



## Research Article

### Isolation and Characterization of Nematodes from Soil and Root Samples of Tomato

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#### ABSTRACT

The present study selected and identified nematodes from soil and root samples of tomato (*Solanum lycopersicum*) from soil in the tomato field at Lapai, Niger State, Nigeria. Five tomato fields with two tomato varieties (Roma VF and Ife-1) were sampled using the stratified random sampling technique to obtain soil and root samples. Baermann funnel method was used for soil samples and modified centrifugal flotation method for root samples to extract nematodes, which were identified according to their morphological features observed under a compound microscope, and morphological measurements were used for confirmation of the taxonomic classification. Four of the five taxa of nematodes identified belonged to genera (*Meloidogyne* spp., *Heterodera* spp., *Pratylenchus* spp., and *Xiphinema* spp.), while the fifth was identified to species (*Rotylenchulus reniformis*). Root samples contained significantly higher numbers of nematodes ( $135 \pm 8$  nematodes/g of root,  $n = 50$ ) than soil samples ( $75 \pm 5$  nematodes/g of soil,  $n = 100$ ; Welch's  $t$  (68.7) = 48.51;  $p < 0.001$ ). The most common taxon in both habitats was *Meloidogyne* spp. and it was not significantly different between the two tomato varieties. Key contributions from morphological measurements were in species identification and classification. The results of this study indicate the importance of plant parasitic nematodes in tomato production and their ecological function in soil-root interactions and the need for integrated nematode management in the study area.

**Keywords:** *Meloidogyne* spp.; Morphological characterization; Nematode ecology; Nematode isolation; Population density; Soil-root interactions; Tomato

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#### INTRODUCTION

In agricultural developed countries there has been a remarkable progress in plant nematology. Plant parasitic nematodes (PPNs) have been reported to cause significant losses in various countries, and are

currently a research priority in global agriculture (Mesa-Valle *et al.*, 2020). PPNs, particularly in subtropical and tropical regions with hot and dry climates, are a major threat to irrigated crops. In tropical and subtropical regions, plant parasitic

nematodes cause losses of 14.6% of the crop each year, and some fields suffer significant losses (Nicol *et al.*, 2011; Musa *et al.*, 2025). These obligate plant parasites are root parasites and may infect almost all vascular plants (Jones *et al.*, 2013a).

Typical PPNs of tomato crop are *Meloidogyne* spp., *Rotylenchulus* spp., *Pratylenchus* spp., *Helicotylenchulus* spp. and *Hoplolaimus* spp. (Lutuf *et al.*, 2018). PPNs are worms, which are small, worm-like, and have bilateral symmetry and a pseudocoelomate composed of multi-cellular structures. They exhibit diverse life styles, such as predatory, aquatic, terrestrial and parasitic (ectoparasitic, endoparasitic, semi-endoparasitic e.g. *Tylenchulus semipenetrans* and sedentary (Jones *et al.*, 2013b). They are unsegmented, but appear segmented because of annulations, lacking circulatory and respiratory systems but having developed feeding, digestive, excretory and reproductive systems (Jones *et al.*, 2013a). Information is available that *Helicotylenchulus* spp. in combination with other nematodes, can significantly reduce yields in *Amaranthus cruentus* and *Telfairia occidentalis* fields in Nigeria (Ogundele *et al.*, 2016). Further, *Rotylenchulus* has been regularly located in tomato crops in West Africa, but the impact on tomato production has been poorly investigated (Lutuf *et al.*, 2018).

Increased use of continuous nematicides, inorganic fertilizers, and growing nematode susceptible crops in light soils with little organic matter have been blamed for the increase of PPNs (Coyne *et al.*, 2018). Root-knot nematodes (RKN) (*Meloidogyne* spp.) are the most widespread and economically damaging PPNs causing more than 100 billion dollars of crop damage worldwide every year (Elling, 2013). They thrive best at soil temperatures around 25°C to 30°C (Faske *et al.*, 2021), are destructive on tomato crops, especially in small-holder farming systems (Noling, 2016) and are responsible for damage in smallholder farming systems.

Nematodes present in the soil and root samples collected from tomato crop of Lapai, Niger State were therefore isolated and characterized in order to determine the species composition, population density and morphology of nematodes.

