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# Influence of Elevational and Environmental Factors on Parasitic Nematode Distribution in Arabica Coffee in the Gayo Highlands, Indonesia

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**Abstract**

Highland agricultural landscapes are sensitive to environmental variation, particularly in regions like the Gayo Highlands of Aceh, Indonesia, where Arabica coffee (*Coffea arabica* L.) is a major crop. While parasitic nematodes are known to affect crop health and soil ecosystems, little is known about how their abundance and distribution vary with elevation in tropical coffee systems. The Gayo Highlands, despite their significant contribution to national coffee production, have been understudied in terms of soil biodiversity and nematode-related threats. To address this knowledge gap, we assessed the composition and abundance of parasitic nematodes in coffee plantations across three elevation zones: 800–1000 m, 1001–1200 m, and 1201–1400 m above sea level. We collected soil and root samples from symptomatic coffee plants, extracted nematodes using the Baermann funnel method, and identified them to the genus level. The study found three genera: *Pratylenchus*, *Meloidogyne*, and *Rotylenchus*. *Pratylenchus* was the most abundant, particularly at 800–1,000 m (34 individuals/10 ml), while the highest total nematode abundance occurred at 1,001–1,200 m (7.2 ± 1.44 individuals/10 ml). Statistical analysis showed significant differences in nematode abundance between elevation zones. These results indicate that elevation influences nematode populations, likely through environmental factors such as temperature, soil moisture, and pH. Understanding these patterns is important for developing site-specific strategies for pest management and maintaining soil health in highland coffee systems.

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## 1. Introduction

Coffee cultivation plays a vital role in the economic and cultural identity of the Gayo Highlands in Aceh, Indonesia [1]. Among the most valued crops is *Coffea arabica L.*, which thrives in highland agroecosystems and supports the livelihoods of thousands of smallholder farmers [2]. Gayo Arabica coffee is a prominent agricultural commodity cultivated in Central Aceh Regency, Aceh Province. As of 2021, its productivity reached 813 kilograms per hectare, with a total plantation area of approximately 43,364 hectares distributed across 14 subdistricts. The region's topography ranges from 200 to 2,600 meters above sea level (masl), with the majority of coffee plantations situated at elevations between 1,000 and 1,600 masl. This altitude range is considered optimal for cultivating Arabica coffee [3].

However, the sustainability of coffee production is increasingly challenged by environmental issues such as soil degradation, declining biodiversity, and the emergence of parasitic organisms that threaten plant health and yield stability [4]. Elevation is known to influence not only temperature and humidity but also the biodiversity of soil organisms, including nematodes, which play a role in nutrient cycling and are suspected to impact long-term land productivity [5]. Elevation-driven changes in soil temperature and moisture can directly influence nematode survival, metabolic activity, and reproductive capacity [6]. Cooler temperatures at higher altitudes may reduce nematode mobility and feeding behavior, while variations in soil pH and microbial communities can mediate interspecific competition and host-nematode interactions [7]. These ecological mechanisms highlight the importance of altitude as a structuring force in nematode community composition. According to Reddy et al. [8], nematodes are among the key plant pests capable of causing up to 80% damage and mortality in coffee plants.

The primary factors influencing the diversity and abundance of nematodes along elevation gradients vary greatly and include differences in climate, soil properties, and vegetation [9]. Soil plays a crucial role in shaping nematode abundance, as acidic soils with a pH below 5.0 negatively affect nematode survival and reproduction [10]. According to Wulandari and Indarti [11], in Central Java, soil temperature and pH can either promote or inhibit the abundance of soil nematode communities. Moreover, nematode abundance tends to increase with rising precipitation. At the same time, nitrogen enrichment has been shown to reduce nematode populations in the surface soils of temperate forests in the Changbai Mountains, China [12].

Despite being one of Indonesia's most productive and internationally recognized Arabica coffee regions, the Gayo Highlands remain understudied in terms of soil biodiversity and nematode-related threats. The region's unique combination of high-altitude volcanic soils, traditional farming practices, and extensive monoculture cultivation may foster distinct soil ecological dynamics compared to other coffee-growing areas such as Java or Vietnam. These factors suggest that parasitic nematode challenges in Gayo may be shaped by environmental and agronomic conditions not present elsewhere, making it crucial to investigate their composition and ecological drivers.

