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POPULATION DYNAMIC OF PLANT-PARASITIC NEMATODES AND VARIETAL SUSCEPTIBILITY IN SOLANACEAE AND CUCURBITACEAE CROPS IN YAMO USSOUKRO, CENTRAL CÔTE D'IVOIRE

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ABSTRACT

Vegetable crops play a significant role in Côte d'Ivoire's agriculture but face challenges from various pests, including plant-parasitic nematodes. Integrated pest management (IPM), which combines selecting resistant crop varieties and optimizing chemical treatment timing, is one strategy to manage these pests. This study aimed to investigate nematode population dynamic and varietal susceptibility in Solanaceae and Cucurbitaceae crops in Yamoussoukro, Côte d'Ivoire. Eight vegetable crop varieties were planted in a randomized block design under natural conditions over two consecutive years without nematicide application. The tested crops included cucumber (F1 Tokyo and Poinsett+), zucchini (Color and Koubera), bell pepper (Simbad and Yolo Wonder), and tomato (F1 Cobra 26 and Mongal). Observations at flowering and harvest stages provided data on aerial and root symptoms, prevalence, severity, and nematological analysis. These data were subjected to analyses of variance at the 5% significance level. Based on the severity and population density of the nematodes, a hierarchical analysis of principal components (HCPC) was carried out to cluster the different varieties. The main symptoms were root galls, leaf yellowing, wilting, and stunted growth. Five plant parasitic nematode genera were identified: *Meloidogyne*, *Radopholus*, *Pratylenchus*, *Helicotylenchus*, and *Rotylenchulus*, with *Meloidogyne* being dominant, representing 48% and 87% of the nematode populations in cucumber and bell pepper, respectively. The population of *Meloidogyne* decreased globally from 15,999 individuals per 100 g of root in year one to 5,992 in year two. However, populations increased from the flowering (6,009 individuals/100 g root) to the harvest stage (15,522 individuals/100 g root). F1 Tokyo, Poinsett+, and F1 Cobra 26 varieties were susceptible to root-knot nematode because their severity was greater than 50%. The moderately resistant varieties were Simbad, Yolo Wonder, Color, Koubera and Mongal, with severity levels of between 10-50%. These findings offer valuable insights for growers on varietal selection and treatment timing and support the recommendation of crop rotation, mainly to avoid successive crop plantings from the same family. Additionally, Yolo Wonder, Simbad, Mongal, Poinsett+, and Koubera should be recommended for cultivation in nematode infested areas.

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INTRODUCTION

Cultivated plants face numerous challenges, both abiotic and biotic. Abiotic factors include nutrient deficiencies, temperature fluctuations, soil moisture, drought, and soil salinity (Srivastava *et al.*, 2024), while biotic threats encompass infestations and infections caused by pests such as insects, rodents, viruses, bacteria, fungi, and plant-parasitic nematodes (PPNs) (Bolaji *et al.*, 2021). Among these, PPNs significantly hinder agricultural productivity, especially in vegetable crops (Indarti *et al.*, 2023). Global agricultural losses attributable to nematode infestations account for approximately 14% of crop yield reductions, amounting to nearly USD 125 billion annually (Mesa-Valle *et al.*, 2020).

The primary PPNs affecting vegetables include *Meloidogyne* spp., *Rotylenchulus reniformis*, *Pratylenchus* spp., *Helicotylenchus* spp., *Hoplolaimus* spp., *Heterodera* spp., and *Globodera* spp. (potato cyst nematode), with the root-knot nematode (*Meloidogyne* spp.) being the most pervasive and destructive (Khan *et al.*, 2023). Losses caused by these nematodes are more pronounced in tropical regions than in temperate ones (De Waele & Elsen, 2007), with some estimates suggesting that annual crop yield reductions in Africa could be much higher (Onkendi *et al.*, 2014). The most vulnerable crops are from the Solanaceae and Cucurbitaceae families, with tomatoes being particularly susceptible to PPNs (Tagiev, 2015). For instance, in tomato crops in tropical regions, losses can reach up to 30% (Baale *et al.*, 2021). In South Africa, annual losses of agricultural and horticultural crops due to nematodes exceed 14%, representing an economic impact of over € 1.9 billion (Lado *et al.*, 2020). In Egypt, the root-knot nematode of the genus *Meloidogyne* occurred at a frequency of 100% in vegetable crops (El-Nuby *et al.*, 2019). Frequencies between 50 and 100% were recorded for this nematode in chili crops, according to a study conducted in Niger (Haougui *et al.*, 2013). In Mali, out of nine nematode genera associated with vegetable crops, the genera *Meloidogyne* was dominant, with a frequency of 100% in the peri-urban area of Bamako (Touré *et al.*, 2019).

In Côte d'Ivoire, *Meloidogyne*, *Radopholus*, *Pratylenchus*, *Rotylenchulus*, and *Helicotylenchus* were associated with tomato cultivation with a higher frequency of the genera *Meloidogyne*, 100% in soil and root samples (Kacou *et al.*, 2021). In addition, a 91.67% prevalence of root galls due to the root-knot nematode *Meloidogyne* sp. was recorded in tomato crops in the Tchologo region (Coulibaly *et al.*,

2023). In addition, about ten nematode genera were associated with yam cultivation, including *Meloidogyne* sp. In the same study, root galls, cracks, and dry rot were the main symptoms observed on yam tubers, with severity indices ranging from 8.33 to 75% (Kouakou, 2018). In banana plantations, the nematode species *Radopholus similis*, *Pratylenchus coffeae*, *Helicotylenchus multicinctus*, *Hoplolaimus pararobustus*, and *Meloidogyne* spp. were recorded, with the first two species dominating (Yéo, 2019; Gnonhour, 2021). Additionally, *Meloidogyne* spp. have been documented to infest a high percentage of tomato roots and zucchini rhizospheres in Côte d'Ivoire (Yao *et al.*, 2023). *Meloidogyne* spp. pose a significant threat as they infest plant roots, causing severe physiological disruptions that result in reduced yields and lower product quality (Hamed *et al.*, 2024).

Identifying the presence of PPNs in agricultural plots is challenging due to their microscopic size, non-specific aerial symptoms, and habitat within the soil and root systems (Suyadi & Rofiansyah, 2017). Furthermore, continuous cropping of susceptible plants often leads to the proliferation of PPNs, making them a primary factor in reducing crop yields and quality (Saidova *et al.*, 2023). Moreover, high moisture, ferralitic soils with a sandy-clay texture, and high temperatures (25-30°C) are favorable conditions for the development of plant-parasitic nematodes (Gowda *et al.*, 2017; Tileubayeva *et al.*, 2021). Intensive vegetable cultivation is prevalent in regions such as Yamoussoukro in central Côte d'Ivoire, particularly in urban and peri-urban areas. Continuous cropping, often without crop rotation, exacerbates nematode infestations. Chemical control methods have been widely adopted to manage nematode populations. However, excessive use, especially without proper knowledge of varietal susceptibility or optimal application periods, presents significant health and environmental risks (Bhatt *et al.*, 2013). These challenges highlight the importance of researching nematode population dynamics and crop varietal resistance, which are crucial for developing effective integrated pest management strategies.

In Côte d'Ivoire, no studies have been conducted on the population dynamics of nematodes in vegetable crops, and research on the host status of plant varieties has been limited to yam, banana, and tomato. This study aims to assess nematode population dynamics and evaluate the susceptibility of various Solanaceae and Cucurbitaceae varieties cultivated in Yamoussoukro, Côte d'Ivoire. The

findings will contribute to the development of effective nematode management strategies.

MATERIALS AND METHODS

Study Site

The study was conducted in Yamoussoukro (Figure 1), located in central Côte d'Ivoire (5°30'W to 5°10'W and 6°36'N to 7°10'N). The region experiences a transitional equatorial climate, which supports a savannah woodland ecosystem interspersed with gallery forests. It is situated in the eastern part of the Bandama watershed and is characterized by low plateaus ranging in elevation from 32 to 471 meters. The soils in this area are essentially ferrallitic, stony, and gravelly, with some hydromorphic zones in low-lying areas (N'Guessan *et al.*, 2014). They vary in depth and exhibit rejuvenated, clayey-sandy textures with localized induration, all developed on granite (Yao-Kouamé & Allou, 2008). Yamoussoukro has significant

agricultural potential, benefiting from favorable climatic, environmental, and edaphic conditions that support the cultivation of food crops such as rice, yams, cassava, maize, soybeans, and groundnuts, as well as market garden produce, including cabbage, tomatoes, lettuce, cucumbers, and aubergines. These crops are grown both for commercial purposes and household consumption. Agriculture is the primary source of income for 89% of producers and represents, on average, 83% of farm households (Belmin, 2020). Most of these crops are cultivated in urban and peri-urban areas under an intensive farming system that places significant pressure on the land, creating favorable conditions for the proliferation of soilborne pathogens, including plant-parasitic nematodes (Kouakou *et al.*, 2016). The study site was specifically selected due to its history of severe nematode infestations, as reported by Kakou (2022) and Yao *et al.* (2023).