## **MATERIALS AND METHODS**

### **Study Area**

The study was conducted in the Research and Teaching Farm of Ibrahim Badamasi Babangida University, Lapai, Niger State, Nigeria (9°04'03"N, 6°34'11"E). It is situated under a highland equatorial

climate with an annual average rainfall of about 1600 mm, short rain period being March to June and long rain period being August to October. The temperature ranges from 25°C to 37°C (maximum) and 20°C to 31°C (minimum). The soils are mainly loamy and coupled with the rains it is very agricultural with dairy, horticulture and maize production leading. The environment of these climates is conducive to growing tomatoes but also to the development of parasitic nematodes.

The geographical location of Ibrahim Badamasi Babangida University, Lapai, Niger State, Nigeria, is presented in Figure 1. The map was adapted from the authors' previously published study conducted at the same location (Tafida *et al.*, 2026).

### **Research Design**

In this study descriptive research design has been used to describe the morphological characters of the parasitic nematodes. This design allows for a detailed observation and documentation of physical attributes, important for accurate identification and classification. The study focused on the use of this approach, which was designed to allow a full description of several morphological characteristics, important for taxonomic and species analysis.

### **Sampling Techniques**

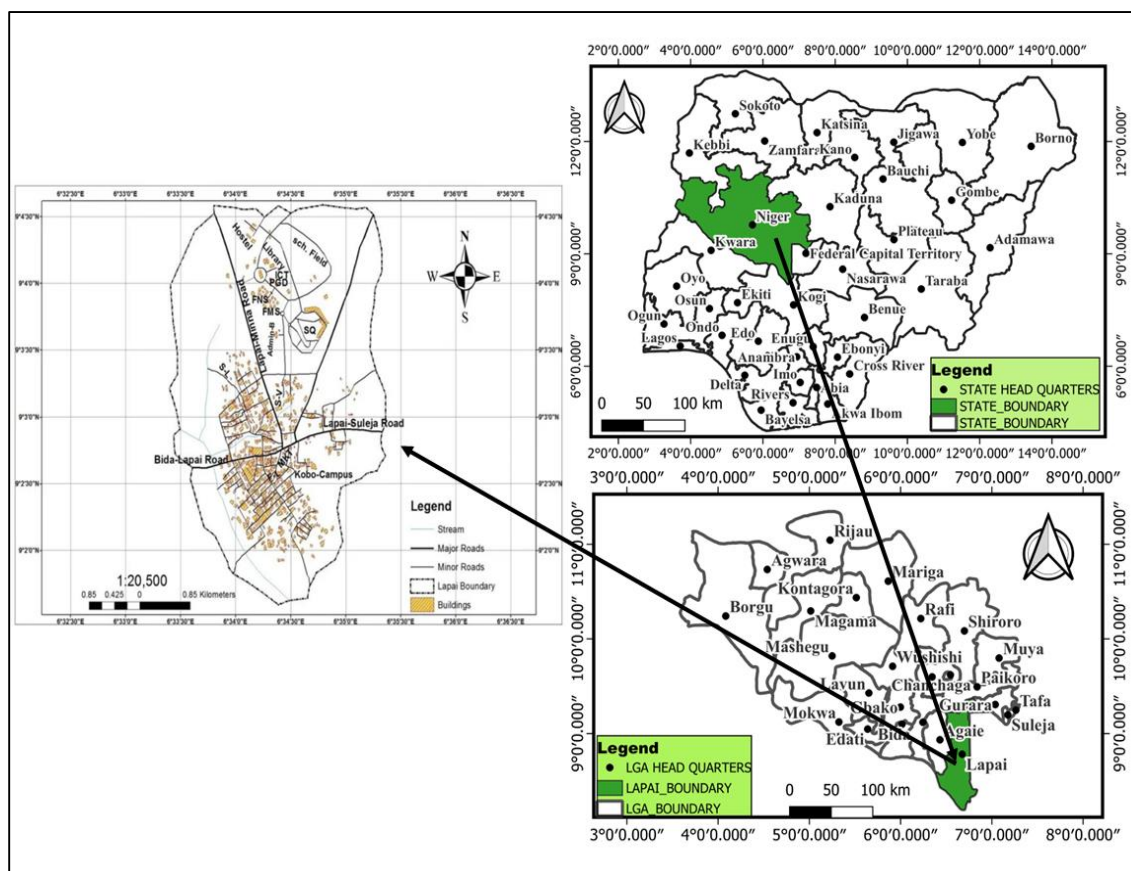
Two tomato varieties, 'Roma VF' and 'Ife-1', were used for this study. These varieties were selected by economic significance and the likelihood of being infested with nematodes (Noling, 2016).