In Arabica coffee plantations, understanding how elevation affects the abundance and diversity of parasitic nematodes is crucial for developing environmentally sustainable pest management strategies. Moreover, since nematodes can serve as bioindicators of soil health [13], studying their populations provides valuable insights into the ecological integrity of agricultural landscapes.

However, studies investigating the abundance and diversity of parasitic nematodes specifically associated with Arabica coffee (*Coffea arabica*) in the highland region of Gayo remain scarce. This study addresses this gap by providing the first detailed report on the parasitic nematode composition, abundance, and diversity in Arabica coffee plantations across different altitudinal gradients in the Gayo Highlands**.** The findings are expected to contribute novel insights into nematode-plant interactions in highland coffee ecosystems, which have been largely overlooked in previous research. This study specifically investigates how variations in elevation influence the composition and abundance of parasitic nematodes associated with Arabica coffee plants. It is expected that nematode populations will exhibit distinct patterns along altitudinal gradients, with higher abundance due to more optimal abiotic conditions, such as temperature and soil moisture. The results are expected to provide a deeper understanding of soil biodiversity patterns and support the implementation of agroecological approaches in sustainable coffee farming systems amid increasing environmental pressures.

Therefore, this study aims to investigate the composition, abundance, and diversity of parasitic nematodes associated with Arabica coffee (*Coffea arabica* L.) across three elevation zones in the Gayo Highlands. Specifically, the research aims to investigate how altitudinal variation affects nematode distribution patterns and to identify the dominant genera that impact coffee plant health. The results are expected to support the development of elevation-specific pest management strategies and contribute to the understanding of soil biodiversity in highland coffee agroecosystems.

## 2. Materials and Methods

### *2.1. Study Workflow*

The workflow of this study, illustrated in Figure 1, followed six key steps to assess nematode abundance across different altitudes in coffee farming areas of Central Aceh. The selection process began with the identification of three research sites based on elevation, followed by the selection of symptomatic coffee plants. Soil and root samples were then collected from these

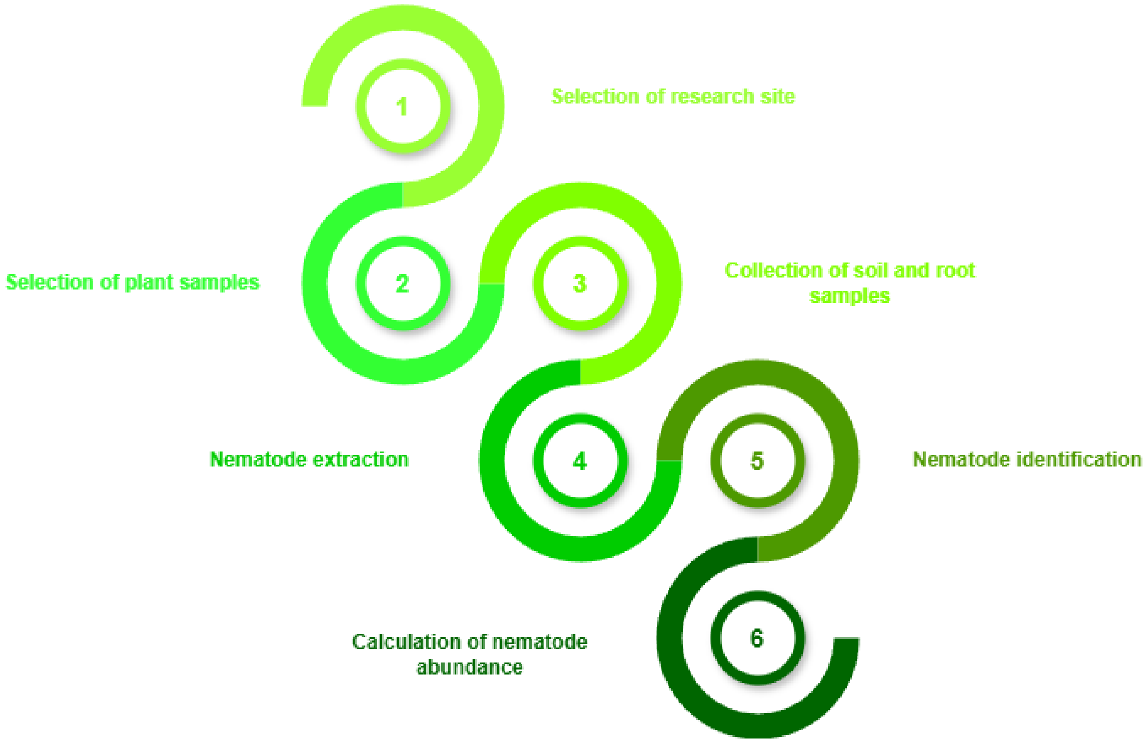


**Figure 1.** Workflow of the study.

plants, and nematodes were extracted using the Baermann funnel method. Extracted nematodes were identified to the genus level through microscopic examination, and their abundance was calculated from averaged subsample counts. This structured approach ensured a systematic evaluation of nematode populations across altitudinal gradients.

