Nematode fauna in pea production areas of Cundinamarca, Colombia

Nematofauna en zonas productoras de arveja en Cundinamarca, Colombia

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ABSTRACT

Despite their importance, the presence of plant-parasitic nematodes that affect pea crops in Colombia remains unknown. To determine the nematode fauna present in the pea crop areas of Cundinamarca (Colombia), 68 soil samples were collected from the municipalities of Une, Subachoque, Madrid, and Mosquera and analyzed. Nematodes were extracted using a sieving centrifugal-flotation technique and identified using standard taxonomic keys. *Tylenchus* was common across all locations, and *Pratylenchus* was found in three of the four municipalities under study. In addition, *Helicotylenchus, Paratylenchus,* and *Globodera* were found in two of four locations. *Rotylenchus* and *Tylenchorhynchus* were only recollected in Subachoque, while *Monotrichodorus* was found only in Une, and *Nothocriconemoides*, in Mosquera. Regarding relative abundance: Une, Mosquera, and Subachoque showed high percentages of plant-parasitic nematodes (68.0%, 54.8%, and 35.7%, respectively). In contrast, bacterial feeder nematodes were more abundant in Madrid (51.3%). Subachoque had the greatest diversity (0.83), followed by Une (0.80), Mosquera (0.76), and Madrid (0.59), according to Simpson's diversity index. The genera *Monotrichodorus* and *Nothocriconemoides*, found in pea-producing areas of Colombia, had not been previously reported. The results obtained represent the first approach to nematode fauna in pea-producing regions of Cundinamarca.

Keywords: ecology, leguminous plants, Simpson diversity index, soil pathogens, trophic levels.

RESUMEN

A pesar de su importancia, aún se desconoce la presencia de nematodos fitoparásitos que afectan los cultivos de arveja en Colombia. Para determinar la nematofauna presente en zonas de cultivo de arveja de Cundinamarca (Colombia), se recolectaron y analizaron 68 muestras de suelo de los municipios de Une, Subachoque, Madrid y Mosquera. Los nematodos se extrajeron mediante la técnica de tamizado y centrifugación y se identificaron mediante claves taxonómicas estándar. Como resultado, *Tylenchus* fue común en todas las localidades, *Pratylenchus* se encontró en tres de los cuatro municipios de estudio y los géneros *Helicotylenchus, Paratylenchus* y *Globodera,* en dos de los cuatro municipios. *Rotylenchus* y *Tylenchorhynchus* sólo se encontraron en Subachoque, en tanto, *Monotrichodorus* solo se encontró en Une y *Nothocriconemoides* en Mosquera. En cuanto a la abundancia relativa, Une, Mosquera y Subachoque mostraron porcentajes elevados de nematodos fitoparásitos (68,0%, 54,8% y 35,7%, respectivamente), mientras que los nematodos bacteriófagos fueron más abundantes en Madrid (51,3%). Subachoque presentó la mayor diversidad (0,83), seguido de Une (0,79), Mosquera (0,76) y Madrid (0,59) según el índice de diversidad de Simpson. Los géneros *Monotrichodorus* y *Nothocriconemoides* identificados en este estudio no han sido previamente reportados en zonas productoras de arveja en Colombia. Los resultados obtenidos son una primera aproximación a la nematofauna presente en zonas productoras de arveja en Cundinamarca.

Palabras clave: ecología, leguminosas, índice de diversidad de Simpson, patógenos del suelo, niveles tróficos.

Introduction

Peas (*Pisum sativum* L. var. *Hortense*) are widely cultivated in cold areas in the tropics. In Colombia, peas are grown at elevations of 2000-3000 m a.s.l., especially on hillside areas (Tamayo, 2000). In the country, peas are second in importance after beans, and their production is mainly intended for fresh consumption. Nariño is the largest producer, followed by Cundinamarca, Boyacá, and Tolima (FENALCE, 2023).

Diseases caused by plant-parasitic nematodes are among the main constraints for pea crops. According to Singh *et al.* (2013) and Burrows *et al.* (2020), root-knot nematodes *Meloidogyne incognita* (Kofoid & White) Chitwood and *M. hapla* Chitwood, lesion nematodes *Pratylenchus neglectus* Filipjev and Schuurmans-Stekhoven, *P. penetrans* (Cobb) Filipjev and Schuurmans-Stekhoven, and *P. thornei* Sher and Allen, pea cyst nematode *Heterodera goettingiana Liebscher,* pin nematodes *Paratylenchus hamatus* Thorne

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and Allen, and *P. nanus* Cobb, and stem and bulb nematode *Ditylenchus dipsaci* (Kühn) Filipjev are parasitic to peas.

According to Lankubee *et al.* (2024), *M. incognita* causes early yellowing and root rot in peas and may cause up to 50% yield losses when it is associated with the occurrence of *Hoplolaimus uniformis* Thorne and *Fusarium oxysporum* Schlecht, *et al.* f. sp. *pisi* race 3. Correia *et al.* (2023) report that *Rotylenchulus reniformis* Linford and Oliveira is an important pest in legumes (cowpea, pea, and beans); Castillo *et al.* (2008) cite that *R. reniformis* is responsible for 80% of pea pod losses under greenhouse conditions in Spain. The pea cyst nematode *Heterodera goettingiana* is reported to be harmful to various leguminous crops in the USA (CABI, 2020).

Plant-parasitic nematodes cause mechanical damage to the roots, leading to their decay or facilitating the entry of other plant pathogens; and some may interfere with the sink-source relationship in the plant (Ferraz & Brown, 2016; Mo *et al.*, 2021). The main symptoms they cause in plants are the formation of galls in the roots (root-knot nematodes), root rot (root-lesion nematodes), yellowing, plant stunting, and wilting, as they affect water and nutrient use efficiency. Since their symptomatology can be confused with that of other causative agents, determining the presence of nematodes requires diagnostic tests based on plant and soil samples (Mashela *et al.*, 2017).