### **Soil and Root Sampling**

The sampling was done during a 7-day period (May 12–18, 2025), which coincided with the flowering to the early fruiting stage of tomato crop. Five tomato fields in the university Research and Teaching Farm were sampled, with sites selected strategically using stratified random sampling in order to have representative soil and root samples. The samples were collected in four quadrants of each field, with the centre and periphery of each quadrant sampled at 15-30 cm depth, where nematodes are likely to be concentrated and where sampling is most likely to increase the chance of capturing nematodes in the root zone and soil matrix (Coyne *et al.*, 2018). This period falls within the short rainy season in Lapai, Niger State. The samples were taken from both varieties of tomatoes (Ife-1 and Roma VF) in each field. Ten soil samples and five root samples were collected in each of the two varieties in each field (n = 100 soil, 50 root). Nematode counts were standardized per gram of fresh root or soil weight to ensure consistency across samples.

Mean environmental conditions were recorded across the five fields during the sampling period. The soil was slightly acidic (pH  $6.4 \pm 0.2$ ) and loamy (about 45% sand, 35% silt and 20% clay). The soil moisture was  $22 \pm 3\%$  gravimetrically and soil temperature in

15–30 cm range of the soil profile was  $27.5 \pm 1.2\text{ }^{\circ}\text{C}$  during daytime and  $22\text{--}24\text{ }^{\circ}\text{C}$  during night. Ambient air temperature ranged  $29\text{--}32\text{ }^{\circ}\text{C}$  during day and  $22\text{--}24\text{ }^{\circ}\text{C}$  at night with relative humidity of 65–70%.



**Figure 1.** Map showing the geographical location of Ibrahim Badamasi Babangida University (IBBU), Lapai, Niger State, Nigeria

*Adapted from Tafida et al. (2026) under a Creative Commons Attribution (CC BY 4.0) license*

### Laboratory Procedures

Soil and root samples were processed by the Baermann funnel method (Baermann, 1917) and a modified centrifugal flotation method (Jenkins, 1964) for the recovery of nematodes. These methods are useful for extracting nematodes from soil and plant tissues and maintaining the morphology of the nematodes (Hallmann and Subbotin, 2018). Nematodes were removed for detailed study, and fixed in a solution of 4% formaldehyde, preserving their morphology. The fixed specimens were later transferred to a glycerin/water mixture for long-term preservation (Abebe et al., 2011). Nematodes were preserved in a drop of glycerin on a glass slide, covered with a coverslip and fixed with paraffin wax. This method makes specimens very clear and stable

for detailed morphological analysis (Hallmann and Subbotin, 2018).

### Morphological Characterization

Nematodes were studied using a compound microscope at 100x-1000x. Measurements and notes of key morphological characteristics such as body length and width, shape and size of the stylets, shape of the tail, and reproductive structures were taken (Powers et al., 1997). Nematode identification was made based on the standard taxonomic keys and descriptions from reputable sources such as the CABI Plant Nematology Handbook (Sikora et al., 2018) and the EPPO nematode extraction diagnostic protocol (EPPO, 2013). Most specimens were identified to genus level, although only species level identification was possible where diagnostic morphological

characters enabled a confident resolution (as with *Rotylenchulus reniformis*). Identification was cross checked with published morphological identification keys and available reference/voucher specimens and reference collections with regard to the observable morphological and morphometric features and selected representative specimens were kept as voucher material for confirmation.