*2.2. Study Site and Experimental Design*

The research was conducted in three coffee farming areas in Central Aceh Regency, representing distinct altitudinal gradients within the Gayo Highlands. These included Kampung Selon (Site 1; 800–1,000 masl), Kampung Kekuyang (Site 2; 1,001–1,200 masl), and Kampung Kute Lintang (Site 3; 1,201–1,400 masl). The experimental design employed a non-factorial Randomized Block Design (RBD), with each altitude level treated as a block. Each treatment included 10 replications, corresponding to the number of sampled coffee plants per plot. Figure 2 illustrates the geographical location of the three study sites.

*2.3. Rationale for Altitudinal Range Selection*

The selected elevation ranges reflect ecologically meaningful transitions in the Gayo Highlands, a major region for Arabica coffee production. The 800–1,000 masl range typically experiences higher temperatures and increased microbial activity, which can influence nematode population dynamics [14]. The 1,001–1,200 masl range is considered optimal for Arabica coffee, offering moderate temperatures and balanced soil moisture, which support both the health of the coffee plant and nematode development [15]. Meanwhile, the 1,201–1,400 m asl range has cooler conditions that may limit nematode survival and behavior, depending on species-specific thermal tolerances [16]. These categories also align with local agricultural zoning practices and are recognized by farmers and agronomists as representative of varying coffee production conditions.

*2.4. Sampling Procedure*

A total of 10 symptomatic coffee plants were randomly selected at each site. Symptoms used to indicate potential nematode infestation included stunted growth, chlorotic or yellowing leaves, wilting, and poor root development. In some cases, root galls or necrotic lesions were observed during initial field inspections [17]. Soil and root samples were collected from these symptomatic plants using a standardized method. Four subsampling points were established around each plant at a 10 cm radius from the main stem and a depth of 20 cm. The soil from the four points was combined to produce approximately 1 kg of composite soil, and about 100 g of root material was collected separately. All samples were labeled and stored in plastic bags for laboratory analysis.

*2.5. Nematode Extraction*

Nematodes were extracted from soil and root samples using the Baermann funnel method. Prior to extraction, samples were cleaned to remove debris. Root samples