The degree of nematode pathogenicity varies with species and host; however, root-knot nematodes of the genus *Meloidogyne* cause the most significant damage and are the most widespread (Rusinque *et al.*, 2023). The species *M. incognita* and *M. javanica* (Treub) Chitwood can reduce pea yield by more than 50% (Tamayo, 2000). Likewise, lesion nematodes of the genus *Pratylenchus* cause necrotic lesions, tissue detachment, and root rot, generating significant yield reductions in several crops, including legumes (Lugo *et al.*, 2010; Tamayo, 2000). In the USA, Dobosz and Krawczyk (2019) reported that *M. hapla* affects the quantity and quality of leguminous plant yields. This species can survive the winter and has a wide range of hosts for cultivated plants and weeds. In Brazil, *M. incognita* and *M. javanica* are the most common species in peas (Charchar *et al.*, 2005). Recently, Pinto *et al.* (2024) report 14 pea genotypes susceptible to *Meloidogyne enterolobii*. *Meloidogyne arenaria* (Neal) Chitwood and *M. hapla* have also been reported in peas, with *M. hapla* mainly found in temperate climates.

In Colombia, there are few reports of plant-parasitic nematodes in peas, and farmers are often unaware of their presence and importance in their crops. Buriticá (1999) reports the genera *Aphelenchoides, Aphelenchus, Criconemoides, Helicotylenchus, Meloidogyne, Paratylenchus, Pratylenchus, Trichodorus,* and *Xiphinema* in pea crops. In addition, Tamayo (2000) reports the presence of root-knot and lesion nematodes in peas in Caldas, Antioquia, Cundinamarca, and Boyacá; but their economic importance has not been studied.

Determining the density, diversity, and ecological indices of nematodes, particularly plant-parasitic nematodes, is necessary for a better understanding of soil nematode fauna in agricultural systems. This is important since practices such as pesticide use and soil management can affect these populations. In general, the nematode diversity and density decrease with the application of pesticides (Timper *et al.*, 2012). Many studies have shown that organic or inorganic fertilization affects nematode abundance differently, depending on the nematode feeding habit (Atira *et al.*, 2025; Hu & Qi, 2010; Jiang *et al.*, 2018). In addition to free-living nematodes, plant-parasitic nematodes are found in soil and cause damage to many crops. Studies by Melo *et al.* (2025) find that plant-parasitic nematodes predominate in agricultural crops. In contrast, in forest systems, free-living nematodes are more prevalent.

Factors such as soil chemical and physical characteristics, rainfall, and agricultural practices influence plant-parasitic nematode populations (Pires *et al.*, 2023). As these variables are interrelated, conducting studies to understand the population dynamics of nematode fauna in agricultural crops is important (Puissant *et al.*, 2021). Based on the above, the objective of this study was to evaluate the diversity, population density, and frequency of the nematode fauna occurring in pea crops in the municipalities of Une, Madrid, Mosquera, and Subachoque (Cundinamarca) to fill the gap in knowledge related to the inventory at the genus level and the biological balances of nematodes found in the soil of pea production areas.

Materials and methods

Area of study

Pea-producing commercial farms located in the municipalities of Une, Madrid, Mosquera, and Subachoque, Cundinamarca (Colombia), were selected for this study (Fig. 1). The municipality of Subachoque, located in the Western Savanna Province, is characterized by an average temperature of 12-15°C, 600-1000 mm of accumulated annual rainfall, and altitudes between 2550 and 2750 m a.s.l. The same province includes the municipalities of Mosquera and Madrid.

Mosquera has temperatures ranging from 7°C to 20°C and an average altitude of 2,516 m a.s.l.; Madrid has temperatures ranging from 7°C to 20°C and an average altitude of 2,554 m a.s.l. Finally, it is located in the Eastern province with an average temperature of 20°C, an average annual rainfall of 479 mm, and an average altitude of 2376 m a.s.l.

Sampling

Commercial farms of different sizes and with diverse crop histories were selected in 2019. The farms were chosen at random from the municipalities of Une, Madrid, Mosquera, and Subachoque, all renowned for pea production in Cundinamarca. The sampled farms were selected because they were sown with peas at the time of the study, and the farmers were willing to allow crop sampling and provide information about the cropping history. Plant species used along with peas (Fabaceae) varied across municipalities and belonged to five botanical families. In Une, rotations was mainly done with planting chard (Amaranthaceae), potato (Solanaceae), and cauliflower (Brassicaceae); in Subachoque, carrot (Apiaceae), potato (Solanaceae), and corn (Poaceae); in the municipality of Madrid, carrot (Apiaceae), potato (Solanaceae), corn (Poaceae), celery (Apiaceae) and cauliflower (Brassicaceae); and, in Mosquera, the species included in crop rotation were potato (Solanaceae), pea (Fabaceae), leek (Amaryllidaceae) and corn (Poaceae).

At each farm, the sampling area was established by dividing the crop (field) into a 2.0 m^2 grid of squares, and the number of samples per plot varied according to the size of the cultivated area. The number of samples per plot and municipality was established based on the number of samples per ha suggested by Ferris *et al.* (1981) and Coyne *et al.* (2007). In Une, three plots (U1, U2, U3) were studied (25 samples), in Subachoque five plots (S1, S2, S3, S4, S5) (22 samples), in Madrid, one plot (Ma1) (seven samples), and two plots (Mo1, M2) were evaluated in Mosquera (14 samples) (Fig. 1). Soil samples (500 g) were collected in each grid (2.0 m^2) at the depth of the crop root system (15-20 cm) using a Dutch auger soil sampler. Five soil subsamples were randomly collected within the grid to obtain the composite soil sample. The samples were packed separately in plastic bags, labeled according to the grid, and transported under refrigeration. They were then taken to the Plant Pathology Laboratory at the Facultad de Ciencias Agrarias of the Universidad Nacional de Colombia, Bogotá campus, and stored at 6°C for 7 d until processing.

