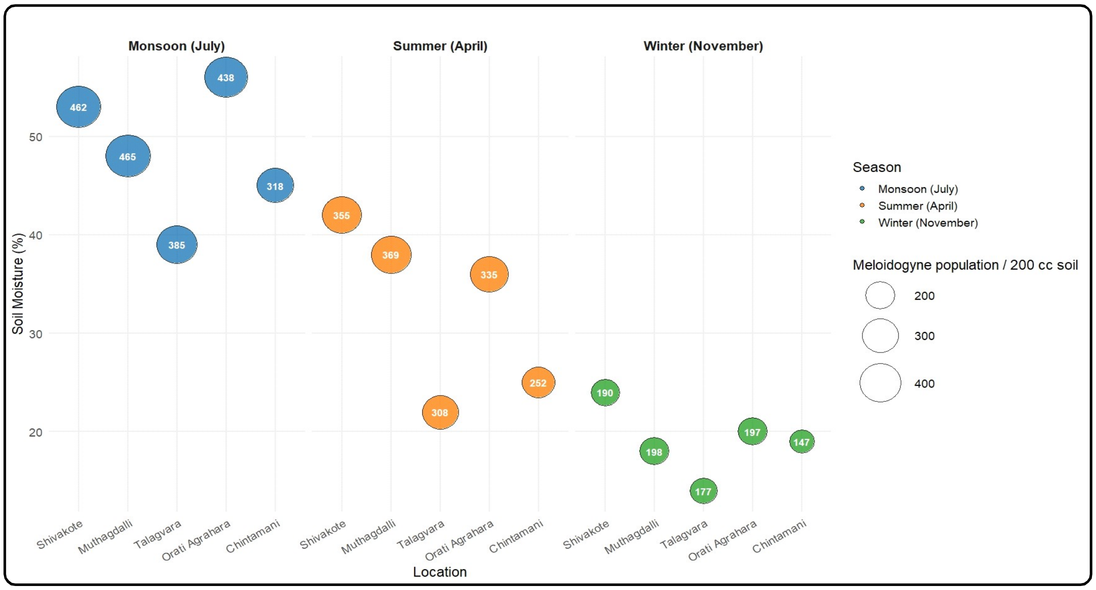

Fig. 4 : Bubble plot illustrating the relationship between soil temperature content and the population density of *Meloidogyne* juveniles in soil across three different seasons

conditions affecting reproduction and survival. In winter, soil temperatures dropped to 18-22 °C, coinciding with the lowest J2 populations, indicating reduced nematode activity under cooler soil conditions. Overall, these findings highlight that both soil moisture and temperature are critical determinants of *Meloidogyne* population dynamics. Optimal conditions of moderate to high soil moisture combined with warm temperatures enhance nematode multiplication, whereas extreme conditions-either low moisture or low temperature-limit their population growth.

The findings of this study deepen our understanding of plant-parasitic nematode (PPN) ecology in guava orchards in the Eastern Dry Zone of Karnataka, particularly emphasizing the increasing threat posed by *M. enterolobii*. While earlier work has documented its presence (Suresh *et al*., 2016 and Ghule *et al*., 2020), this study's detailed seasonal and soil-property correlations allow us to draw more nuanced conclusions relevant formanagement.

The detection of *M. enterolobii* across multiple districts underlines its shift from being a localized concern to a more widespread problem in guava production in India. Surveys in Uttarakhand, Uttar Pradesh, Haryana and now Karnataka have recorded its presence in increasingly diverse environments and orchard ages, including both mature and young trees (Rashid *et al.,* 2019). This expansion suggests that *M. enterolobii* is not only adapting to local soil and climatic conditions but is likely being spread via nursery stock, soil or weed hosts. Resistance screening in guava genotypes (Nagachandrabose *et al*., 2024) has begun to identify variation, but widespread resistant cultivars are as yet not available in many orchards.

The clear association between high nematode population densities during the monsoon and reductions in winter and summer is consistent with many PPN ecology studies. Soil moisture appears to act as a limiting factor for nematode reproduction and movement, especially for juvenile stages which desiccate more easily (Lei *et al*., 2025). These abiotic stress periods (low moisture, high temperature) seem to suppress PPN populations but may also select for more tolerant species (e.g. *Helicotylenchus*) capable of persisting under suboptimal conditions.

The seasonal variation in nematode populations observed in the present study highlights the strong influence of environmental conditions on their survival and multiplication. The higher densities of *Helicotylenchus* during summer, particularly at Shivakote and Muthagdalli, may be attributed to their spiral body form and ability to with stand drier conditions, which has been noted to favor their persistence in warmer soils (Fortuner and Merny, 1979). Similarly, *Pratylenchus* spp. showed higher populations during monsoon and summer, with sharp reductions in winter, reflecting their preference for moist conditions and active root growth phases (Castillo and Vovlas, 2007).