#### **Data Analysis**

Data for morphological measurements and population density for each nematode species was presented as descriptive statistics (means, ranges and standard deviations) (McCune and Grace, 2002). The IBM SPSS Statistics software (Version 27; Field, 2018) was used for all statistical analysis. The formal normality testing was not performed; and the Welch's t-test was chosen because it does not require equal variances between groups and for moderate-to-large sample sizes per comparison ( $n = 50-100$ ) is fairly insensitive to moderate departures from normality. The overall comparison between nematode population density of soil and root samples, as well as for each of the five nematode taxa, was done using this test at the 5% significance level on a sample size of 100 nematodes per sample of soil and 50 nematodes per sample of root. The differences in frequency of occurrence of each taxon in Roma VF and Ife-1 tomato varieties were tested using the chi-square test of independence ( $n = 75$  tomato variety each). A Bonferroni correction was applied throughout these analyses (corrected for multiple testing at  $p < 0.01$ ) since 5 taxon level comparisons were made for each analysis. Note that samples were nested within five tomato fields, and these comparisons should be interpreted with caution; in future studies with larger numbers of samples a mixed-effects model with field as a random effect would be recommended to formally account for clustering at the field level.

## **RESULTS**

#### **Nematode Taxonomic Identification**

Five nematode taxa were identified from soil and root samples obtained from the tomato fields, four genera (*Meloidogyne* spp., *Heterodera* spp., *Pratylenchus* spp. and *Xiphinema* spp.) and one fully determined species, *Rotylenchulus reniformis* (Table 1). All the taxa had distinct morphs which allowed them to be identified and classified according to the criteria given in the CABI Plant Nematology Handbook (Jones *et al.*, 2013b).

#### **Nematode Population Density**

Table 2 shows population density of nematode species found in root and soil samples collected from the tomato fields and the results of species-level Welch's t-tests (Bonferroni adjusted threshold  $p < 0.01$ ). The root-knot nematode, *Meloidogyne* spp. was the most abundant, with a higher mean number found in roots ( $80 \pm 5$ ) than in soil ( $30 \pm 3$ ), this difference was significant ( $t(67.2) = 65.09$ ,  $p < 0.001$ ) due to their parasitic lifestyle. The root population was significantly greater than soil population of *Heterodera* spp. ( $25 \pm 3$  vs  $15 \pm 2$ ;  $t(71.5) = 21.32$ ,  $p < 0.001$ ) with cysts forming within root tissues providing *Heterodera* with survival and reproductive opportunities. *Pratylenchus* spp. (migratory nematode) was found significantly higher in roots ( $15 \pm 2$ ) than in soil ( $10 \pm 1$ ;  $t(61.5) = 16.67$ ,  $p < 0.001$ ) showing that they are not as specialized in parasitism as *Meloidogyne* spp. and *Heterodera* spp. but can infect and colonize root tissue. *Rotylenchulus reniformis* was also significantly more abundant in roots ( $10 \pm 1$ ) than in soil ( $5 \pm 1$ ;  $t(98.1) = 28.87$ ,  $p < 0.001$ ). The other four taxa had greater abundance in the roots, and significantly more abundance in the soil than did *Xiphinema* spp. ( $15 \pm 2$  roots vs.  $5 \pm 1$  soil;  $t(148.0) = -40.83$ ,  $p < 0.001$ ; respectively), suggesting *Xiphinema* spp. is better adapted to soil environments and has comparatively little colonization of roots. Overall, there were  $75 \pm 5$  nematodes per gram of soil and  $135 \pm 8$  nematodes per gram of root, indicating a higher concentration of nematodes in the roots.

#### **Nematode Distribution by Tomato Variety**

Table 3 gives the frequency of occurrence of each nematode taxon in the 75 samples collected from each tomato variety (Roma VF and Ife-1). Both varieties had a high percentage of occurrence of *Meloidogyne* spp. In Ife-1, the number of occurrences per 100 samples was higher for all five taxa, but chi square tests of independence, with the adjusted threshold of  $< 0.01$ , revealed no significant difference between Ife-1 and Roma VF, and no strong evidence that Ife-1 is more susceptible to any of the taxa examined at this sample size.

#### **Morphological Measurements**

Summary of morphological measurements for the identified species of nematodes is given in Table 4. *Xiphinema* spp. had the longest body (mean length  $2100 \mu\text{m}$ ) and *Heterodera* spp. the shortest (mean length  $350 \mu\text{m}$ ). The length of the stylet also differed between the species; the longest stylet (mean =  $145 \mu\text{m}$ ) was seen in *Xiphinema* spp., consistent with its ectoparasitic feeding habit. The measurements are

very important for correct identification and taxonomy of the species.