Nematode extraction

Free-living nematode extraction from soil was performed using the centrifugal-flotation method described by Jenkins (1964), which involves centrifugal extraction from samples of 100 g of soil (Hernández-Ochandia *et al.*, 2016; Wiesel *et al.*, 2015). Each sample was homogenized, and a 100 g subsample was separated. The subsample was placed in a bucket with 2 L of water, stirred for 30 s, and allowed to settle for 2 min for the sedimentation of soil particles. This suspension was passed through a series of 45, 120, and 400-mesh sieves (mesh sizes: 350 µm, 125 µm, and 37 µm, respectively). The sucrose centrifugation method was used to isolate nematodes from the soil suspension obtained with a 37 µm mesh sieve. The aqueous suspension was first centrifuged at 3500 rpm for 5 min to discard the supernatant. Subsequently, the sediment was re-suspended in a sucrose solution (456 g L^{-1}) and centrifuged again at 1500 rpm for 2 min. Finally, nematodes were collected from the supernatant using a 37 µm sieve. The suspension with nematodes was washed with sufficient water to remove excess sucrose, and the nematodes were then placed in a beaker for subsequent death and fixation. For cyst nematode extraction, the method was based on flotation, as described by EPPO (2017). The samples were processed at the Plant Pathology Laboratory at the Universidad Nacional de Colombia, Bogotá campus.

Death and fixation of nematodes

The nematodes extracted from each sample were placed in test tubes heated to 60°C for 1 min and subsequently fixed with a Golden 2X solution (Cares and Huang, 2012). Once the tubes were heated, they were allowed to rest for 30 min, and the excess supernatant was removed using a pipette, leaving a nematode suspension of 10-20 ml. Subsequently, an equal volume of the Golden 2X solution was added.

Nematode identification

The population in the total volume of each sample was estimated using a stereoscope (Olympus® SZ61/SZ51-60) and microscope (Zeiss® German Primo Star Binocular) using nematode counting dishes. Subsequently, the nematodes were classified according to genus, family, and trophic groups, which consisted of five categories: plant parasites, fungal feeders, bacterial feeders, omnivores, and predators, based on the characteristics of their mouthparts and feeding habits (Yeates *et al.*, 1993). Nematodes were fixed and glycerin infiltrated according to the method described by Seinhorst (1959). They were then mounted on permanent slides to facilitate their examination and genus identification (Seinhorst, 1959). A light microscope was used to study their morphology. Nematode identification based on morphological characters was based on specialized taxonomic literature (Decraemer, 1995; Geraert, 2010; Hunt, 1993; Loof, 1991; Oliveira *et al.*, 2016; Santos *et al.*, 2009). Once genus-level identification was completed, a photographic record was made using a BM 2000 tri-ocular microscope (Zeiss® Stemi 2000) and Scope Photo 3.0 using a digital camera for microscopy.

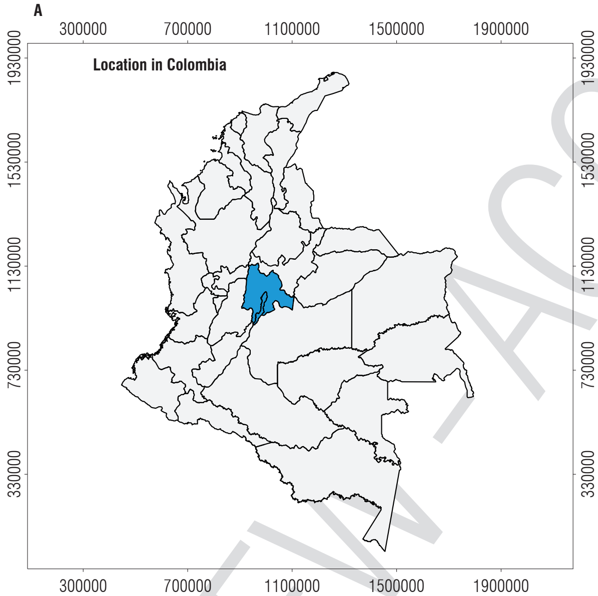
Diversity analysis

After identification, total taxa and relative abundances were calculated for each plot and location. The percentages of each trophic level at each location were calculated. The respective estimations of the measurement of diversity indices were calculated (Cares & Huang, 2012): Abundance/richness index (SDoI): $D = S/\log_2 N$; where: S = number of species and N = number of individuals; Simpson's Diversity Index (SdiI): $Ds = 1- \Sigma(pi)^2$, where pi = genus percentage "" in total abundance; Genera Richness Index (RIG PP): d = (S-- 1)/log N, where S = number of genera, N = total number of nematodes, total richness index of genera (RIG Total), fungal feeders/bacterial feeders (F/B) and (fungal feeders + bacterial feeders)/plant parasites: [(F + B)/PP] ratios were calculated.