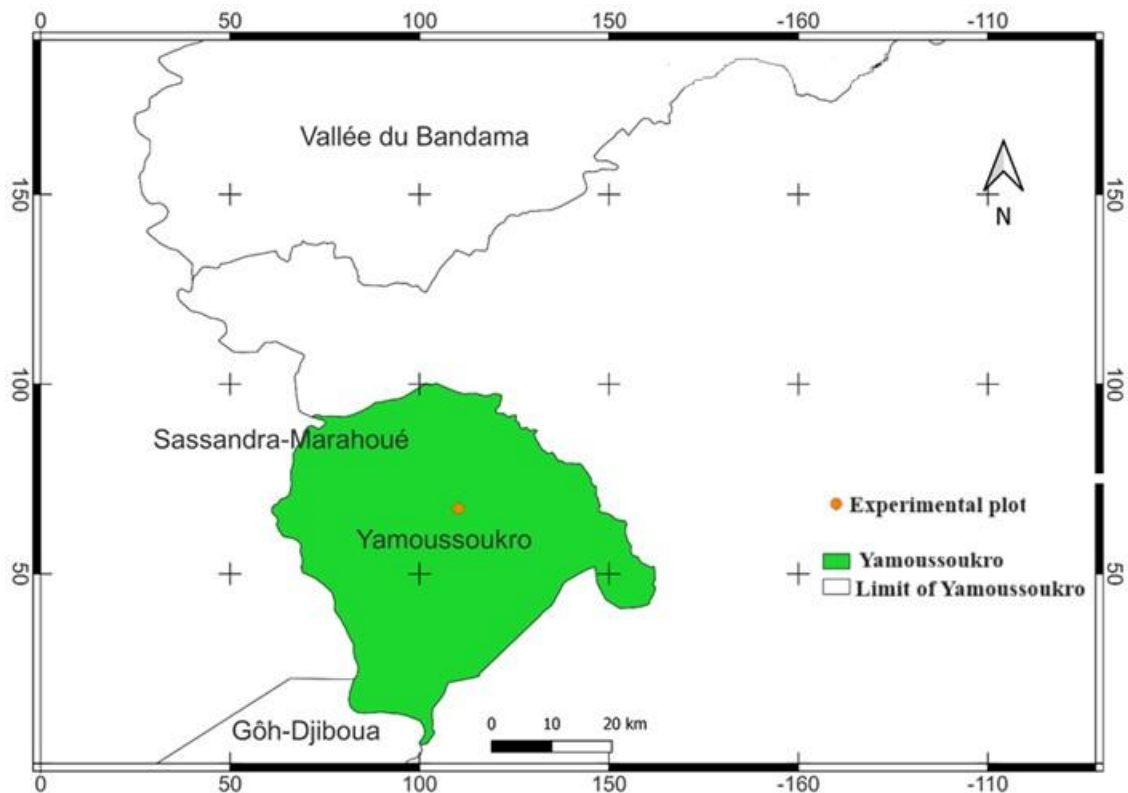


Figure 1. Location of the study site.

Plant Material

The plant material (Table 1) consisted of eight varieties from the Solanaceae and Cucurbitaceae families. Each crop species had two varieties: Solanaceae included

tomatoes (Mongal and F1 Cobra 26) and bell peppers (Simbad and Yolo Wonder), and Cucurbitaceae comprised zucchinis (Color and Koubera) and cucumbers (F1 Tokyo and Poinsett +). These varieties were chosen based on

their availability, pest resistance, and widespread use by market gardeners in the Yamoussoukro region. These varieties are appreciated by growers for their better post-

harvest conservation and their adaptation to hot, humid tropical conditions.

Table 1. Commonly Used Crop Varieties in Yamoussoukro Market Gardens.

Families	Species	Varieties
Solanaceae	Tomato (<i>Solanum lycopersicum</i> L.)	Mongal F1 Cobra 26
	Bell pepper (<i>Capsicum annuum</i>)	Simbad Yolo Wonder
	Zucchini (<i>Cucurbita pepo</i> L.)	Koubera Color
Cucurbitaceae	Cucumber (<i>Cucumis sativus</i> L.)	F1 Tokyo Poinsett+

Experimental Design

A completely randomized block design was used, with a single factor studied (variety) and four replicates. The total experimental plot measured 25 m × 20 m. Each elementary plot consisted of 40 plants of a given variety, totalling 320 plants for the eight varieties, with an overall total of 1,280 plants. Each elementary plot covered 80 m² and included one of the eight varieties (treatments). Within an elementary plot, the variety was distributed across two beds, each covering 5 m², with a spacing of 0.5 m between beds. The planting density was 0.5 m between plants and 0.7 m between rows within the same bed.

The experiment was conducted during the wet season (June–October) over two consecutive years (2021–2022) to monitor nematode population dynamic. Solanaceae seedlings were raised in nurseries for 28 days (tomatoes) and 35 days (bell peppers) before transplanting. Cucumber and zucchini seeds were sown directly at the time of Solanaceae transplantation. Regular maintenance, including watering, weeding, and staking (for cucumbers and tomatoes), was carried out throughout the experiment.

Symptom Description

Symptom observation was done visually on the plants' aerial and root parts. Aerial symptoms included chlorosis, wilting, and stunted growth. For root observations, plants were uprooted, and damage to the primary and secondary roots was recorded.

Sample Collection

The plant roots constituted the samples. Sampling took place one and two months after transplanting/planting, corresponding to the flowering and harvest stages of

Solanaceae. For Cucurbitaceae, samples were collected three and six weeks after seed sowing corresponding to the flowering and harvest stages. From each plot, 20 plants were selected. The roots were cut and transported to the laboratory for nematological analysis. A total of 32 root samples were taken, four per variety.

Nematode Extraction and Identification

Nematodes were extracted exclusively from root samples three days after sampling. The extraction was performed using the double centrifugation method described by Coolen and D'Herde (1972). A total of 25 g of fresh roots, cut into 1-2 cm pieces, were ground in a blender twice for 10 seconds, with a 5-second pause between each cycle, following the double centrifugation procedure. The roots were passed through a series of sieves (500, 80, 40, and 32 µm mesh size). The residues retained on the 40 µm and 32 µm meshes were recovered and subjected to two rounds of centrifugation at 2500 rpm for 5 minutes, with kaolin and magnesium sulfate used to separate the nematodes. After the second centrifugation, the supernatant containing the nematodes was filtered through a 5 µm mesh sieve. The contents of the sieve were collected by spraying water into a flat-bottomed container, and the nematodes were transferred to a glass vial for further examination under a light microscope.

The isolated nematodes were identified using morphological keys from Siddiqi (2000), Hunt *et al.* (2002), and Mekete *et al.* (2012) based on both morphological and morphometric characteristics of the genera. Nematodes were counted in 2 ml aliquots using a gridded counting plate under an AmScope light microscope at 40X and 100X magnification. The counts

were performed in triplicate, and the mean values were expressed as nematodes per 100 g of roots or soil, following the method of Yeo (2019).

$$N = 100 (n \times v) / m$$

N: number of nematodes per 100 g of roots or soil; n - number of nematodes ml of suspension; v: volume of nematode suspension obtained (ml); m: mass of roots used for extraction.

Abundance of the Main Nematode Genera

The relative abundance of the nematode genera observed, expressed as a percentage, was calculated by dividing the number of individuals of each genus by the total number of nematodes counted and then multiplying the result by 100 (Kouadio *et al.*, 2023).

Prevalence and Severity of *Meloidogyne* Infestation

Determination of prevalence and severity was limited to infestations of *Meloidogyne*, which is known to cause root galls. It is also the most damaging nematode in vegetable crops.

The prevalence of galls on Solanaceae and Cucurbitaceae plants was assessed using the method outlined by Coulibaly *et al.* (2023). The prevalence (P%) was calculated using the following formula:

$$P(\%) = \left(\frac{P_t}{N} \right) \times 100$$

Where:

P (%) is the prevalence in percentage; P_t is the total number of plants exhibiting galls; N is the total number of plants sampled.

The gall index was determined using a 0-10 scale from Netscher & Sikora (1990), as shown in Table 2. The severity of symptoms was then calculated using Zeck's (1971) formula.

$$S(\%) = \frac{\sum(n_i \times n)}{N_t \times n_{ie}}$$

Where:

- S (%) represents the severity of galls,
- n_i is the severity grade assigned to the galls on each plant,
- n is the number of plants with the assigned severity grade,
- N_t is the total number of plants sampled,
- n_{ie} is the highest severity grade recorded in this study.