**Table 1. Nematode taxa identified from soil and root samples of tomato**

| Nematode Species                | Common Name         | Habitat(s) Detected |
|---------------------------------|---------------------|---------------------|
| <i>Meloidogyne spp.</i>         | Root-knot nematodes | Soil/Roots          |
| <i>Heterodera spp.</i>          | Cyst nematodes      | Soil/Roots          |
| <i>Pratylenchus spp.</i>        | Lesion nematodes    | Soil/Roots          |
| <i>Rotylenchulus reniformis</i> | Reniform nematodes  | Soil/Roots          |
| <i>Xiphinema spp.</i>           | Dagger nematodes    | Soil/Roots          |

All five taxa were detected in both soil and root samples; relative abundance in each habitat is presented in Table 2

**Table 2. Population density of nematode species in soil and root samples of tomato**

| Nematode Species                | Soil (Nematodes/g) | Root (Nematodes/g) | Welch's t (df) | p-value | Cohen's d |
|---------------------------------|--------------------|--------------------|----------------|---------|-----------|
| <i>Meloidogyne spp.</i>         | 30±3               | 80±5               | 65.09 (67.2)   | <0.001* | 13.22     |
| <i>Heterodera spp.</i>          | 15±2               | 25±3               | 21.32 (71.5)   | <0.001* | 4.21      |
| <i>Pratylenchus spp.</i>        | 10±1               | 15±2               | 16.67 (61.5)   | <0.001* | 3.54      |
| <i>Rotylenchulus reniformis</i> | 5±1                | 10±1               | 28.87 (98.1)   | <0.001* | 5.00      |
| <i>Xiphinema spp.</i>           | 15±2               | 5±1                | -40.83 (148.0) | <0.001* | -5.77     |
| Total                           | 75±5               | 135±8              | 48.51 (68.7)   | <0.001* | 9.74      |

Values are mean  $\pm$  standard deviation. \*Significant after Bonferroni correction for five comparisons (adjusted threshold  $p < 0.01$ ). A positive  $t$  indicates higher density in roots; a negative  $t$  (*Xiphinema spp.*) indicates higher density in soil. Cohen's  $d$  was calculated from the reported means and pooled standard deviations (positive values indicate higher density in roots, consistent with the sign convention for  $t$ ). Samples were nested within five tomato fields; see Materials and Methods and Limitations for the corresponding caveat.

**Table 3. Frequency of occurrence (%) of nematode taxa in Roma VF and Ife-1 tomato samples**

| Nematode Taxon                  | Roma VF (%) | Ife-1 (%) | Combined (%) | $\chi^2$ (p-value) |
|---------------------------------|-------------|-----------|--------------|--------------------|
| <i>Meloidogyne spp.</i>         | 64.0        | 74.7      | 69.3         | 0.62 (0.433)       |
| <i>Heterodera spp.</i>          | 28.0        | 36.0      | 32.0         | 0.77 (0.381)       |
| <i>Pratylenchus spp.</i>        | 45.3        | 52.0      | 48.7         | 0.34 (0.558)       |
| <i>Rotylenchulus reniformis</i> | 37.3        | 44.0      | 40.7         | 0.44 (0.506)       |
| <i>Xiphinema spp.</i>           | 20.0        | 25.3      | 22.7         | 0.47 (0.493)       |

Values represent the percentage of samples (out of  $n = 75$  per variety) in which each taxon was detected. Because more than one taxon could be detected in the same sample, percentages within a column do not sum to 100%. Chi-square tests (1 df) compared Roma VF vs. Ife-1 for each taxon; none were significant after Bonferroni correction for five comparisons (adjusted threshold  $p < 0.01$ ).