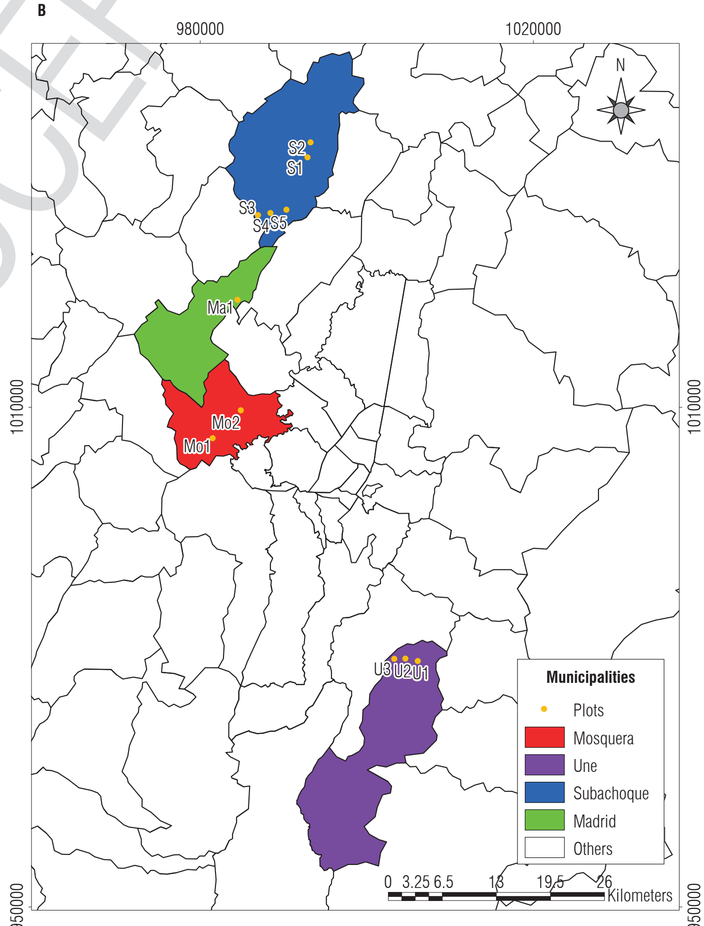
Statistical analysis

A multinomial logistic regression model was fitted to analyze nematode populations. The response variable was divided into categories corresponding to the counts of different nematode genera, and the probability of occurrence for each category was determined. The independent variables used in the model analysis were location, plots, and sampled points, and their effect on nematode count was evaluated ($P \leq 0.05$). When performing a stepwise multinomial regression analysis, these independent variables were found to be significant in the count. Additionally, to select the best model, the Akaike information criterion (AIC) was used along with the ANOVA function in the software R to identify the model with the lowest AIC and the statistically significant variables. The model adjusted under the AIC criterion included location, plot nested under location, and sampled points, with an AIC value = 3730.96. An additional model was made for the counts of all genera in the response variable: a zero-inflated negative binomial model

A



B



C

Municipality	Plot	m a.s.l.	Georeferenced location
Subachoque	S1	2660	4°57'33.6"N 74°08'33.3"W
	S2	2600	4°58'29.4"N 74°08'18.9"W
	S3	2600	4°53'44.7"N 74°11'42.3"W
	S4	2600	4°53'51.7"N 74°10'53.1"W
	S5	2663	4°54'04.9"N 74°09'51.3"W
Madrid	Ma1	2554	4°48'14.9"N 74°13'00.5"W
Une	U1	2376	4°24'39.6"N 74°01'19.9"W
	U2	2308	4°24'50.8"N 74°02'08.6"W
	U3	2260	4°24'49.6"N 74°02'52.2"W
Mosquera	Mo1	2516	4°39'13.3"N 74°14'38.2"W
	Mo2	2540	4°40'58.6"N 74°12'54.0"W

FIGURE 1. Location of the study areas. A) Location of Cundinamarca in Colombia, B) location of the municipalities in Cundinamarca and sampled plots per municipality: Subachoque five plots (S1, S2, S3, S4, and S5), Madrid one plot (Ma1), Une three (U1, U2, U3), and Mosquera two plots (Mo1, Mo2), C) altitude and georeferenced location of the plots per municipality.

due to the high presence of zeros in the response variable, which has the advantage of being able to separately model the non-zero and the zero counts, which allows contrasting the results obtained through the multinomial model. The AIC information criterion was used to choose the best model, with a value of 525.68. Data analysis was performed with the free software R version 4.4.1 (R Core Team, 2024).

Results

The mean population densities of nematodes in the pea crops at each location are shown in Table 1. In the municipality of Une, six genera of plant-parasitic nematodes were identified: *Tylenchus*, *Helicotylenchus*, *Pratylenchus*, *Paratylenchus*, *Globodera* (Fig. 2), and *Monotrichodorus* (Fig. 3D-H). *Globodera* had the highest population density, followed by *Tylenchus* and *Monotrichodorus*. In Madrid, three plant-parasitic genera were found: *Tylenchus*, *Pratylenchus*, and *Meloidogyne*, with low average population densities per 100 g of soil. In Subachoque, a total of eight genera were identified, both with relatively low population densities. In addition to those mentioned else where, *Rotylenchus* and *Tylenchorhynchus* were found to have relatively low population densities. In Mosquera, only the genera *Tylenchus* and *Nothocriconemoides* (Fig. 3A-C) were detected (49 and 55.1/100 g, respectively). The nematodes of the different trophic groups found at the four locations are shown in Figure 3.

For the trophic groups identified, Table 1 shows the percentage of nematodes in pea commercial plots at each study location. In Madrid, all trophic levels were found in the pea crops, except for predators. In the municipalities of Une, Mosquera, and Subachoque, the trophic level with the highest percentage was plant parasites (68%, 54.8%, and 35.7%, respectively), followed by bacterial feeders (15.9%, 26.3%, and 29.9%, respectively). For Une and Mosquera, the lowest trophic level was that of fungal feeders (0.5% and 1.8%, respectively). In contrast, for Subachoque, it was that of predators (0.2%). In Madrid, the highest percentage was for bacterial feeders (61%), followed by fungal feeders (34.9%). In contrast, the lowest values were for plant parasites (7.8%) and omnivores (0.6%).

TABLE 1. Mean number of nematodes/100 g of soil per location, families, genera, and relative abundances (RA) of genera in four locations associated with pea crops from producing areas in Cundinamarca, Colombia. The number of plots evaluated per municipality was 3 plots in Une, five plots in Subachoque, one plot in Madrid, and two plots in Mosquera.

Feeding habit			Number of nematodes/100 g of soil				Relative abundance (%)			
	Family	Genus	Une	Madrid	Mosquera	Subachoque	Une	Madrid	Mosquera	Subachoque
Plant parasites	Tylenchidae	*Tylenchus*	56.7	10.0	49.0	61.0	15.4	3.0	15.6	17.7
	Hoplolaimidae	*Helicotylenchus*	15.3	0.0	0.0	10.6	4.2	0.0	0.0	3.1
	Hoplolaimidae	Rotylenchus	0.00	0.0	0.0	9.6	0.0	0.0	0.0	2.8
	Pratylenchidae	*Pratylenchus*	18.7	6.0	0.0	13.8	5.1	1.9	0.0	4.0
	Heteroderidae	*Globodera*	131.7	0.0	0.0	2.2	35.8	0.0	0.0	0.6
	Meloidogynidae	*Meloidogyne*	0.0	10.0	0.0	8.6	0.0	3.0	0.0	2.5
	Paratylenchidae	*Paratylenchus*	3.3	0.0	0.0	1.6	0.9	0.0	0.0	0.5
	Criconematidae	*Nothocriconemoides*	0.0	0.0	55.1	0.0	0.0	0.0	17.5	0.0
	Belonolaimidae	*Tylenchorhynchus*	0.0	0.0	0.0	15.2	0.0	0.0	0.0	4.4
	Trichodoridae	*Monotrichodorus*	24.7	0.0	0.0	0.0	6.7	0.0	0.0	0.0
	Percentage per location (%)		68	7.8	54.8	35.7				
Fungal feeders	Aphelenchidae	*Aphelechus*	2.0	117.0	7.0	26.2	0.5	34.9	2.2	7.6
	Aphelenchoididae	*Aphelenchoides*	0.0	10.0	10.0	46.2	0.0	0.0	3.2	13.4
	Percentage per location (%)		0.5	34.9	1.8	21.1				
Omnivores	Dorylaimidae		47.0	20.0	46.0	45.4	12.8	6.0	14.7	13.2
	Percentage per location (%)		12.8	6.0	13.6	13.2				
Bacterial feeders	Rhabditidae	*Acrobeles, Rhabditis*	58.7	172.0	134.0	102.6	15.9	51.3	42.7	29.9
	Percentage per location (%)		15.9	51.3	26.3	29.9				
Predators	Mononchidae	*Mononchus*	10.0	0.0	12.5	0.6	2.7	0.0	4,0	0.2
	Percentage per location (%)		2.7	0.0	3.5	0.2				