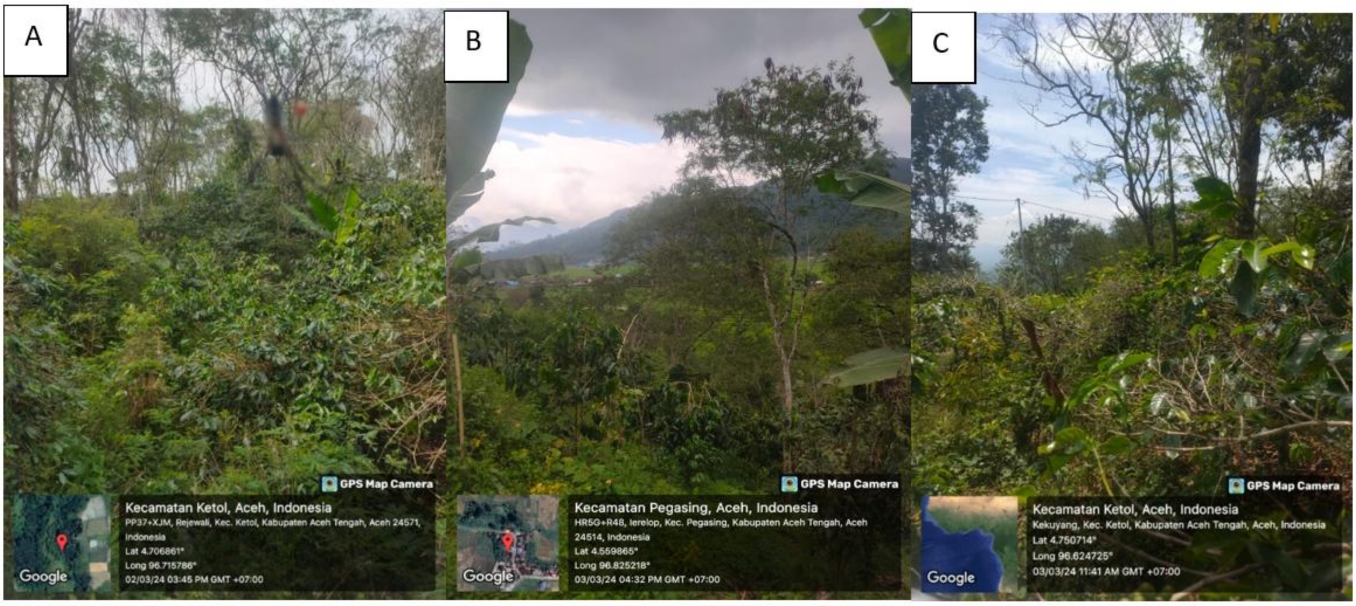


**Figure 2.** Map showing the sampling locations of coffee plants across three different altitudinal zones in the study area; A: Kampung Selon (Site 1; 800-1,000 masl); B: Kampung Kekuyang (Site 2; 1,001-1,200 masl); C: Kampung Kute Lintang (Site 3; 1,201-1,400 masl).

were cut into 0.5–1 cm fragments and weighed to 5 g, while 10 g of soil was used for each extraction. Each sample was placed in filter paper, tied, and suspended in a Baermann funnel containing 100 ml of distilled water, ensuring contact without submergence. The setup was left undisturbed for 24 hours to allow nematodes to migrate into the water. Separate funnels were used for soil and root samples to prevent cross-contamination. The resulting nematode suspension was collected in test tubes for further analysis.

*2.6. Identification and Quantification of Nematodes*

Nematodes were identified to the genus level using a compound microscope, referencing *Goodey's Soil and Freshwater Nematodes*. For quantifying nematode morphospecies abundance, a 10 ml aliquot was taken from each 100 ml suspension. From the 10 ml, three 1 ml subsamples were extracted using a dropper for microscopic observation. The number of nematode morphospecies from the three subsamples was averaged to determine the abundance per plant. These averages were compiled to estimate the average nematode abundance per field.

*2.7. Statistical Analysis*

To evaluate differences in nematode abundance among altitudinal treatments, data were analyzed using Analysis of Variance (ANOVA) based on the randomized block design. Prior to conducting ANOVA, the assumptions of normality and homogeneity of variances were tested using the Shapiro-Wilk and Levene's tests, respectively. When significant differences were found, the Least Significant Difference (LSD) test was applied to compare treatment means at a 5% significance level ($p < 0.05$).

### 3. Results and Discussion

Based on the observations, the most common characteristic of parasitic nematodes is the presence of a stylet in the mouth region, along with slower movement compared to non-parasitic nematodes. The identification process revealed three genera of parasitic nematodes: *Meloidogyne*, *Pratylenchus*, and *Rotylenchus*. These three genera were found in both the root and soil samples of Gayo Arabica coffee plants. The morphological characteristics and abundance of *Meloidogyne*, *Pratylenchus*, and *Rotylenchus* identified in this study are described as follows.

*3.1. Meloidogyne*

The identified *Meloidogyne* nematodes were in the second juvenile stage (J2), which is the infective phase responsible for penetrating host tissues [18]. This stage is referred to as the resting phase, in which the nematodes appear straight in shape [19]. Morphological characteristics include a straight body form, a non-set-off lip region (without a distinct lip offset), and a relatively long stylet. At this stage, the reproductive structures are not yet fully developed, and the tail end appears slightly tapered. These observations align with Hunt et al. [20], who noted that *Meloidogyne* in the J2 stage possesses a relatively long stylet and a distinctively shaped tail. The morphology of *Meloidogyne* is shown in Figure 3.

Azlay et al. [21] stated that *Meloidogyne* nematode infections, commonly known as root-knot disease, are


**Figure 3.** Morphology of *Meloidogyne* sp. (juvenile stage); (a) entire body view; (b) posterior region; (c) anterior region (stylet).