Host Status of the Tested Varieties

The susceptibility and host status of the varieties were analyzed using the classification scale outlined by Anwar (2007), as shown in Table 3.

Table 2. Root Gall Rating Scale (0-10) – Adapted from Netscher & Sikora (1990).

Score	Characteristics
0	Complete, healthy root system: no infestation
1	Very few small galls
2	Small galls that cannot be easily removed
3	Numerous small galls and root system still complete
4	Numerous small galls, a few large galls, and root system still functioning
5	25% of the root system contains galls and is no longer functioning
6	50% of the root system contains galls and is no longer functioning
7	75% of the root system has galls and is no longer functioning
8	Virtually no rootlets left, a string of large galls on the primary roots; the plant can no longer feed itself
9	Root system is reduced and filled with large galls, preventing the plant from feeding
10	Plant and roots dead

Table 3. Classification scale of susceptibility and host status of varieties based on gall index and severity (Anwar *et al.*, 2007).

Severity (%)	Susceptibility	Host Status
0	Immune	Non-host
1-10	Resistant	Bad host
11-20	Moderately resistant	Moderate host
21-50		
50-80	Susceptibility	Good host
81-100		

Data Analysis

Prevalence, severity, and nematode population density

data were analyzed using a Kruskal-Wallis test with XLSTAT version 2014 (Addinsoft, Paris, France) to

compare mean values across the different varieties. When significant differences were detected at the 5% significance level, Conover-Iman's post hoc test was employed to identify homogeneous groups.

Nematode population dynamics were evaluated based on the phenological stages and crop cycles, using ANOVA to compare nematode populations at flowering and harvest over the two study years. Population abundances of the main nematode genera were determined by applying the $\text{Log}(X+1)$ transformation, where X represents the population density (individuals per gram of root). A population was considered abundant if its density exceeded 10 individuals per gram of root, corresponding to a $\text{Log}(X+1)$ value greater than 1 (De Guiran, 1983).

A Hierarchical Clustering on Principal Components

(HCPC) analysis was conducted to group the varieties based on their susceptibility to nematodes. This classification was based on the average values of prevalence, severity, and nematode population densities observed in both soil and roots at flowering and harvest across the two crop cycles.

RESULTS

Symptoms Observed

The main symptoms identified across Solanaceae and Cucurbitaceae crops were chlorotic spots, leaf yellowing, stunting, and wilting at the aerial level. Root galls were the predominant symptom observed at the root level across all crops (Figure 2).

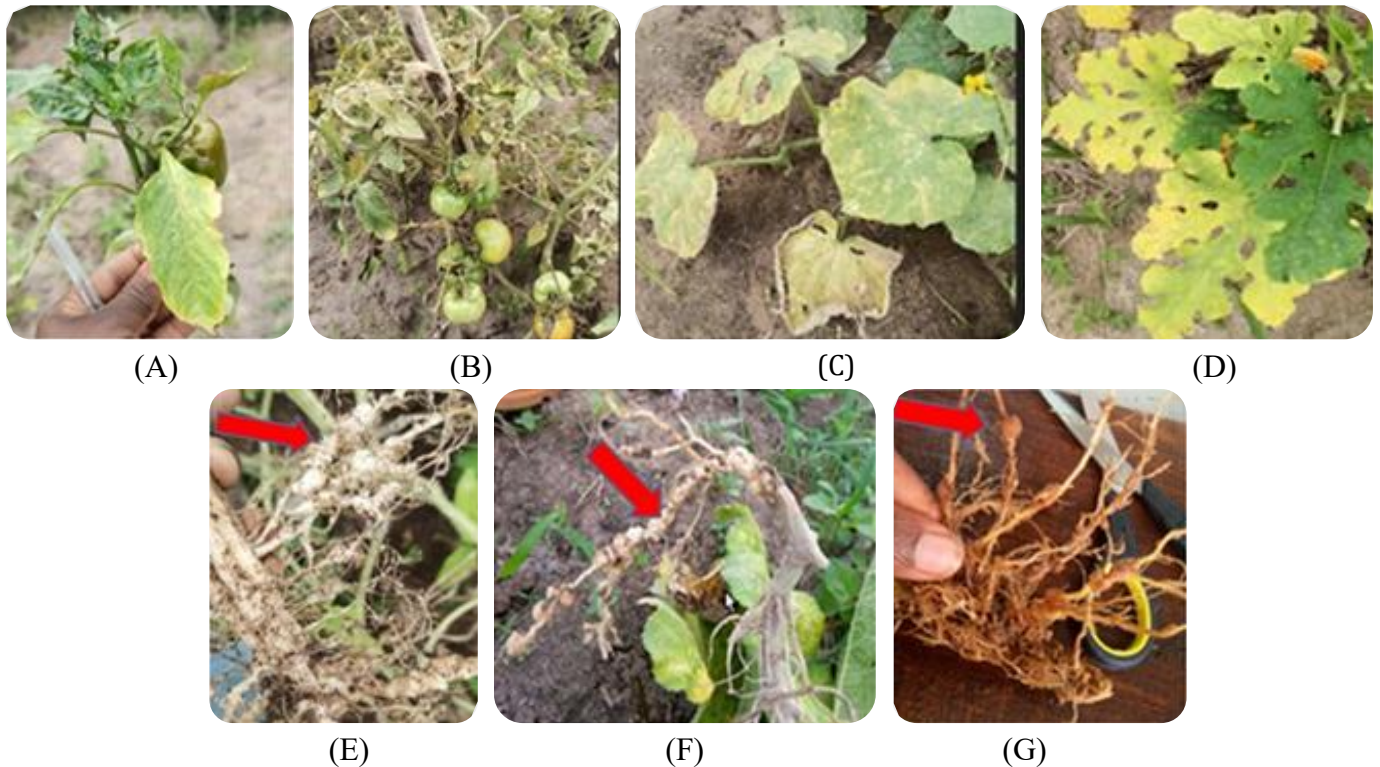


Figure 2. Main aerial and root symptoms observed on different crops.

A: stunted bell pepper plant + yellowing of leaves, **B:** wilted tomato plant, **C:** yellow spots on cucumber leaves, **D:** yellowing of zucchini leaves, **E:** root galls on cucumber plants, **F:** root galls on zucchini plants, **G:** root galls on tomato plants.

Nematode Genera Detected

Nematode extractions revealed the presence of five primary genera: *Meloidogyne*, *Radopholus*, *Pratylenchus*, *Rotylenchulus*, and *Helicotylenchus* (Figure 3). The genera *Meloidogyne* was the most abundant across all crops, with the highest proportions recorded in zucchini (76%), bell pepper (87%), and tomato (81%). *Pratylenchus* was

predominantly abundant in cucumber (36%), while *Radopholus* occurred in cucumber, zucchini, bell pepper, and tomato with lower relative abundances. *Helicotylenchus* and *Rotylenchulus* were less prevalent, representing 1–2% of the nematode population in most crops (Figure 4).

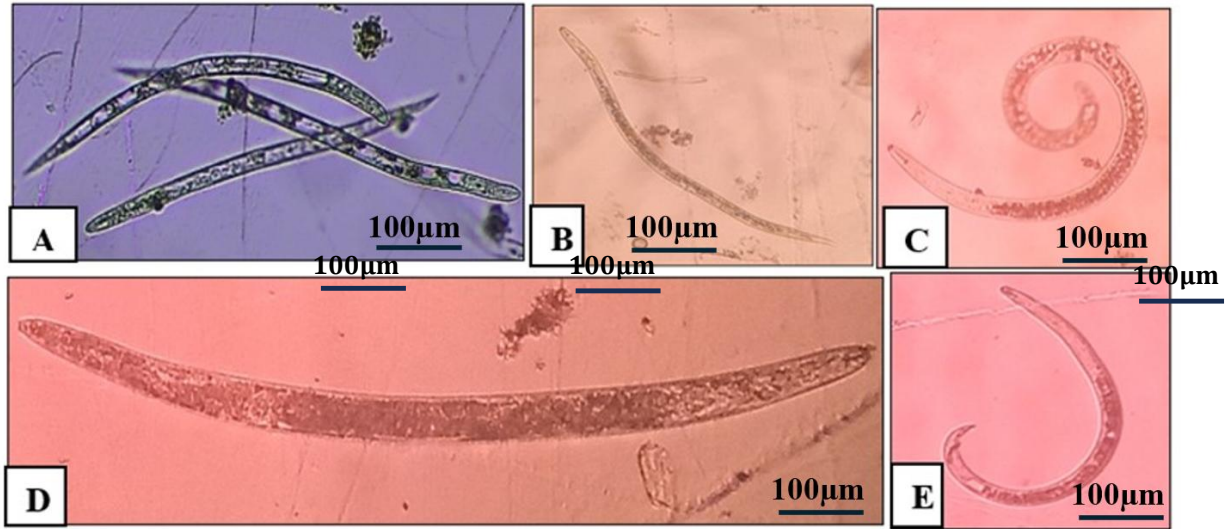


Figure 3. Microscopic view of the main nematode genera observed.
A: *Meloidogyne*, **B:** *Radopholus*, **C:** *Helicotylenchus*; **D:** *Pratylenchus*, **E:** *Rotylenchulus*.