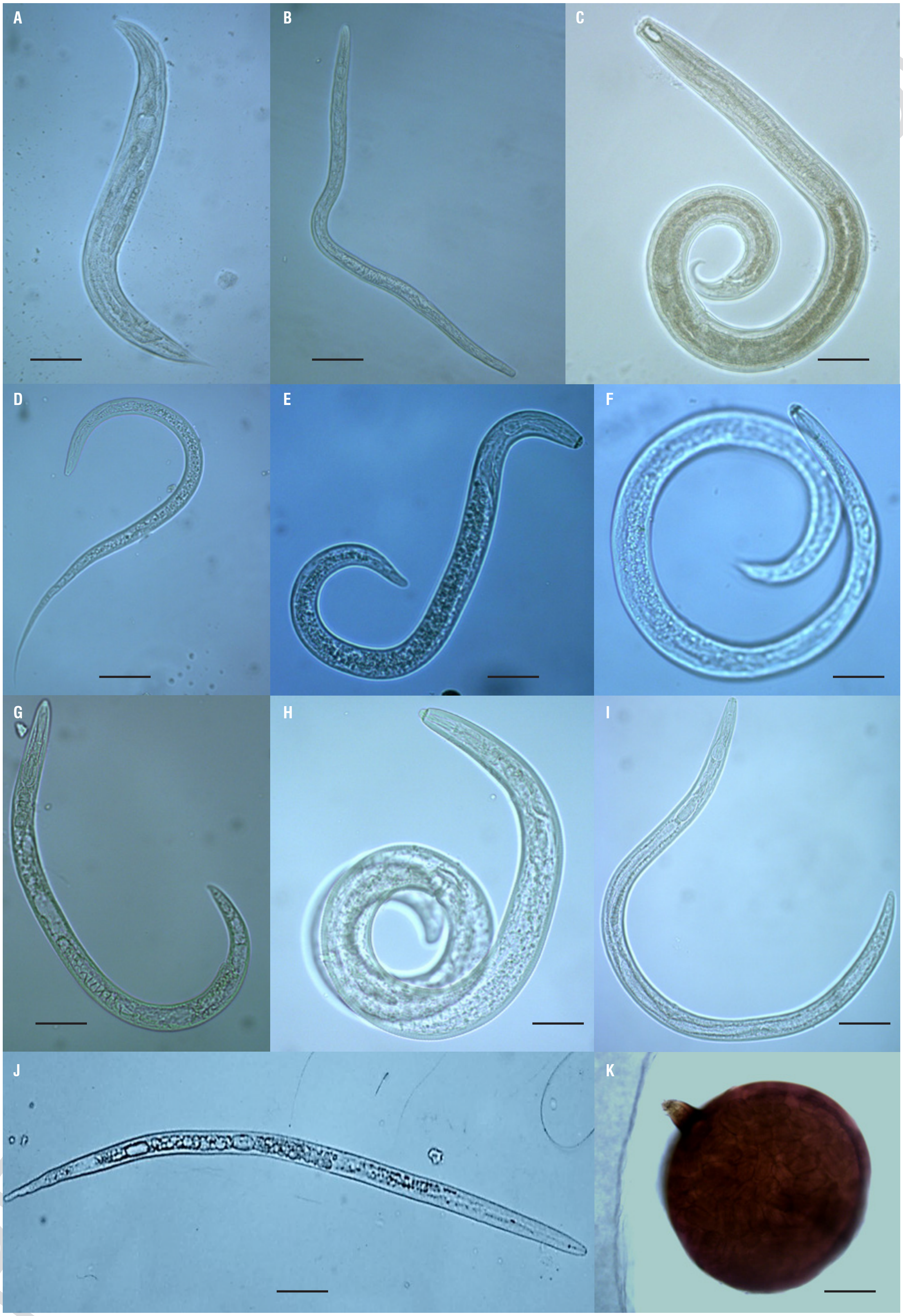


FIGURE 2. The main nematode genera found in pea crops in four locations in Cundinamarca. A) Bacterial feeder, B) Fungal feeder, C) Predator, D) *Tylenchus*, E) *Pratylenchus*, F) *Helicotylenchus*, G) *Paratylenchus*, H) *Rotylenchus*, I) *Tylenchorhynchus*, J) *Meloidogyne* (J2), K) *Globodera* (cyst). Scale bars: A-J = 50 mm; K = 100 mm.