**Table 1**. Abundance of *Meloidogyne* sp. based on elevation in Gayo Arabica coffee plants / ml.

| Site | Coffee Plants | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X | |
| Site 1 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 19 |
| Site 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 13 |
| Site 3 | 6 | 0 | 2 | 2 | 2 | 4 | 0 | 0 | 5 | 0 | 21 |

characterized by the formation of galls or knots on the roots of infected plants. These root galls are formed as a plant response to the feeding activity of female nematodes within the root tissue, leading to root swelling and distortion. Such damage disrupts the transport of water and nutrients in the soil, resulting in stunted growth, chlorotic leaves, wilting, and ultimately reduced crop yields. Severely infected plants often exhibit dwarfism and significant root damage, making them more susceptible to secondary infections by pathogens such as fungi and bacteria. The total abundance of *Meloidogyne* based on three different altitude levels can be seen in Table 1.

*3.2. Pratylenchus*

The identified *Pratylenchus* nematodes exhibited a slender body shape, with a non-set-off head region, low head profile, and flat lips [22]. The nematodes observed had a short and robust stylet with a basal knob, relatively fine body annulations, and a long, slightly blunt tail. The morphology of *Pratylenchus* nematodes is shown in Figure 4.

According to Thompson and Clewett [23], *Pratylenchus* nematodes cause several types of damage that can significantly reduce plant growth and productivity. The primary symptoms observed on roots include discoloration from brown to black, which eventually develops into necrosis or root rot, rendering the roots brittle and easily broken. Damage to the root system leads to chlorosis or yellowing of the leaves, reduction in leaf size, and a decrease in both the number and size of branches. Overall, this results in stunted and dwarfed plant growth [24]. The total abundance of *Pratylenchus* based on three different altitude levels can be seen in Table 2.

*3.3. Rotylenchus*

The identified *Rotylenchus* nematodes exhibited a curved body shape with a stylet that has a basal knob, and both the head and tail are rounded, resembling a half-sphere. This is consistent with the description provided by Eisenback and Triantaphyllou [25], who noted that *Rotylenchus* nematodes have a curved body, a conical-shaped head with smooth body contours, an irregular head region, and a blunt conical tail. The morphology of *Rotylenchus* nematodes is shown in Figure 5.

The attack of *Rotylenchus* nematodes on coffee plants can cause significant symptoms, especially in the root system. The roots affected by this nematode typically show necrosis in the form of brown to black spots, with growth deformities such as abnormal branching, small wounds, or even total root system damage. These symptoms result in disturbances in nutrient and water absorption, leading to stunted plant growth. Above-ground symptoms include yellowing (chlorosis), curling, or rolling of leaves, often accompanied by a decrease in coffee fruit production. In severe cases, the attack can lead to plant death [26]. The total abundance of

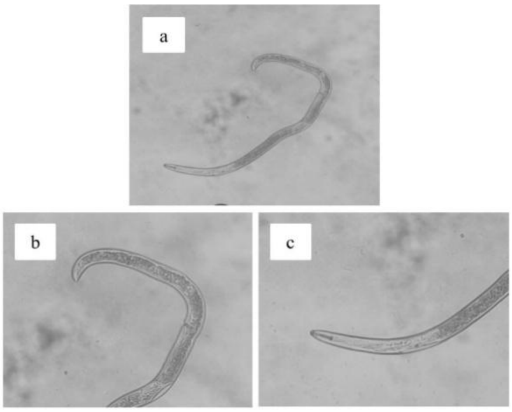


**Figure 4.** Morphology of *Pratylenchus* sp. (female); (a) entire body view; (b) posterior region (vulva); (c) anterior region (stylet).

**Table 2**. Abundance of *Pratylenchus* sp. based on elevation in Gayo Arabica coffee plants / ml.

| Site | Coffee Plants | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X | |
| Site 1 | 6 | 3 | 6 | 2 | 2 | 3 | 4 | 3 | 3 | 2 | 34 |
| Site 2 | 2 | 1 | 2 | 1 | 2 | 2 | 1 | 1 | 3 | 2 | 17 |
| Site 3 | 5 | 3 | 2 | 3 | 2 | 2 | 5 | 3 | 2 | 4 | 31 |

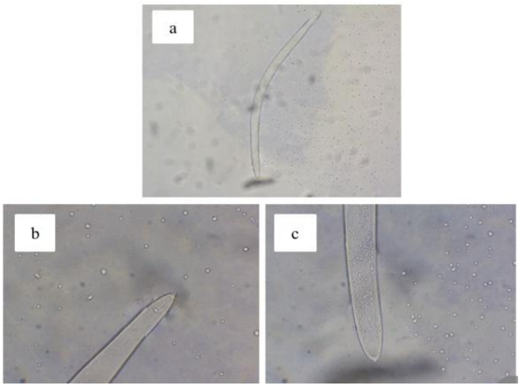


**Figure 5.** Morphology of *Rotylenchus* sp. (male); (a) entire body view; (b) anterior region (stylet); (c) posterior region.