The peak densities of *Rotylenchus* and *Tylenchorhynchus* during monsoon, particularly in Shivakote, suggest that increased soil moisture and moderate temperatures during this season provide favourable conditions for their reproduction, consistent with earlier reports linking these genera with high soil moisture regimes (Sikora and Fernández, 2005). Although *Tylenchus* populations were comparatively low, they followed the same declining pattern from monsoon to winter, further supporting the role of soil and climatic factors in regulating nematode dynamics.

Overall, the seasonal abundance pattern-Monsoon > Summer > Winter-indicates that monsoon conditions are most favourable for the proliferation of plant-parasitic nematodes, while winter conditions markedly suppress populations. Similar seasonal declines under cold and dry conditions have been documented for several nematode species in tropical and subtropical systems (Barker & Koenning, 1998 and Carneiro *et al*., 2007). These findings emphasize the role of seasonal climatic factors in nematode ecology and have implications for timing management strategies to reduce nematode damage in guava ecosystems.

While moisture and temperature are key, other soil properties such as pH, nutrient status (K, N, P), organic carbon and texture modulate the severity of infestation in guava. For instance, the work of Vanitha & Subbarayappa (2022) showed that different forms of potassium and soil properties are strongly related, which could influence nematode proliferation indirectly through effects on plant nutrition and soil micro environment. Soils with suboptimal K availability may stress guava trees, reducing their ability to tolerate or suppress nematode damage. Similarly, organic carbon in soil influences microbial communities that may antagonize nematodes or influence root health. Also, there could be interactions: soils with high EC (electrical conductivity) during monsoon may stress plants, weakening defense or may affect nematode mobility or viability. Such interactions are less studied, but the present data suggest that management of soil fertility and structure could be an effective adjunct to direct nematode control.

The presence of *M. enterolobii* even in non-optimal seasons (albeit at lower densities) means that interventions should not only be timed for peaks (monsoon) but also maintain vigilance in off seasons. Off-season soil solarization, orchard floor hygiene (weed hosts), removal of infected roots might reduce inoculum carryover. Resistance screening is promising but adoption of resistant genotypes must consider region specific soil and climate interactions: a genotype resistant in one area might be less durable under the more moisture/temperature extremes of another. Moreover, eco-friendly control methods (e.g. organic amendments, bioagents) as emphasized by Nandan *et al*. (2022) have dual benefits: improving soil health and potentially reducing PPN damage.

Despite the insights generated in this study, several gaps remain that warrant further investigation. One major area of uncertainty is the ability of *Meloidogyne enterolobii* and other plant-parasitic nematodes to with stand environmental stress such as low soil moisture and high temperatures. Their survival strategies-whether through dormancy, migration to deeper soil layers or physiological adaptation-are not well documented. With climate change projections indicating more frequent droughts and erratic rainfall, there is a potential risk of selecting for more resilient nematode populations, thereby complicating control strategies. Another important gap lies in the complexity of pathogen interactions. Guava decline rarely results from nematodes alone; rather, *M. enterolobii* often interacts with fungal pathogens, root rots and opportunistic microbes, with these interactions likely modulated by soil moisture conditions. In wetter soils, for example, nematode-induced root injuries can greatly increase susceptibility to secondary fungal infections, aggravating disease severity.

The importance of early detection and monitoring cannot be overstated. Because visible symptoms such as wilting and yellowing typically appear only after severe root damage, reliance on symptom-based diagnosis results in delayed management. Molecular markers, nursery inspections and systematic surveillance across guava-growing districts can enable early identification of *M. enterolobii* infestations, reducing the risk of widespread establishment and providing farmers with timely windows for intervention.

In summary, this study reinforces that *M. enterolobii* poses a serious and growing threat to guava orchards in Karnataka, with establishment supported by moisture-temperature regimes common in monsoon, soil properties that affect root health and possibly by inadequate resistance in available genotypes. Effective management will likely require integrated strategies: deploying resistant guava genotypes, leveraging soil health improvements (organic matter, balanced nutrients), implementing cultural controls timed to the seasonal nematode cycle and exploring biologicals. Given the projected climate variability (changes in rainfall pattern, more frequent droughts/extreme weather), management strategies must be robust and adaptive. Further research should aim for multi-site, multi-season trials of promising eco-friendly approaches, as well as modelling of nematode population dynamics under future climatic scenarios, to anticipate risk and plan mitigation in guava cultivation.

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