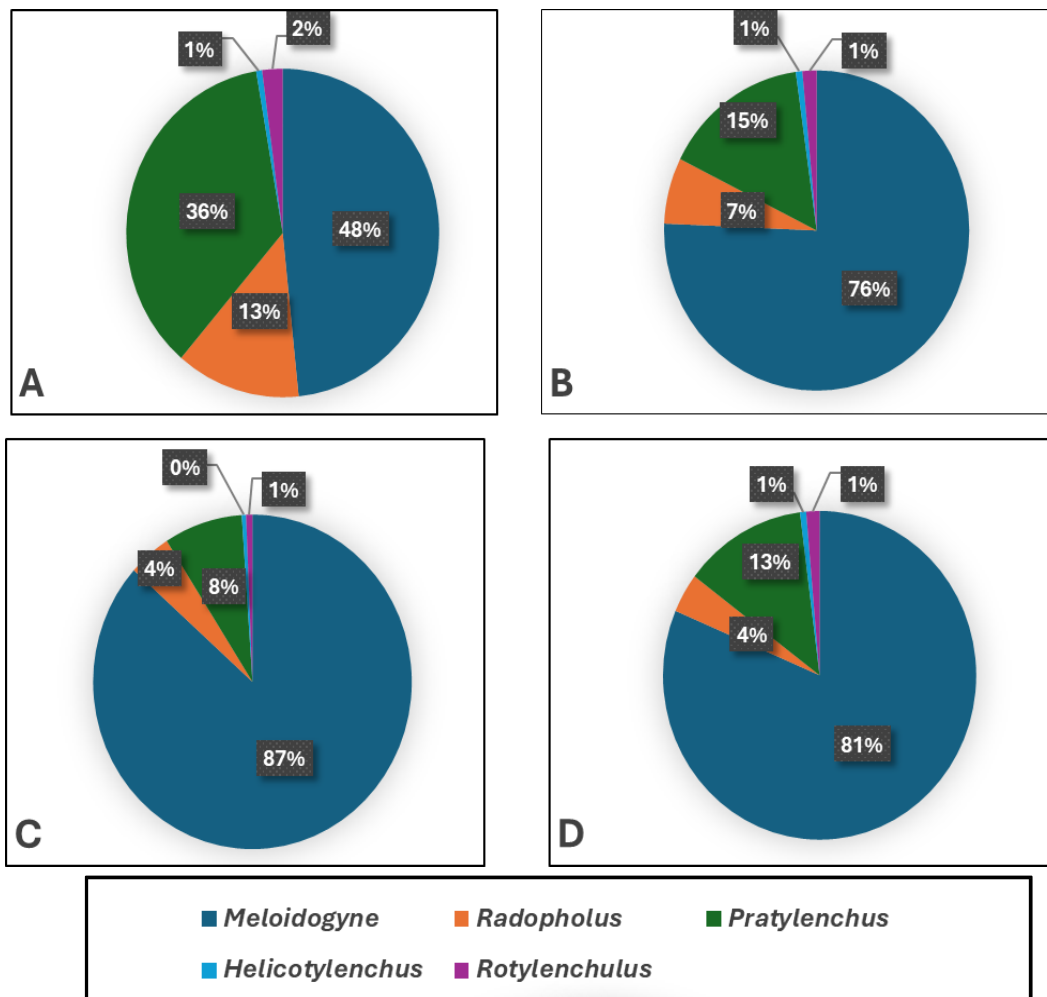


Figure 4. Relative abundance of the main nematode genera isolated from studied crops
A: cucumber, **B:** zucchini, **C:** bell pepper, **D:** tomato.

Population Dynamic

Nematode populations fluctuated significantly across years and phenological stages ($P < 0.05$) of *Meloidogyne* and *Pratylenchus*. *Meloidogyne*'s population densities in roots decreased markedly from 15,599 individuals per 100 g of roots in the first year to 5,992 individuals in the second year. Conversely, *Pratylenchus* and *Radopholus* exhibited increasing population densities, rising from 1,704 to 3,030 and 611 to 1,147 individuals per 100 g of roots, respectively. A similar trend was observed for *Rotylenchulus*, where the

population increased from 127 to 263 individuals per 100 g of roots. Population densities of *Meloidogyne* and *Helicotylenchus* rose significantly from flowering to harvest, with *Meloidogyne* increasing from 6,009 to 15,522 individuals per 100 g of roots and *Helicotylenchus* rising from 65 to 105 individuals. In contrast, *Radopholus*, *Pratylenchus*, and *Rotylenchulus* populations decreased from flowering to harvest, indicating possible shifts in nematode-host interactions or environmental factors affecting nematode proliferation.

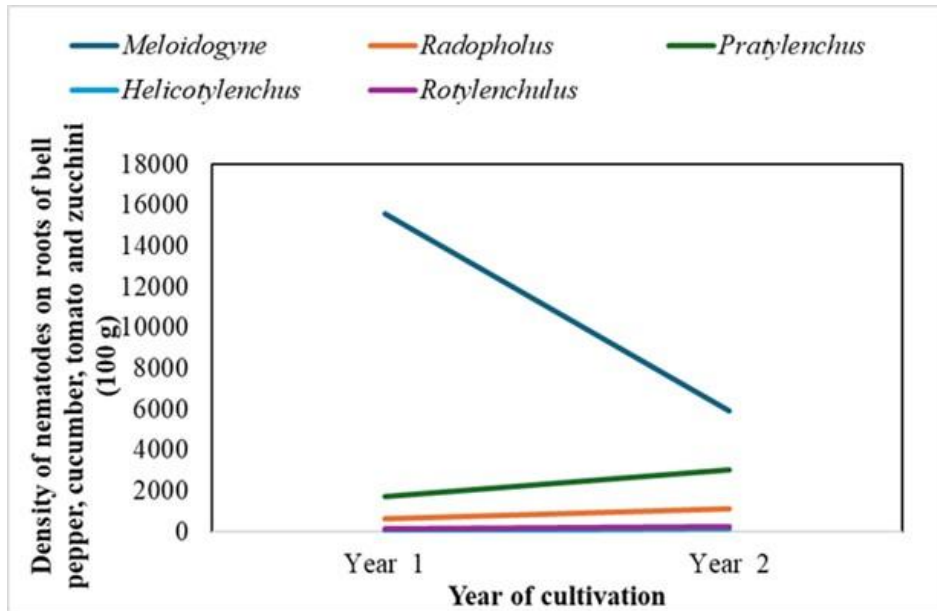


Figure 5. Dynamics of Nematode Populations Across Phenological Stages in the Roots of Bell Pepper, Cucumber, Tomato, and Zucchini.

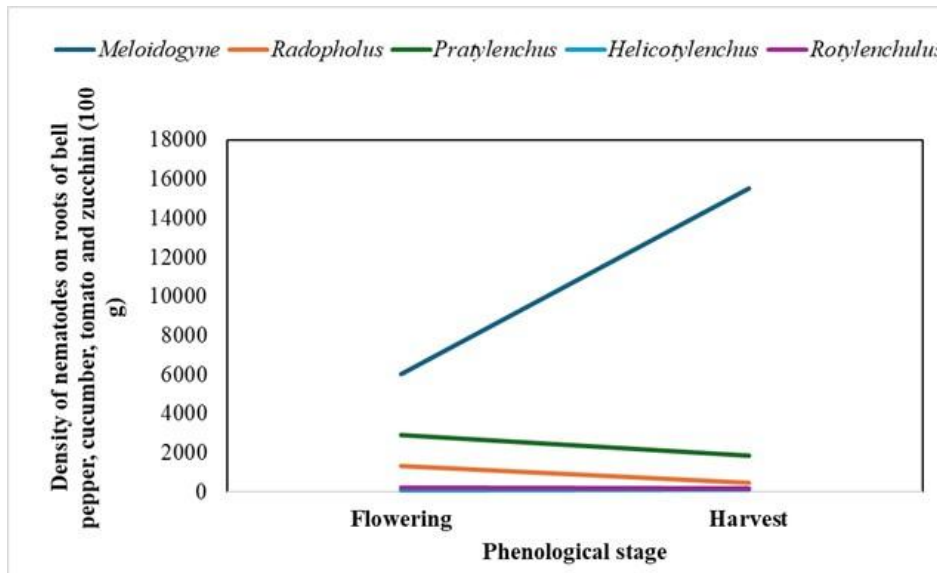


Figure 6. Nematode population dynamics across phenological stages in the roots of bell pepper, cucumber, tomato, and zucchini. Abundance of Nematode Populations in Crop Roots at Flowering and Harvest Across Crop Cycles.