**Table 3**. Abundance of *Rotylenchus sp.* based on elevation in Gayo Arabica coffee plants /ml.

| Site | Coffee Plants | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X | |
| Site 1 | 3 | 2 | 1 | 3 | 1 | 1 | 3 | 0 | 1 | 4 | 19 |
| Site 2 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 8 |
| Site 3 | 0 | 4 | 0 | 0 | 3 | 1 | 3 | 0 | 0 | 0 | 11 |

*Rotylenchus* based on three different altitude levels can be seen in Table 3.

### *3.4. Nematode Abundance*

Abundance refers to the number of individuals of each genus within a community. Soil and root samples from the coffee plants, after being extracted, were observed under a microscope to calculate the abundance of parasitic nematodes. The nematodes were separated according to their respective genera after identification. The total number of individuals from each nematode genus was observed across different coffee plantation sites in the Gayo Arabica coffee region at varying altitudes.

The observations show that elevation can affect the abundance of parasitic nematodes, where differences in the average abundance of parasitic nematodes were found on Gayo Arabica coffee plants based on elevation at the farmer's land in Kampung Selon (800-1,000 masl), Kampung Kekuyang (1,001-1,200 masl) in Ketol Subdistrict, and Kampung Kute Lintang (1,201-1,400 masl) in Pegasing Subdistrict, Central Aceh Regency, as shown in Table 4.

**Table 4**. Abundance of parasitic nematodes based on elevation in Gayo Arabica coffee plants / 10 ml.

| **Nematodes** | **Pratylenchus (individu/10 ml)** | **NP (%)** | **Rotylenchus (individu/10 ml)** | **NP (%)** | **Meloidogyne (individu/10 ml)** | **NP (%)** | **Mean ± SD** |
|---|---|---|---|---|---|---|---|
| Site 1 | 34 | 47.2 | 19 | 26.4 | 19 | 26.4 | 7.2b ± 1.44 |
| Site 2 | 17 | 44.7 | 8 | 21.1 | 13 | 34.2 | 3.8a ± 1.44 |
| Site 3 | 31 | 49.2 | 11 | 17.5 | 21 | 33.3 | 6.3b ± 1.44 |
| **Total/100 ml** | **82** | | **38** | | **53** | | |

Note: NP = Nematode Percentage, the number of nematodes observed in all samples divided by the total number of nematodes; Mean ± SD followed by the same letter in the same column are not significantly different according to the Least Significant Difference (LSD) test at the 0.05 significance level

In Table 4, it is evident that three genera of nematodes were identified on coffee plants at the three sites with varying elevations. The Meloidogyne nematode was found at each elevation. The abundance of *Pratylenchus sp.* and *Rotylenchus sp.* was highest in Site 1, with total abundances of 34 and 19 individuals/10 ml, respectively, while the abundance of *Meloidogyne sp.* was highest in Site 3, with a total of 21 individuals/10 ml. *Pratylenchus* is one of the parasitic nematodes that exhibits the highest population abundance on coffee plants at elevations of 800–1,000 m above sea level (masl). The warm temperature and more optimal soil moisture conditions at this elevation are the main factors supporting the development and biological activity of *Pratylenchus* [27]. Additionally, coffee plants grown at this elevation provide a more suitable host environment for this nematode compared to other nematode species that are less well-adapted to similar conditions [28].

The dominance of *Pratylenchus* across all elevation sites may be attributed to its wide ecological tolerance and aggressive parasitic behavior. As root lesion nematodes, *Pratylenchus* species are capable of penetrating root tissues and feeding on cortical cells, causing extensive damage while remaining endoparasitic and mobile within the root system [29]. This adaptability allows them to thrive under a broader range of soil and climatic conditions compared to sedentary endoparasites such as *Meloidogyne*. Similar trends have been reported in tropical agroecosystems, where *Pratylenchus* spp. dominate under fluctuating temperature and moisture regimes due to their facultative migratory behavior and wide host range [30]. Moreover, *Pratylenchus* is known to reproduce rapidly under moderate temperature and moisture conditions [31], which are present to varying degrees at all three study sites. The ability to exploit a wide host range, coupled with efficient mobility and reproduction, likely contributes to their numerical dominance in the nematode communities observed in this study.