**Table 4. Morphological measurements of nematode species identified in tomato samples**

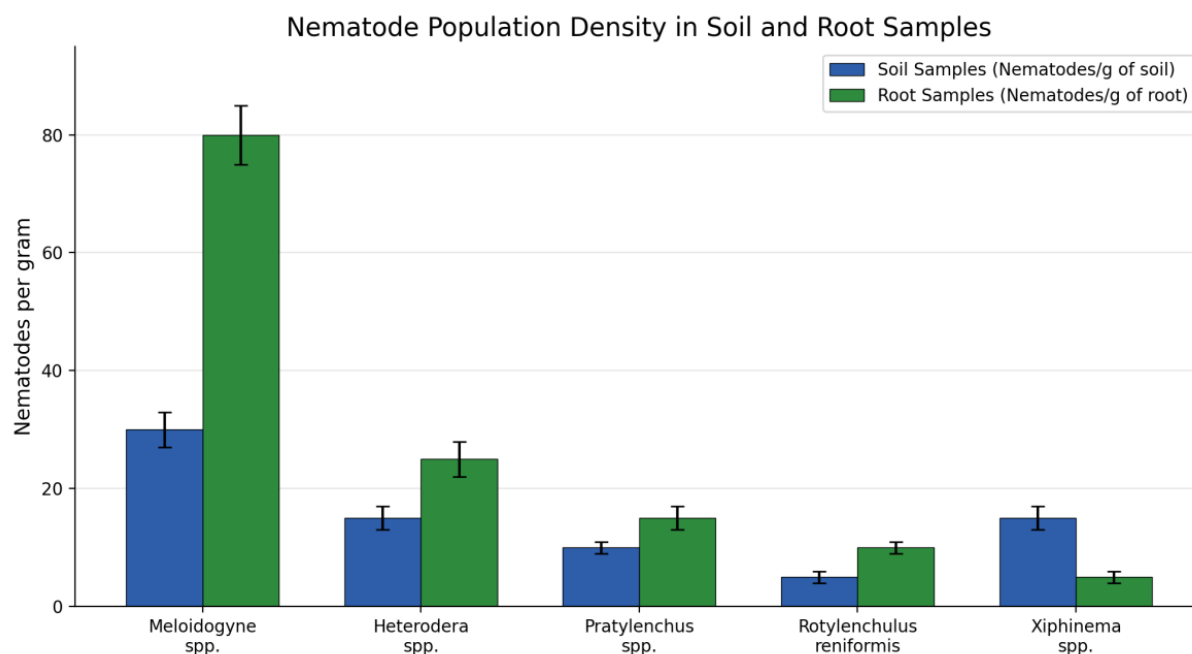
| Nematode Species                | Body Length ( $\mu\text{m}$ ) | Stylet Length ( $\mu\text{m}$ ) | Tail Length ( $\mu\text{m}$ ) |
|---------------------------------|-------------------------------|---------------------------------|-------------------------------|
| <i>Meloidogyne spp.</i>         | 750 $\pm$ 50                  | 18 $\pm$ 2                      | 70 $\pm$ 10                   |
| <i>Heterodera spp.</i>          | 350 $\pm$ 30                  | 20 $\pm$ 2                      | 45 $\pm$ 5                    |
| <i>Pratylenchus spp.</i>        | 600 $\pm$ 40                  | 12 $\pm$ 1                      | 60 $\pm$ 8                    |
| <i>Rotylenchulus reniformis</i> | 500 $\pm$ 35                  | 14 $\pm$ 2                      | 50 $\pm$ 7                    |
| <i>Xiphinema spp.</i>           | 2100 $\pm$ 250                | 145 $\pm$ 12                    | 75 $\pm$ 10                   |

The following diagnostic characters were used in addition to morphometric measurements summarised in Table 4 to identify each taxon. The characteristic perineal pattern was present in all the females of *Meloidogyne spp.*, which had a high dorsal arch, coarse striae and prominent lateral lines, whereas the males had an elongated body and a relatively short stylet. *Heterodera spp.* were

identified by lemon-shaped cysts with a vulval cone bearing a fenestra and underbridge, and the presence of bullae. *Pratylenchus spp.* were recognised as slender migratory endoparasites with a short stylet ( $\sim 12 \mu\text{m}$ ), oesophageal glands overlapping the intestine, and a rounded tail tip. *Rotylenchulus reniformis* was characterized by the reniform (kidney-shaped) body of mature females that is semi-

endoparasitic, the anterior end being embedded in the root cortex and the posterior end free in the soil. *Xiphinema* spp. were identified by a long odontostyle with a flanged base (~145 µm), slit-like amphidial apertures, and a conoid tail with a rounded terminus. Morphometric measurements were taken from 25 individuals of *Meloidogyne* spp., 20 of *Heterodera* spp., 20 of *Pratylenchus* spp., 15 of *Rotylenchulus reniformis*, and 20 of *Xiphinema* spp. Preserved

voucher samples on glycerin slides were submitted to the Nematology Laboratory Department of Biology, Ibrahim Badamasi Babangida University, Lapai Nigeria under the numbers IBBU-NEM-2025-01 to IBBU-NEM-2025-100 with 15–25 voucher slides catalogued per taxon. Photomicrographs of diagnostic structures were not taken in this study, but will be added in future work to complement the morphometric data presented here.