Meloidogyne population

The *Meloidogyne* populations in the roots were abundant in nearly all crop varieties during both years and at both observation periods (flowering and harvest). Specifically, the abundance values for this genus in the roots were generally above 1, with exceptions for the Koubera variety of zucchini, which had lower abundance values at flowering (0.30) and harvest (0.60) in the second year, and the Mongal tomato variety, which recorded an abundance of 0.25 at harvest in the first year. *Meloidogyne* populations were higher at flowering than harvest for most of the varieties studied (Figure 7).

Radopholus and Pratylenchus Populations

The *Radopholus* genus showed greater abundance (abundance > 1) at flowering compared to harvest in all crops during both years (Figure 7). Notably, this genus was absent from the Koubera variety of zucchini at flowering in the second crop cycle. In contrast, low abundances were recorded for the bell pepper varieties Simbad (0.65) and Yolo Wonder (0.31) at flowering in the second crop cycle (Figure 7).

Pratylenchus populations were generally abundant (abundance > 1) in most varieties across both crop cycles at flowering and harvest (Figure 7). However, lower abundance values were observed in Koubera (zucchini) at harvest in year 2 (0.65), Simbad (bell pepper) at flowering in year 2 (0.27), and F1 Cobra 26 (tomato) at harvest in year 2 (0.52).

Helicotylenchus and Rotylenchulus Populations

The *Helicotylenchus* genus was abundant in cucumber and tomato crops, with abundance values equal to or exceeding 1. This genus was more prevalent at flowering than at harvest for both crops, except in the Mongal tomato variety, where *Helicotylenchus* was more abundant at harvest (1.50) than at flowering (1.28) in the second year of cultivation. *Helicotylenchus* was either absent or present in other crops at low abundances (less than 1) (Figure 7).

When present, the *Rotylenchulus* genus displayed abundance values of less than or equal to 1 across both crop cycles at flowering and harvest. However, the highest abundance of *Rotylenchulus* was observed in the Mongal tomato variety at flowering in the second year (2.94) (Figure 7).

Prevalence and Severity of Root Galls Across the Studied Crop Varieties

The mean prevalence and severity for the varieties of the different crops are shown in Tables 3 and 4, respectively. The symptom prevalence of the two cucumber varieties

did not vary at flowering ($P=0.884$ and $P=0.777$) and harvest ($P=0.372$ and $P=1.000$) in years 1 and 2, respectively. In the first year of cultivation, the average prevalences of the F1 Tokyo and Poinsett + varieties at flowering were 72.50% and 80%, respectively. In the second year, the prevalence was less than 10% at flowering and over 90% at harvest. A significant difference was observed between the two varieties at flowering in the first year ($P=0.038$) at harvest in the second year of cultivation ($P=0.040$) for zucchini. The Color variety showed the highest prevalence (95.83%) compared with the Koubera variety (37.50%).

In the pepper crop, Kruskal-Wallis's test showed no significant difference between varieties at flowering ($P=0.233$ for year 1) and harvest ($P=0.770$ and $P=0.462$) for the two years. In the first year, the prevalences were 20% at flowering, ranging from 54.17% to 62.50% at harvest for the Simbad and Yolo Wonder varieties. In the second year, prevalence was zero at flowering and between 20% and 50% at harvest. Kruskal-Wallis's test revealed a significant difference between tomato varieties at flowering ($P=0.019$) in the first year and at harvest ($P=0.047$) in the second year. In fact, the F1 Cobra 26 variety recorded the highest prevalence (77.50%) in contrast to the Mongal variety (32.50%) at flowering. At harvest, the F1 variety Cobra 26 recorded the highest prevalence (100%) compared to the Mongal variety (45.83%).

For the severity parameter, Kruskal-Wallis's test for the cucumber crop revealed no significant difference between varieties at flowering ($P=0.383$ and $P=0.767$) and at harvest ($P=0.381$ and $P=0.309$) in years 1 and 2, respectively. At flowering in year 1, the severities of the F1 Tokyo and Poinsett + varieties were 50.33% and 39.50%, respectively. At harvest, they increased to over 70% for both varieties. In the second year, at flowering, severity was low for F1 Tokyo (2.5%) and Poinsett+ (5%). At harvest, the respective severities for these two varieties were 60.83% and 40.42%. Furthermore, in the zucchini crop, the Kruskal-Wallis's test for severity showed no significant difference between varieties either at flowering ($P=0.245$ and $P=0.317$) or at harvest ($P=1.000$ and $P=0.248$) for years 1 and 2, respectively.

In year 1, the severity of Color and Koubera was 22% and 8.50% respectively. At harvest, the respective severities were 45.00% and 43.33%. In the second year, the severity of the zucchini varieties ranged from 0 to 4.58% at flowering and from 19.17% to 32.08%.

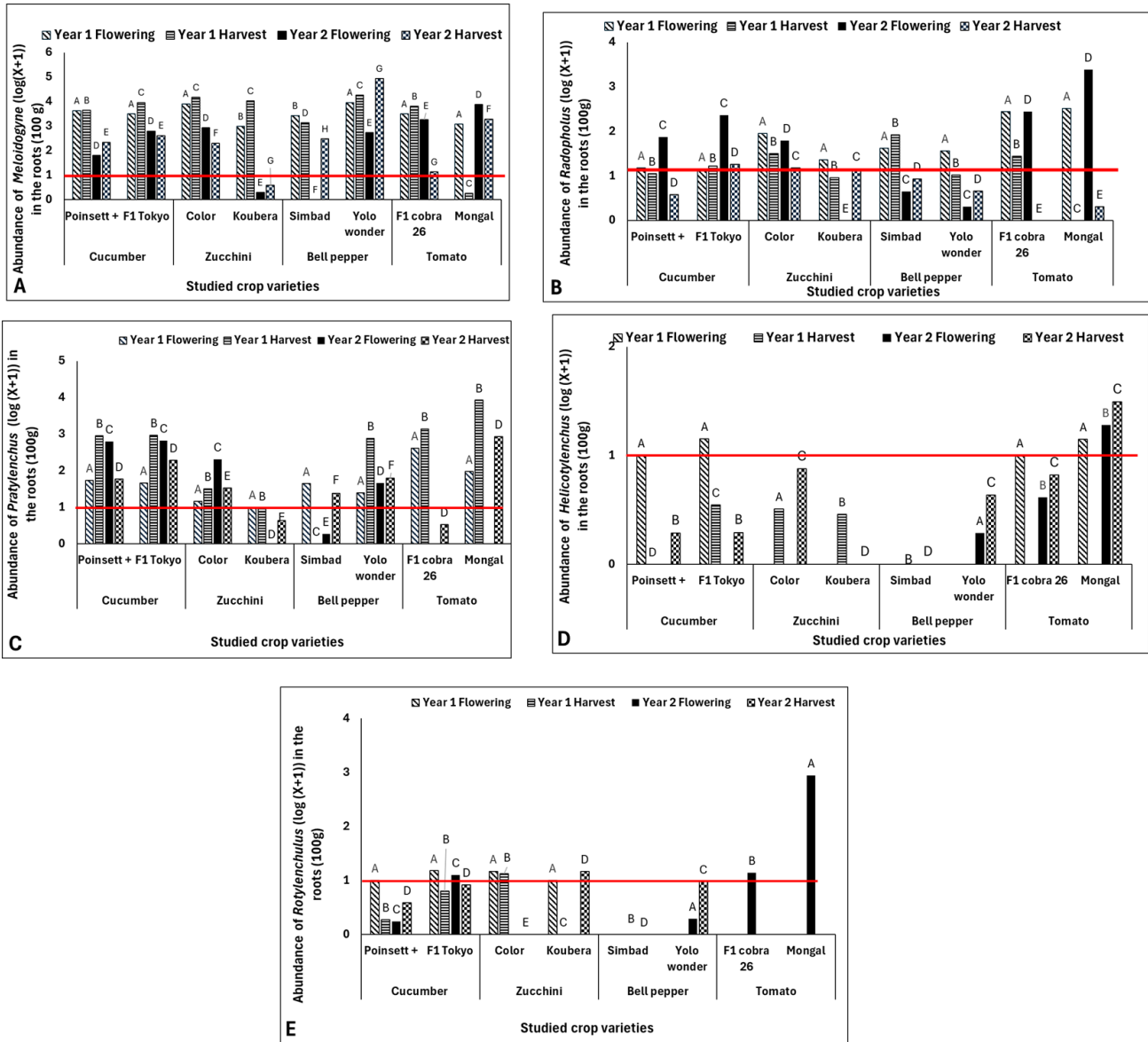


Figure 7. Abundance of major nematode populations in relation to phenological stages and crop cycles across different crop varieties. Nematode population densities were transformed into $\log(X+1)$, where X is the number of nematodes found in 10 g of roots.