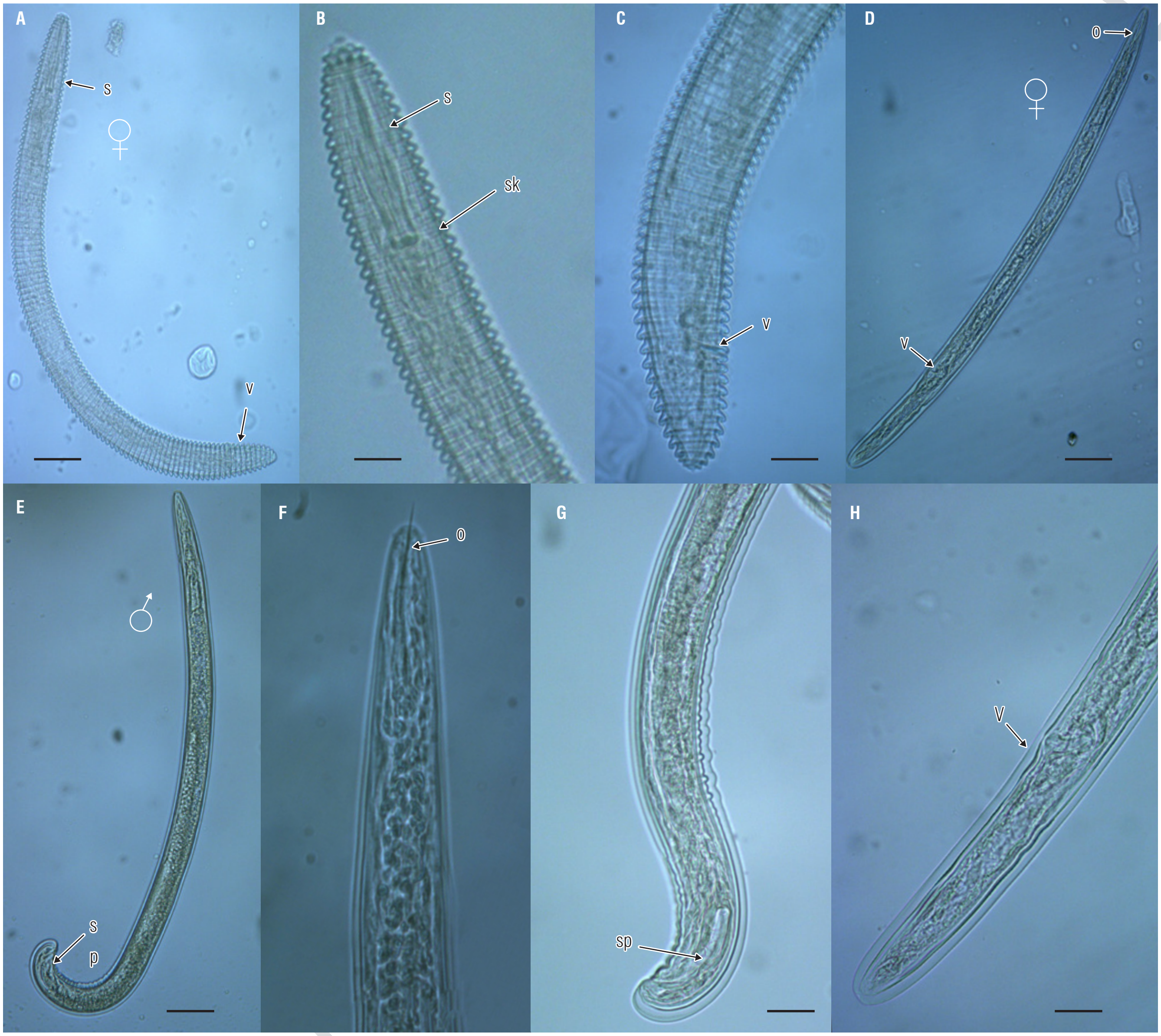


FIGURE 3. Genera *Nothocriconemoides* and *Monotrichodorus* found in pea crops in Cundinamarca. *Nothocriconemoides* (municipality of Mosquera): A) Female, B) Head detail, C) Tail detail, *Monotrichodorus* (municipality of Une): D) Female, E) Male, F) Head detail, G) Tail detail (male), H) Tail detail (female). s: stylet; sk: stylet knob; v: vulva; o: onchiostylet; sp: spicule. Scale bars: A, D, E = 50 mm; B, C, F, G, H = 10 mm.

In pea crops from Une, the genera *Globodera* and *Tylenchus* were the most abundant in the group (35.8% and 15.4%, respectively), accounting for 51.2% of the total nematode fauna at this location. They were followed by bacterial feeders and omnivores (15.9% and 12.8%, respectively), whereas fungal feeders had the lowest abundance (0.5%). In the municipality of Madrid, the bacterial feeders stood out for their high abundance (61%). *Aphelenchus* and *Aphelenchoides* were only present within the fungal feeders (35% and 10%, respectively), and the genera *Tylenchus* and *Meloidogyne* each showed the same abundance (3.0%) within the plant parasites. In Mosquera, bacterial feeders were the most abundant group (42.7%). The plant-parasite genus *Nothocriconemoides* was the most abundant, with 17.5% abundance, followed by *Tylenchus* with 15.6%. In Subachoque, the bacterial feeders were the most abundant group (29.9%). Within the plant parasites, the most abundant genera were *Tylenchus* (17.7%), followed by *Tylenchorhynchus* (4.4%) and *Pratylenchus* (4.0%) (Tab. 1).

The ecological indices are presented in Table 2, including the mean number of soil nematodes (plant-parasitic and free-living) per 100 g of soil by family and genus, and relative abundances for the four locations. In the municipality of Madrid, pea crops showed greater dominance of genera than in the other locations; therefore, the Simpson's dominance index was lower in this municipality (0.61). The highest Simpson's diversity index (0.83) was found in Subachoque, followed by Une and Mosquera with a diversity index of 0.8 and 0.76, respectively (Tab. 2). The highest richness index of plant-parasitic genera was found in the municipality of Subachoque (2.51), compared to the other locations, where eight plant-parasitic genera were found. This value was followed by Une and Madrid with 1.74 and 1.41, respectively. The lowest index was observed in Mosquera (0.43), where only 2 plant parasites were found. For the total richness index of genera, the highest value was found in Subachoque (3.71) and the lowest in Madrid (1.98). For the F/B ratio, Subachoque showed the highest value (0.70), with one of the highest populations of fungal-feeding nematodes, followed by Madrid (0.68). The lowest F/B ratio was recorded in Une, the population of fungal feeders compared to bacterial feeders. Regarding RIG PP, Subachoque presented the highest rate (2.51), followed by Une (1.74), Madrid (1.41), and Mosquera (0.43). For the F+B/PP ratio, the highest values were observed in Madrid (11.12), where the largest population of fungal and bacterial feeders relative to plant parasites was observed. In contrast, the lowest value was for Une (0.24), where the population of plant parasites was the highest among he free-living locations, compared to the other places (Tab. 2).