**Figure 2.** Bar chart showing nematode population density in root and soil samples of tomato. Error bars represent  $\pm 1$  standard deviation

## DISCUSSION

The aim of this study was to identify, morphologically characterize and find the distribution of parasitic nematodes in soil and root samples of tomato. Results indicated the presence of a variety of nematode species, with *Meloidogyne* spp., *Heterodera* spp. and *Pratylenchus* spp. the most common. Notably, *Meloidogyne* spp. made up a high proportion of the nematode population, with the densities of nematodes in the root samples reaching 80 nematodes/g, while in soil samples it was 30 nematodes/g (Table 2). The predominance of *Meloidogyne* spp. is a reflection of the general pattern observed across vegetable production systems in West Africa, where the genus has been reported to cause severe reductions in plant productivity, such as that of *Amaranthus cruentus* and *Telfairia occidentalis* in Nigeria by Ogundele *et al.* (2016) which reported severe impact of *Meloidogyne incognita* and associated phytoneutodes.

Nematode populations were significantly greater in root samples (mean = 135 nematodes/g) than in soil samples (mean = 75 nematodes/g;  $t(68.7) = 48.51$ ;  $p < 0.001$ ) suggesting nematodes had a strong affinity for the rhizosphere where they can locate nutrients and develop parasitic relationships. This distribution pattern is typical of the ecological behaviour of endoparasitic nematodes, which rely on root tissue as a feeding-site and as a protected reproductive habitat (Jones *et al.*, 2013a), and so can cause a high level of infection in a small area, which can have a significant effect on plant health and yield. Interestingly, this was not true for all taxa, as four taxa out of five had significantly more root than soil abundance at the species level. All three (*Meloidogyne* spp., *Heterodera* spp., and *Pratylenchus* spp.) are sedentary or migratory endoparasites, which reproduce and feed exclusively within root tissue, reflecting their close association with the roots.

*Rotylenchulus reniformis* is also significantly more abundant in the roots, but can be more precisely classified as a semi-endoparasitic species, as its anterior end invades the root cortex to feed, whereas its posterior remains in the surrounding soil. Its significant root association suggests it is more ecologically similar to the fully endoparasitic taxa than to the ectoparasitic *Xiphinema* spp. in this study system. This was the opposite of *Xiphinema* spp. which was significantly more abundant in soil than in roots, being an ectoparasitic dagger nematode which lives on the surfaces of the roots in the surrounding soil and does not enter the root tissues at all.

This taxon-specific divergence indicates that comparing soil and root preference only may mask any significant differences in habitat preference among feeding guilds on the endoparasitic-ectoparasitic continuum, and that management strategy may need to be different within each feeding guild than within the next. The morphological measurements of the identified species of nematodes were also used to gain an additional insight into their characterization: The body length of *Meloidogyne* spp. was largest (mean = 750 µm) among the species analyzed, while the body length of *Heterodogone* spp. was the smallest (mean = 350 µm) (Table 4). This diversity in morphology highlights the difficulties associated with the accurate identification and management of nematodes, and shows the importance of the need for an in-depth morphological characterization for effective management. The results can also be compared with the most similar previous study in the sub-region, that of Lutuf *et al.* (2018) which studied the plant-parasitic nematodes of tomato under three agro-ecological zones in Ghana.

The current study identified four of the five taxa (*Meloidogyne* spp., *Pratylenchus* spp., *Rotylenchulus* spp. and *Xiphinema* spp.) also reported by Lutuf *et al.* (2018), which adds to the consistency of these genera as being encountered with tomato in West Africa. Interestingly, however, the community composition was different in the Ghanaian survey, as *Heterodera* spp., was absent, and *Helicotylenchus* spp., *Hoplolaimus* spp., *Scutellonema* spp. and *Tylenchus* spp. were not found in the present survey, which may be attributed to variations in soil conditions, cropping history and/or nematode distribution between the two areas of study. In accordance with the present results, Lutuf *et al.* (2018) also recorded greater occurrence of *Meloidogyne* spp. in the tomato root (69.3%) as compared to soil (37.4%) and this pattern

of more root colonization than soil colonization with this genus is also noted here.