A: *Meloidogyne*, B: *Radopholus*, C: *Pratylenchus*, D: *Helicotylenchus*, E: *Rotylenchulus*

In the same group of cultures, histogram followed by the same letters are not significantly different at the 5% significance level, according to Turkey test.

In the bell pepper crop, no significant difference was observed between varieties at flowering ($P=0.237$ and $P=0.290$, in years 1 and 2, respectively) or at harvest ($P=0.462$ at harvest in year 2). The respective severities of the Simbad and Yolo Wonder varieties at flowering were 5.25% and 10.25%, compared with 28.33% and 16.25% at harvest in year 1. In year 2, the severities of the two varieties were zero at flowering and less than 15% at harvest. Furthermore, analysis of the severity of tomato varieties showed significant

difference in year 1 ($P=0.042$ at flowering) and no difference, ($P=0.086$ at harvest and year 2 ($P=0.321$ at flowering and $P=0.248$ at harvest). The average severity of the F1 varieties Cobra 26 and Mongal was 21.75% at flowering and 63.96% at harvest in the first year of cultivation. In the second year, the respective severities of F1 Cobra 26 and Mongal at flowering were 4.17% and 0.42%. At harvest, they were 51.67% and 22.92%.

Table 3. Mean Prevalence of Root Galls by Variety, Crop Year, and Observation Period.

Crops	Varieties	Prevalence (%)			
		Year 1 (2021)		Year 2 (2022)	
		Flowering	Harvest	Flowering	Harvest
Cucumber	F1 Tokyo	72.5 ± 14.93 a	100 ± 10.33 a	9.17 ± 4.38 a	91.67 ± 8.33 a
	Poinsett +	80.00 ± 9.13 a	100 ± 10.33 a	25.00 ± 15.96 a	91.67 ± 8.33 a
	p-value	0.884	0.372	0.766	1.000
Zucchini	Color	65.00 ± 19.36 a	91.67 ± 8.33 a	12.50 ± 12.5 a	95.83 ± 4.17 a
	Koubera	15.00 ± 15.00 b	87.5 ± 7.98 a	0.00 ± 00 a	37.50 ± 21.92 b
	p-value	0.038	0.617	0.317	0.045
Bell-pepper	Simbad	20 ± 7.07 a	54.17 ± 18.40 a	0.0 ± 00 a	50.00 ± 20.41 a
	Yolo Wonder	20 ± 20.00 a	62.50 ± 18.47 a	0.0 ± 00 a	29.17 ± 18.47 a
	p-value	0.234	0.770	-	0.472
Tomato	F1 cobra 26	77.50 ± 4.78 a	95.83 ± 4.17 a	12.5 ± 7.98 a	100.00 ± 0.00 a
	Mongal	32.50 ± 11.81 b	83.33 ± 4.17 a	4.17 ± 4.17 a	45.83 ± 20.83 b
	p-value	0.012	0.356	0.39	0.048

In the same column, means ± SD followed by the same letters are not significantly different at the 5% significance level, according to Conover-Iman's test.

Table 4. Average Severity of Root Galls by Variety, Crop Year, and Observation Period.

Crops	Varieties	Severity (%)			
		Year 1 (2021)		Year 2 (2022)	
		Flowering	Harvest	Flowering	Harvest
Cucumber	F1 Tokyo	50.33 ± 6.33 a	80.00 ± 3.78 a	2.50 ± 1.08 a	60.83 ± 15.40 a
	Poinsett +	39.50 ± 9.26 a	73.75 ± 4.58 a	5.00 ± 3.19 a	40.42 ± 9.77 a
	P-value	0.383	0.381	0.767	0.309
Zucchini	Color	22.00 ± 10.23 a	45.00 ± 5.57 a	4.58 ± 4.58 a	32.08 ± 5.94 a
	Koubera	8.50 ± 4.97 a	43.33 ± 9.18 a	0.00 ± 00 a	19.17 ± 14.02 a
	p-value	0.245	1.000	0.317	0.248
Bell-pepper	Simbad	5.5 ± 1.55 a	28.33 ± 9.15 a	0.0 ± 00 a	12.50 ± 8.20 a
	Yolo Wonder	10.25 ± 10.25 a	16.25 ± 4.97 a	0.0 ± 00 a	8.75 ± 7.64 a
	P-Value	0.237	0.387	-	0.46
Tomato	F1 cobra 26	31.75 ± 9.53 a	78.33 ± 6.56 a	4.17 ± 3.15 a	51.67 ± 5.05 a
	Mongal	11.75 ± 3.22 b	49.58 ± 12.39 a	0.42 ± 0.41 a	22.92 ± 18.59 a
	P-value	0.042	0.083	0.321	0.248

In the same column, means ± SD followed by the same letters are not significantly different at the 5% significance level, according to Conover-Iman's test.

Varietal Susceptibility

Nematode population densities differed in crop roots variety

Harvest data were used to compare nematode densities between varieties. Analysis of variance of nematode population densities showed a significant difference between tomato varieties for the genera *Meloidogyne* (P=0.0127). The F1 variety Cobra 26 recorded the highest population density (58028.37 individuals/100g of roots) compared with 5808.92 individuals/100g of roots for the Mongal variety. No significant differences were observed

between the two varieties for the genera *Pratylenchus*, *Radopholus*, *Helicotylenchus*, and *Rotylenchulus* (P>0.05). Significant differences were observed between the varieties in the population densities of the genera *Meloidogyne* (P=0.0038) and *Pratylenchus* (P = 0.0253). The Yolo Wonder variety was the most infested with *Meloidogyne* (24284.33 individuals / 100 g of roots) and *Pratylenchus* (2408.03 individuals / 100 g of roots). In the cucumber crop, a significant difference was found between the two varieties for the *Meloidogyne* genera (P=0.0076). *Meloidogyne* populations were higher in the F1

Tokyo variety (9013.90 individuals/100 g root) than in the Poinsett + variety (3203.43 individuals/100 g root). No significant difference was shown for the other nematode genera ($P>0.05$). *Radopholus* populations ($P=0.1029$) ranged from 287.24 to 1571 individuals/100 g root. *Pratylenchus* populations ranged from 1056.78 to 3296.08 individuals/100g of root. For zucchini, analysis of variance showed no significant difference between the two varieties

for any of the nematode genera recorded ($P>0.05$). *Meloidogyne* populations ranged from 9005.68 (Koubera) to 9321.43 individuals/100 g root (Color). *Radopholus* population densities for both zucchini varieties were below 400 individuals/100 g of root. *Pratylenchus* populations ranged from 1,475.69 individuals/100g of root to 2,545.71 individuals/100g of root.