TABLE 2. Diversity indices of nematodes associated with pea crops in four locations in Cundinamarca: SDoI: Simpson's dominance index, SDiI: Simpson's diversity index, RIG PP: richness index of plant-parasitic genera, RIG Total: total richness index of genera, F/B: fungal feeders/bacterial feeders, and F+B/PP: (fungal feeders + bacterial feeders)/plant parasites ratios.

Index	Une	Subachoque	Madrid	Mosquera
SDoI	0.20	0.17	0.39	0.24
SDiI	0.80	0.83	0.61	0.76
RIG PP	1.74	2.51	1.41	0.43
RIG Total	2.96	3.71	1.98	2.14
F/B	0.03	0.71	0.68	0.13
F+B/PP	0.24	1.43	11.12	1.45

In the multinomial logistic regression model, location and plots were found to have a significant effect on nematode count at the 0.05 significance level. When predicting with the fitted model, the genus most likely to be observed was *Tylenchus*, since it was the most frequent in the four locations. For Une, it was *Globodera*; in Madrid, *Meloidogyne,* and *Tylenchus* were the most frequent. In Subachoque, *Meloidogyne*, *Tylenchus*, and *Helicotylenchus* were the most likely to appear in the pea crops. At the same time, *Nothocriconemoides* and *Tylenchus* were the most probable genera in Mosquera.

In Table 3, the highest probabilities of nematode counts are presented by genus, location, and plot, and the categories not included had very low probabilities with almost zero occurrences; these results were obtained from the fitted multinomial model. From Table 3, the nematodes with the highest probability of occurrence for the pea crop (above 0.5) are in this order: *Tylenchus* and *Globodera* with a high probability in the locality of Une, followed by *Helicotylenchus* concentrated in the locality of Subachoque, along with *Nothocriconemoides* and *Meloidogyne*. In Mosquera, the highest probability was observed for the genus *Nothocriconemoides*.

TABLE 3. Probability of occurrence of different genera of nematodes in pea crops in Cundinamarca (Colombia).

Individual	Genera	Probability of occurrence	Location	Plot
1-11	*Tylenchus*	0.631	Une	1
12-22	Globodera	0.737	Une	2
23-33	*Globodera*	0.443	Une	3
34-44	*Meloidogyne*	0.385	Madrid	1
34-44	*Tylenchus*	0.385	Madrid	1
45-55	*Tylenchus*	0.549	Subachoque	1
56-66	*Tylenchus*	0.412	Subachoque	2
67-77	*Helicotylenchus*	0.774	Subachoque	3
78-88	*Helicotylenchus*	0.522	Subachoque	4
89-99	*Meloidogyne*	0.648	Subachoque	5
100-110	*Nothocriconemoides*	0.512	Mosquera	1
100-110	*Tylenchus*	0.488	Mosquera	1
111-120	*Nothocriconemoides*	0.554	Mosquera	2
111-120	*Tylenchus*	0.446	Mosquera	2

Because the nematode count response variable had an excess of zeros, the data were also modeled under a zero-inflated Negative Binomial (ZINB) model with a logit link, yielding estimates of the parameters associated with each independent variable; in this analysis, standard errors and *P*-values were obtained. For each variable, one category was used as the basis for comparison.

This model considers non-zero counts and, on the other hand, zero in the response variable. In this case, with a significance level of 0.05, there were significant differences in the non-zero nematode counts between Subachoque (P = 0.0063) and Une (P = 0.0168) compared with Madrid. In addition, the nematode count was higher in Subachoque and Une than in Madrid, as confirmed by parameter estimates for these variables (1.81 and 1.68, with standard errors of 0.6626 and 0.7018, respectively). In Mosquera, there were no significant differences in the counts compared to Madrid (P>0.05). The interpretation of these coefficients is that the expected log count for Subachoque is 1.81 higher than for Madrid; similarly, the expected log count for Une is 1.68 higher than for Madrid.

Regarding the genera in the model, *Nothocriconemoides* was used as the base category. No significant differences in the nematode count for the case where the count is different from zero with respect to most of the genera, except for *Paratylenchus* (P = 0.011), whose nematode counts were significantly lower. The expected log count for *Paratylenchus* was 2.761 lower than the expected log count for *Nothocriconemoides*, with a standard error of 1.09. Plots four and five presented significant differences in the nematode count with respect to plot one (P = 0.00016 and P = 0.00067, respectively). The nematode count was lower in these plots than in plot one; the estimated coefficients were -2.66 and -3.78, respectively. And the standard errors were 0.704 and 1.11. Plots two and three did not present significant differences compared to plot one (P>0.05).

For the zero count, there were no significant differences among the locations relative to Madrid. Significant differences were found for *Helicotylenchus* with the reference category *Nothocriconemoides* (P = 0.0288), with lower probabilities of occurrence. For the other genera, there were no significant differences compared with *Nothocriconemoides*. For *Pratylenchus,* differences were significant at the 10% level (P = 0.053). The estimated coefficients were -2.56 and -2.23 with standard errors of 1.17 and 1.15, respectively. For locality and plot, there were no significant differences in the zero counts relative to the base categories of Madrid and plot one. The sampled points variable was not significant at the nematode count of 5%. The Akaike Information Criterion (AIC) of the fitted model was 525.68.

The zero-inflated Negative Binomial model fit to the data matched those results obtained under the multinomial regression model, thus validating the findings.

Discussion

In this study, the nematode fauna associated with peas in the production areas of Cundinamarca was documented, complementing the records of Buriticá (1999) and Tamayo (2000). In three of the four evaluated locations (Une, Mosquera, and Subachoque), the trophic level with the highest percentage was that of plant parasites, which are commonly found in monoculture systems (Cares & Huang, 2012; Zhao *et al*., 2022). The principal genera associated with the pea crops were *Pratylenchus, Tylenchus*, and *Tylenchorhynchus.* Nematodes of specific genera were only found in particular municipalities: *Nothocriconemoides* was identified solely in Mosquera, *Tylenchorhynchus* was found only in Subachoque, and *Monotrichodorus* was detected exclusively in Une.