Trinh et al. [32] reported *Meloidogyne spp.* at 907 m above sea level (masl) in Dak Song District, Vietnam. Budiman et al. [33] found *Meloidogyne* at 1,110 masl in Bondowoso, East Java. Pradana et al. [34] also observed *Meloidogyne* at 1,008 masl in Probolinggo, East Java. Trinh et al. [32] reported Pratylenchus coffea at 907 m above sea level (masl) in Vietnam, with an average of 95 individuals. Budiman et al. [33] confirmed its presence at an elevation of 1,110 m above sea level (masl) in Bondowoso. Based on research by Narzullayev [34], Rotylenchus nematodes were found in Uzbekistan at elevations ranging from 750 to 1,250 m above sea level (masl). Sarmah et al. [35] reported finding *Rotylenchus* nematodes at an elevation of 1,080 m above sea level (masl) in Cipanas District, Cianjur Regency, West Java Province. Oktafiyanto and Ibrahim [36] reported that Rotylenchus nematodes were found at an elevation of 1,200 m above sea level (masl) in Cianjur Regency, West Java Province.

Kumar et al. [37] stated that elevation is one of the factors that influence abiotic components, such as temperature, humidity, rainfall, and sunlight intensity in a region. Each nematode species has a tolerance threshold for various environmental components, including soil type, temperature, and humidity, which influence its growth and development. The types of nematodes found in soils under tropical climates differ from those in soils under temperate climates [38]. This highlights the crucial relationship between nematode populations and their surrounding environmental conditions. The different elevations provide varied abiotic factors, which contribute to the prevalence and distribution of these nematodes. Higher elevations often present cooler temperatures, different humidity levels, and potentially varying soil characteristics, all of which can impact nematode survival, reproduction, and behavior [39].

Altitude is closely related to temperature, where temperature affects the activity, migration, and distribution of nematodes. Changes in soil temperature also influence nematode activity, with the optimal temperature for nematode activity ranging from 15 to 30°C [40]. The soil environment at each altitude has distinct conditions, and the abundance of nematodes is influenced by various abiotic soil factors, including texture, structure, temperature, pH, moisture, and organic matter, all of which impact the growth and development of nematodes [41]. Soil plays a crucial role in influencing nematode abundance, particularly in acidic soils with a pH below 5.0, which can adversely affect the survival and reproduction of nematodes [42]. Soil temperature and pH can promote or inhibit the abundance of nematode communities. Nematode abundance can increase with higher rainfall, while an increase in nitrogen can reduce nematode abundance on the soil surface [42].

Host suitability also affects the development and growth of nematodes. The more suitable the food source is in terms of quality and quantity, the faster the nematode life cycle progresses. In contrast, on less suitable or resistant host plants, the life cycle is slower [43]. This means that plant resistance significantly influences nematode development and growth, if the plant is susceptible, nematodes will develop more rapidly, and their population will increase [44]. Nematode populations will increase if the host plant conditions are favorable for the attacking nematodes. Abundant food availability and supportive environmental conditions can accelerate the nematode life cycle. In contrast, unfavorable environmental conditions, limited food reserves, and resistant host plants can lead to a shorter life phase [45].

Based on the analysis of variance, elevation has a significant effect on the abundance of parasitic nematodes. Table 4 shows that the average abundance of parasitic nematodes at elevations of 1,001-1,200 meters above sea level (masl) is significantly different from other elevations. Meanwhile, the elevations of 800-1,000 m asl (site 1) and 1,201-1,400 m asl (site 3) do not show significant differences. Site 2 falls within the optimal altitudinal range for Arabica coffee and likely presents favorable abiotic conditions, such as moderate temperatures, balanced soil moisture, and an optimal pH, that support nematode survival and reproduction, especially for *Pratylenchus* spp. In contrast, Site 1, though warmer, may experience greater microbial competition or suboptimal soil chemistry [46], while Site 3, with cooler temperatures, may limit nematode activity due to thermal stress [47].