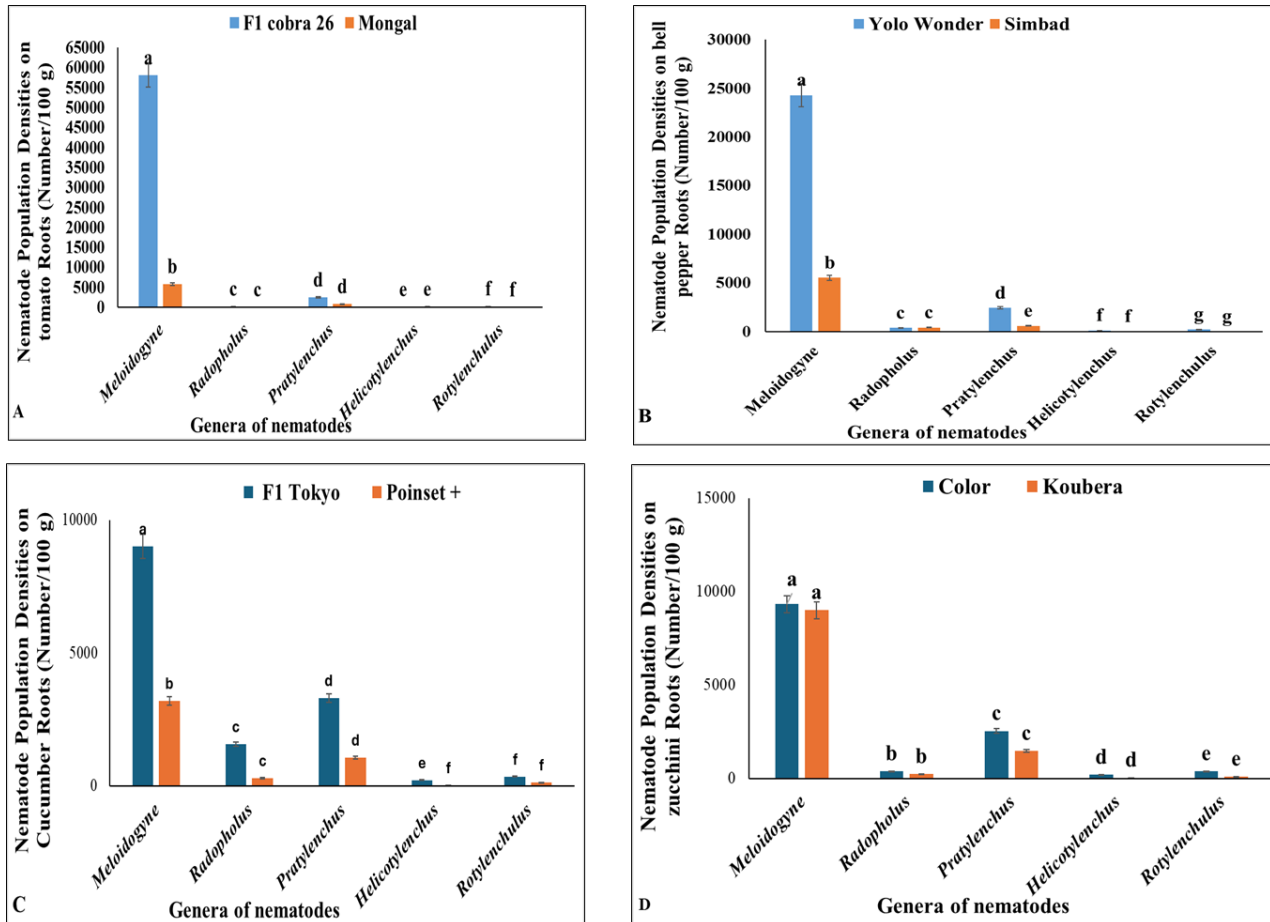


Figure 8. Infestation levels of Solanaceae and Cucurbitaceae varieties.

A: tomato, B: Bell pepper, C: cucumber, D: zucchini. According to Tukey’s test, bars followed by the same letters are not significantly different at the 5% significance level.

Susceptibility and Host Status

The Kruskal-Wallis’s test showed no significant difference between the average severity of varieties at harvest for cucumber ($P = 0.155$), zucchini ($P = 0.559$), pepper ($P = 0.370$) and tomato ($P = 0.093$) as shown in table 5. The average root gall severity assessment at harvest allowed for the classification of crop varieties based on their susceptibility and host status to *Meloidogyne* spp. (Table 5). The zucchini varieties

Koubera (31.25%) and Color (38.54%), as well as the pepper varieties Simbad (20.42%) and Yolo Wonder (12.50%), were categorized as moderately resistant and moderately susceptible hosts. Among the two tomato varieties, Mongal exhibited moderate resistance with a severity of 36.25%, whereas F1 Cobra was classified as susceptible, with a severity of 65%. Similarly, both cucumber varieties, Poinsett+ and F1 Tokyo, were identified as susceptible.

Table 5. Host Status and Susceptibility of Solanaceae and Cucurbitaceae Varieties to *Meloidogyne* spp.

Crop	Varieties	Severity (%)	Susceptibility	Host status
Cucumber	Poinsett+	57.08 ± 8.18 a	Susceptible	Good host
	F1 Tokyo	70.42 ± 8.04 a	Susceptible	Good host
p-value		0.155		
Zucchini	Koubera	31.25 ± 9.00 a	Moderately resistant	Moderate host
	Color	38.54 ± 4.49 a	Moderately resistant	Moderate host
p-value		0.559		
Tomato	Mongal	36.25 ± 32.53 a	Moderately resistant	Moderate host
	F1 cobra 26	65.00 ± 17.91 a	Susceptible	Good host
p-value		0.093		
Bell-pepper	Simbad	20.42 ± 6.43 a	Moderately resistant	Moderate host
	Yolo Wonder	12.50 ± 4.54 a	Moderately resistant	Moderate host
p-value		0.370		

In the same column, means ± SD followed by the same letters are not significantly different at the 5% significance level, according to Conover-Iman’s test.

Varietal Clustering

Hierarchical Clustering on Principal Components (HCPC) grouped the varieties into two distinct categories based on susceptibility to the five nematode attacks. The first group, including F1 Tokyo (cucumber), F1 Cobra 26 (tomato), and Color (zucchini), was characterized by high

nematode population densities and greater prevalence and severity of symptoms. The second group, consisting of Yolo Wonder and Simbad (bell peppers), Mongal (tomato), Poinsett + (cucumber), and Koubera (zucchini), showed lower susceptibility and reduced nematode population densities.

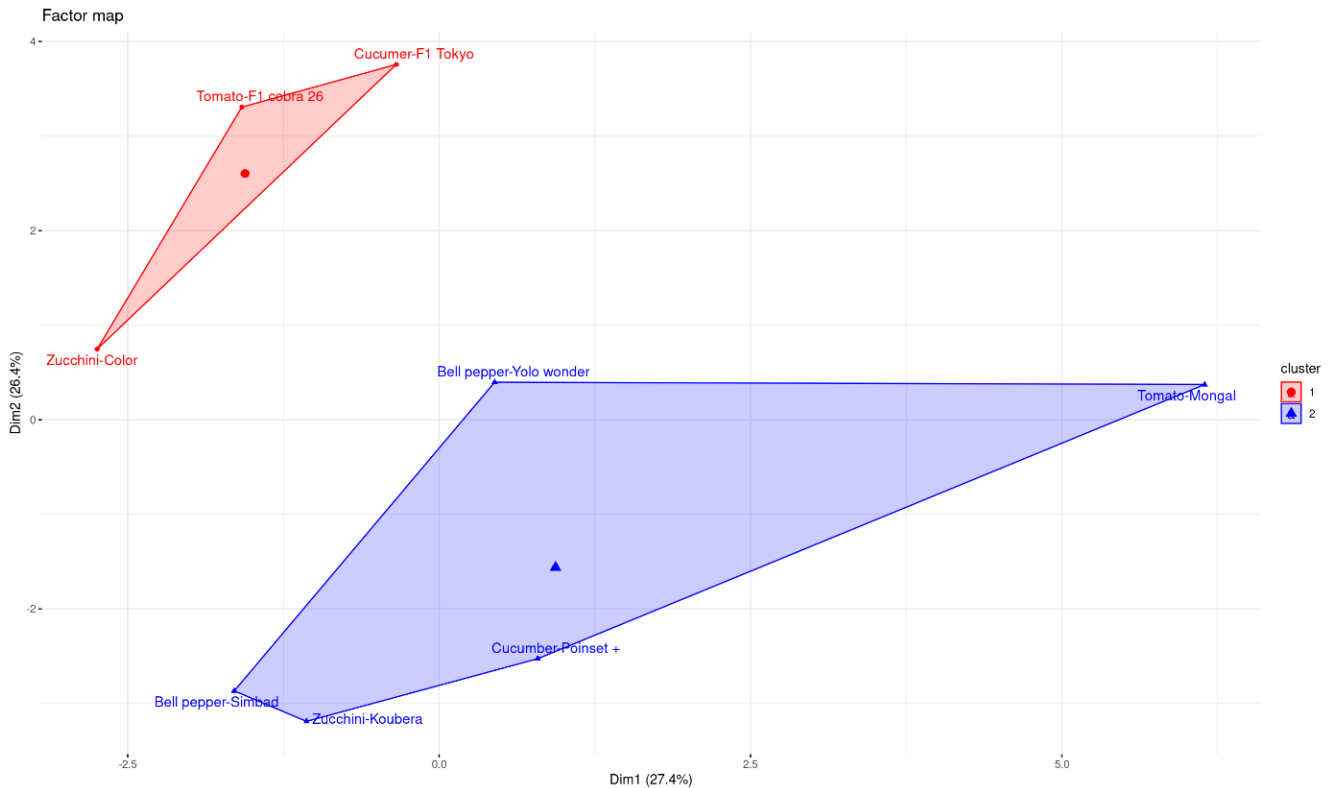


Figure 8. Classification of crop varieties according to their susceptibility to the five predominant nematode genera identified.

DISCUSSION

This study elucidates the symptoms associated with plant-parasitic nematodes in vegetable crops, notably the manifestation of root galls, discoloration, wilting, and stunting of plants. Five genera of PPNs were identified: *Meloidogyne*, *Pratylenchus*, *Radopholus*, *Helicotylenchus*, and *Rotylenchulus*, with *Meloidogyne* predominating, particularly in pepper crops. The diversity of observed symptoms can be attributed to multiple nematode genera and their respective modes of action (Kouakou *et al.*, 2016). The *Meloidogyne* genus is an obligate sedentary endoparasite nematode known for inducing root galls (Favery *et al.*, 2020). Second-stage juveniles of *Meloidogyne* penetrate host roots using their stylet and migrate to the central vascular cylinder, where their salivary secretions facilitate the formation of permanent feeding sites composed of hypertrophied cells (Djian-Caporalino *et al.*, 2018). This hypertrophy results in gall formation, which is a hallmark of root-knot nematode infection (Kouamé *et al.*, 2018).