Overall, the frequencies of occurrence (Table 3) recorded in the present study were, however, significantly higher across all five taxa compared to the corresponding soil prevalence levels reported by Lutuf *et al.* (2018) (e.g. 11.0% for *Rotylenchulus* spp. and 1.4% for *Xiphinema* spp. in Ghana, vs 40.7% and 22.7% respectively in the present study) and this should not be taken as necessarily representing a higher level of infestation in the region, but rather be interpreted in the context of the smaller more intensively sampled area of the present study (one research farm) compared to the wider multi-community study design used by Lutuf *et al.* (2018). The present results also contribute to the goal set by Lutuf *et al.* (2018) of further exploring the economic effects of *Rotylenchulus* spp. on tomato as its effect in West Africa was shown to be under studied, although it consistently appeared in the roots. The significant difference in root-versus-soil density for *Rotylenchulus reniformis* observed here (Table 2) provides new quantitative evidence for the distribution pattern of *Rotylenchulus* spp. in tomato which supports further investigation into the effects of *Rotylenchulus* spp. on tomato. The highest frequency of occurrence of *Meloidogyne* spp. was in both the Roma VF and Ite-1 varieties. The occurrence was slightly higher in the Ite-1 for all five taxa; however, none of these differences was statistically significant at this sample size based on chi-square testing (Table 3) and so there was no strong evidence of differential susceptibility between the two varieties. The overall high frequency of occurrence for both varieties nevertheless indicates the economic importance and vulnerability of tomato crops to nematode attack, similar to global estimates for plant-parasitic nematodes which result in significant losses in tropical and subtropical crops (Nicol *et al.*, 2011).

Furthermore, the high root:soil ratios of nematodes were not only substantiated by the significant difference between root and soil samples ( $t(68.7) = 48.51$ ,  $p < 0.001$ ), but they also support the idea that root systems provide a crucial shelter and feeding ground for nematodes, a place in which they can grow and be active (Jones *et al.*, 2013a). This finding must be interpreted with some caution because the samples were nested within five fields, and should be replicated by a study with a mixed-effects design that considers the clustering of samples within fields. The findings also indicate that there may be certain farming activities that may contribute to the build-up

of nematodes: continuous cropping of susceptible tomato varieties may result in higher nematodes density, since more of the root samples were found to be infested with nematodes. This highlights the importance of managing nematodes in an integrated pest management program using crop rotation and resistant varieties.

The overall and species-level soil-versus-root comparisons were statistically significant, but may underestimate the uncertainty of those estimates due to the fact that samples were nested within five tomato fields; future studies should adopt a mixed-effects model design with field included as a random effect to formally account for the uncertainty due to field-level clustering. Species identification was done only by using morphological characteristics; molecular confirmation (e.g., PCR-based diagnostics) would improve future species identification.

## CONCLUSIONS

In the present study, five taxa of parasitic nematodes were identified, four genera and one fully resolved species in the soil and root samples of tomato, and *Meloidogyne* spp. was found to be the most abundant. Results showed significantly higher density of nematodes in root samples, suggesting their preference for root surface; this is where nutrients are available and where they have the opportunity to start developing parasitic relationships. The results highlight the significant effect of nematode attack on tomato productivity and the importance of proper management. To reduce the detrimental impact of these pests, enhanced identification procedures, IPM strategies, and frequent monitoring are recommended.

## AUTHOR CONTRIBUTIONS

Conceptualization, A.M.T.; supervision, Y.A.; sample collection, A.M.T.; methodology and laboratory analysis, K.M.S.; formal analysis and data curation, A.M.; investigation and morphological characterization, G.G.D.; investigation and data collection, B.Y.D.; writing original draft, A.M.T.; writing review and editing, Y.A., K.M.S., A.M. and G.G.D. All authors read and approved the final manuscript.

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## DECLARATION OF AI (Artificial Intelligence)

The authors hereby declare that no generative Artificial Intelligence (AI) technologies such as Large Language Models (ChatGPT, COPILOT, XLNet, Emie 3.0 Titan etc) and text-to-image generators have been used during writing or editing of this manuscript.

## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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