This directly ties the distribution of nematodes to the environment, emphasizing that nematode abundance is not solely determined by biological factors, but also by how environmental variables, such as temperature, moisture levels, and soil composition, interact with these organisms [48]. Although this study did not collect direct measurements of environmental variables, such as temperature, soil pH, or moisture content, at each site, interpretations regarding nematode abundance patterns were made based on established ecological principles and secondary data from published literature. Elevation is a well-documented proxy for changes in abiotic conditions, especially temperature and humidity, which are known to influence nematode activity. Therefore, although site-specific environmental data were not recorded, the discussion draws on previous studies that report typical environmental conditions across similar elevation gradients in the Gayo Highlands. Future research should incorporate direct measurement of key abiotic variables to strengthen the mechanistic understanding of nematode distribution patterns.

The study's findings underscore the importance of considering both ecological and environmental factors when managing coffee crops and their nematode pests [49]. High species diversity of nematodes, both at the ecosystem scale and within soil microhabitats, can enhance the stability of soil ecosystem functions [50]. This diversity allows for functional redundancy, where species with similar functions can replace one another, thereby maintaining ecosystem processes even during disturbances [51]. Nematode abundance plays a crucial role in the functions of soil ecosystems, particularly in processes such as nutrient cycling, organic matter decomposition, and soil structure [52].

Overall, the findings of this study demonstrate that elevation plays a significant role in shaping the composition and abundance of parasitic nematodes in Arabica coffee plantations. The varying environmental conditions across elevation gradients, including temperature, humidity, and soil characteristics, create distinct ecological niches that favor the proliferation of specific nematode genera. The supporting evidence from previous studies reinforces the observed patterns in this research. These insights highlight the importance of incorporating environmental parameters, particularly elevation, into nematode management strategies. By tailoring control measures to specific ecological conditions, coffee farmers and stakeholders can more effectively mitigate the impact of parasitic nematodes and enhance crop productivity in different highland regions.

From a practical standpoint, these findings suggest the need for elevation-specific nematode management strategies in Arabica coffee plantations. At lower elevations (800–1,000 m asl), where Pratylenchus is most abundant, farmers should prioritize the use of resistant coffee varieties, implement crop rotation, and improve soil health through the use of organic amendments to reduce nematode populations. At mid-elevations (1,001–1,200 m asl), which exhibit overall higher nematode abundance, integrated pest management (IPM) strategies that combine biological control agents with soil monitoring may be necessary. At higher elevations (1,201–1,400 masl), where *Meloidogyne* becomes more prevalent, focus should be placed on improving drainage and avoiding excessive soil moisture, which can favor root-knot nematodes. These elevation-based recommendations can help farmers optimize their control efforts and reduce economic losses associated with nematode infestations.

## 4. Conclusions

This study highlights the significant relationship between elevation and the abundance of parasitic nematodes in Arabica coffee plantations. Three genera of nematodes *Pratylenchus*, *Meloidogyne*, and *Rotylenchus*, were consistently found across different elevation ranges, with *Pratylenchus* showing the highest overall abundance. The findings indicate that specific elevations, particularly between 1,001 and 1,200 meters above sea level (masl), offer more favorable abiotic conditions, such as optimal temperatures and soil moisture, that support nematode development. These elevation-related variations in nematode abundance demonstrate how environmental gradients shape belowground communities in coffee agroecosystems. This confirms the study's objective to examine elevation-driven patterns in nematode composition and supports the relevance of environmental stratification in nematode ecology research. However, the study is limited by the absence of direct environmental measurements (e.g., soil temperature, pH, and moisture content), as well as the lack of control over potentially influential variables such as coffee variety, farming practices, and land-use history across sites. These limitations may affect the interpretation of the results and should be addressed in future studies.

Beyond their role as pests, parasitic nematodes also serve as bioindicators of soil ecological conditions. The observed patterns of nematode distribution across elevation zones provide initial insight into broader shifts in soil biotic communities and ecosystem function. As such, this study contributes to the understanding of how elevation and environmental variation affect soil health in highland coffee systems, reinforcing the importance of monitoring soil biodiversity. To manage parasitic nematodes effectively, pest control strategies should be adapted to the specific elevation range. At 800–1,000 masl, approaches such as the use of resistant cultivars and organic soil amendments may help reduce *Pratylenchus* populations. At elevations of 1,001–1,200 masl, where nematode abundance is highest, an integrated pest management (IPM) approach combining biological control and soil condition monitoring is recommended. For areas at 1,201–1,400 m above sea level (masl), improvements in soil drainage could help limit the spread of *Meloidogyne*. These findings support the development of targeted, ecologically informed strategies that align with the environmental characteristics of each elevation zone.

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