In contrast, migratory endoparasite nematodes, such as *Pratylenchus* and *Radopholus*, navigate plant tissues intercellularly. The damaged cells secrete toxins that promote necrosis within the roots (Coyne *et al.*, 2010). Ectoparasitic nematodes like *Helicotylenchus* and semi-endoparasites *Rotylenchulus* feed externally on the plant surface, typically targeting absorptive root hairs or the outer cortical tissue, leading to root lesions (Uzma *et al.*, 2015; Abhi, 2017). While most nematode-induced damage occurs at the root level, the aerial parts of the plants may also be affected (Mitkowski and Abawi, 2003). This relationship can be explained by the reduced capacity of galled and necrotic roots to absorb and transport nutrients and water, resulting in symptoms such as chlorosis. Our findings corroborate those of Anwar *et al.* (2016) and Yueling *et al.* (2024), who noted similar symptoms in *Solanum nigrum* and *Trichosanthes dioica*. Additionally, root-knot nematodes may predispose plants to infection by soilborne bacterial and fungal pathogens, exacerbating disease complexes (Khan *et al.*, 2023). This interaction may clarify the chlorotic spots observed on cucumber plants.

Nematode populations increased from flowering to harvest across all crops, with certain exceptions noted in both crop cycles. This observation aligns with the findings of Thakur & Sharma (2020), who reported heightened nematode population densities during the same growth stages. Furthermore, Saidova *et al.* (2023) indicated that

PPNs were particularly prevalent during tomato budding, flowering, and early fruit development. These dynamics suggest that the quantitative and qualitative presence of nematodes is influenced by various factors, including food resources, moisture levels, and soil temperature (Zinovieva *et al.*, 2012). Notably, moist soils harbor higher nematode population densities (Tileubayeva *et al.*, 2021). Additionally, *Meloidogyne* spp. thrive at temperatures ranging from 25 to 30°C, conditions typically met during the harvest period in October, which is characterized by elevated humidity and temperature in Yamoussoukro compared to September when the crops were flowering (Kra *et al.*, 2023). However, the observed decline in root nematode populations at harvest, particularly for migratory nematodes, may result from root decortication, facilitating their release into the soil (Bhatt *et al.*, 2013).

Furthermore, this study highlights a noteworthy increase in nematode populations from the first to the second year of cultivation. These findings are consistent with those of Blasco (2016), who documented an annual increase in root-knot nematode populations over three years. This trend may be attributed to the enhanced virulence of root-knot nematodes when initially resistant genotypes are cultivated repeatedly (Noling, 2000). The variations in nematode populations observed in this study could be attributed to the cropping system since cropping systems, as stated by Mateille *et al.* (2020). Continuous cropping practices fail to provide sufficient time for the soil to rest and recuperate, thus promoting nematode proliferation. The elevated populations observed in the first year could also be linked to the previous cultivation history of the plot, which had previously hosted tomato crops known for their sensitivity to nematodes (Djian-Caporalino *et al.*, 2009). Climatic conditions could explain the difference in population densities observed from one year to the next. Unfavorable environmental conditions, particularly low temperatures and humidity can reduce nematodes' maximum multiplication rate and population density compared with optimal conditions (Seinhorst, 1970).

The prevalence and severity of symptoms exhibited significant variability among different crop varieties. This variation may be explained by the host's physiological characteristics and the specific attraction of nematodes to their roots (Sorribas *et al.*, 2020). Plant responses to parasitic nematodes can range from immunity and resistance to sensitivity and tolerance (Mateille, 1994). The high severity of symptoms in cucumber and tomato

crops suggests heightened susceptibility compared to sweet pepper. Additionally, the severity and prevalence observed in cucumber (F1 Tokyo) and zucchini (Color) crops may be attributed to their elevated water content, as indicated by Nindjin *et al.* (2007). Water is a critical factor influencing the proliferation of soilborne pathogens, particularly plant-parasitic nematodes (Dinardo-Miranda & Fracasso, 2010). Within the same crop, varietal susceptibility varied, as Kouakou *et al.* (2016) reported in yam crops. Consequently, these susceptible varieties provide a favorable environment for nematode reproduction and development, leading to more pronounced damage.

The varieties tested were classified based on their susceptibility to different nematode types. The F1 Tokyo cucumber, F1 Cobra 26 tomato, and Color zucchini varieties demonstrated higher sensitivity to nematode attacks. In contrast, the less sensitive varieties included Yolo Wonder and Simbad for peppers, Mongal for tomatoes, Poinsett + for cucumbers, and Koubera for zucchinis. In this respect, our results corroborate those of Kakou (2022), who stated that the Mongal tomato variety was moderately resistant in his varietal screening study on ten tomato varieties. This discrepancy may be attributed to resistance genes within these crops. For instance, the Me3 gene in pepper provides stable, broad-spectrum resistance to root-knot nematodes (Reddy *et al.*, 2023). Furthermore, Marques *et al.* (2019) reported that some genotypes of *Capsicum* species possess resistance genes against *Meloidogyne enterolobii*. Our findings corroborate this literature, as *Capsicum* species were classified as less susceptible. Additionally, our results align with those of Mukhtar *et al.* (2013), who emphasized the susceptibility of the Poinsett + variety in a study done in Pakistan. Resistance genes act in different ways and could be responsible for the lower sensitivity of the varieties. The Me1 gene present in the *Capsicum* genera induces a late reaction preventing the development of the nematode feeding site, and the Me3 gene induces an early hypersensitivity reaction blocking the penetration of root-knot nematode larvae (Djian-Caporalino *et al.*, 2013). The resistance of certain plants to nematodes is thought to be due to the triggering of a complex defence mechanism by the plant in response to the detection and invasion of these parasites. The biochemical defence responses of plants, include cell wall reinforcement; reactive oxygen species burst; receptor-like cytoplasmic kinases; mitogen-activated protein

kinases; antioxidant activities; phytohormone biosynthesis and signalling; transcription factor activation; and the production of anti-PPN phytochemicals (Meresa *et al.*, 2024). Because nematodes can overcome the resistance of some cultivars, coupled with the harmful effects of synthetic nematicides, it would appear necessary to carry out integrated management of plant-parasitic nematodes by reasonably combining existing techniques in particular, cropping systems, environmental factors, and varietal choice.

CONCLUSION

This study demonstrated that various non-specific aerial symptoms are associated with nematode infestations in vegetable crops. The predominant symptom observed at the root level was root galling, primarily attributed to *Meloidogyne*, which emerged as the most prevalent nematode genus throughout the research. Notably, root galls' prevalence and severity were significantly higher at harvest compared to the flowering stage. Besides *Meloidogyne*, four other nematode genera were identified: *Radopholus*, *Pratylenchus*, *Rotylenchulus*, and *Helicotylenchus*. Overall, nematode populations increased from flowering to harvest and from the first to the second year of cultivation. However, an exception was noted in the tomato crop, where nematode populations declined from flowering to harvest. Additionally, populations of *Helicotylenchus* and *Rotylenchulus* decreased from the first to the second year of cultivation. Critical thresholds for nematode populations were reached in all tested crops during both flowering and harvest stages, although *Rotylenchulus* and *Helicotylenchus* populations remained below the tolerance threshold in pepper crops. Furthermore, the varieties were classified into two distinct groups based on their susceptibility to nematode attacks. The first group included the more susceptible varieties Color (zucchini), F1 Cobra 26 (tomato), and F1 Tokyo (cucumber) while the second group comprised the less susceptible varieties, including Yolo Wonder and Simbad (peppers), Mongal (tomato), Poinsett + (cucumber), and Koubera (zucchini).

Future studies on trials using molecular markers associated with nematode resistance should be carried out to confirm the resistance of varieties less susceptible to root-knot nematodes in this study. Studies into managing plant-parasitic nematodes using biological methods, particularly nematocidal plants, could be envisaged as part of an integrated and sustainable

management system.

This study underscores the significance of understanding nematode population dynamics in developing effective management strategies. It provides critical insights regarding the selection of resistant varieties, optimal treatment periods, and the potential for crop rotation strategies. Future research should focus on the effects of crop rotations involving these identified varieties on plant-parasitic nematode populations. These data are helpful for farmers insofar as they allow them to combine the use of resistant varieties and appropriate cropping systems (crop rotation, fallow) in the management of plant-parasitic nematodes. Political decision-makers should make the resources available to carry out more in-depth studies into the resistance of varieties to nematodes in order to make a variety of varieties available to growers and facilitate the dissemination of the results obtained.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

AUTHOR CONTRIBUTIONS

Conceptualization and methodology: AK, and YAS; Investigation; writing original draft preparation: YAS., and KDJ; Writing, review and editing: YAS., TEO, NJ. KDJ, KKT, and AK; Supervision: KKT and AK; All authors have read and agreed to the published version of the manuscript.

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