Despite its importance, *Meloidogyne* was found only at low densities in Madrid and Subachoque. Nevertheless, Buriticá (1999) and Burrows *et al*. (2020) report that some *Meloidogyne* species affect beans and peas. According to Correia *et al*. (2023), Charchar *et al*. (2005), and Tamayo (2000), peas parasitized by root-knot nematodes may be stunted, wilted, chlorotic, and hadreduced yield in both quantity and quality. The presence of *Pratylenchus* (lesion nematode) was detected in three out of the four municipalities examined, and it is documented as a limiting factor in pea cultivation (Tamayo, 2000). Given its significance, our findings suggest regularly monitoring nematode populations, with particular emphasis on the pea-parasitic nematodes: *Meloidogyne* and *Pratylenchus*, in pea-producing regions of Cundinamarca.

The genera *Nothocriconemoides* and *Monotrichodorus,* respectively, had not previously been reported in these municipalities. *Nothocriconemoides* spp. are migratory or sedentary ectoparasite nematodes reported in *Punica granatum, Citrus* sp., and elm (Geraert, 2010; Maas *et al*., 1971; Maria *et al*., 2020; Raski & Luc, 1987). On the other hand, *Monotrichodorus* Allen (1957) and Andrássy (1976) are reported in Central (Panama, San Salvador, and Costa Rica) and South America (Brazil, Venezuela, and Ecuador) in peas, potatoes, and grasses, among others (Decraemer *et al*., 2013; Nemaplex, 2024). Therefore, further studies are required to confirm *Nothocriconemoides* as a parasitic nematode of pea.

Globodera, a genus of parasitic nematodes on host plants of the family Solanaceae (EPPO, 2024), was found in Une, Subachoque, and Madrid, with Une showing the highest cyst density. Nematodes of this genus do not affect peas. But since rotation with potatoes occurs at the three locations, cysts can remain viable as a soil reservoir for long periods, even after rotation with peas. The presence of *Globodera* is relevant as it could limit potato cultivation. According to Holguin *et al*. (2023), the species *Globodera pallida* and *Globodera rostochiensis* have been reported in Cundinamarca, affecting the central potato-producing regions.

Subachoque had the highest nematode population density of the four locations. The highest percentages were observed for plant parasites and bacterial feeders. In contrast, the lowest percentages were observed for omnivores and predators. These results agree with studies by Kimenju *et al*. (2009) and Nisa *et al*. (2021), who show that plant-parasitic and bacterial-feeding nematodes predominate the nematode fauna of agriculture in tropical and subtropical regions. In the municipalities of Une and Mosquera, the highest percentages were also for plant-parasitic nematodes. In contrast, the lowest population levels are known among fungal feeders and predators (Mononchida), with the latter being more common in slightly altered habitats (Sánchez-Moreno *et al*., 2009).

Based on the diversity data, Subachoque, Mosquera, and Une showed the highest percentages of plant-parasitic populations. Likewise, populations were found in these three locations, consistent with studies by Gomes *et al*. (2003) and Pimentel *et al.* (2023) , which find that predatory nematodes are scarce in tropical forest soils and cultivated habitats. Additionally, changes in soil structure caused by monocultures can influence the density of nematode functional groups (Renčo *et al*., 2020; Yeates *et al*., 2009), as these changes in soil affect K strategists (persistent nematodes), such as omnivorous and predator nematodes.

For Colombia, there are no diversity reports on nematodes in pea or other leguminous crops that allow us to compare the results of this study; therefore, this research represents the first of this type of study in pea production systems. In the analysis of nematode diversity, the Simpson index allowed us to describe the relationship between the number of taxa and their abundance and diversity in each location. According to Du Preez *et al*. (2022), this index indicates how different taxa interact with one another within their food chain and the environment in which they occur. The highest diversity values were observed in pea crops in Subachoque and Une, where rotations include carrot, potato, and corn in Subachoque, and potato, chard, and cauliflower crops in Une.

Nematodes of the genus *Tylenchus* were the most common across all locations, with the highest density. *Tylenchus* spp. are commonly found in soil and the rhizosphere of plants. However, they have not been observed as ectoparasites or endoparasites; their small, strong stylet suggests they probably feed on root hair or fungal mycelia (Nemaplex, 2024). *Helicotylenchus* spp., considered cosmopolitan, were found at low densities in the municipalities of Une, Subachoque, and Madrid.

Among the fungal feeders, the most common genus was *Aphelenchus*, whereas *Aphelenchoides* was only found in Subachoque and Madrid. The M/B ratio indicates the involvement of fungi and bacteria in the ecosystem's decomposition pathways (Coutinho *et al*., 2018). Omnivores and predator nematodes had the lowest values among the other trophic groups; however, predator nematodes showed the lowest values, being absent in Madrid and very low in Subachoque. Different authors report that nematodes of predators and omnivores are highly sensitive to changes in the soil environment due to weather conditions or agronomical practices (Coutinho *et al*., 2018; Sánchez-Moreno *et al*., 2009).

In Madrid, the highest percentage of bacterial feeders was observed, and plant-parasitic nematodes were less abundant, with the fewest genera in this trophic group, in contrast to Une, Subachoque, and Mosquera. This result may also be related to the most significant number of rotations performed in Madrid with Apiaceae, Solanaceae, Poaceae, and Brassicaceae crops (carrot, potato, corn, celery, and cauliflower), where the latter can reduce the population of plant-parasitic nematodes, preserving the soil microflora (Hassan *et al*., 2020; Ribeiro-Correia *et al*., 2023).

In the municipalities of Subachoque and Madrid, the M/B ratio was the highest. In contrast, in Une and Mosquera, it was the lowest. Varela-Benavides (2014) notes that high M/B ratios are typically observed in minimally disturbed soils rich in organic matter. In contrast, low values are often found in agricultural soils subjected to intensive tillage. In the former scenario, fungi dominate the food web. At the same time, in the latter, bacteria prevail, as intensive soil tillage promotes the bacterial decomposition of organic matter. The M/B ratio observed, suggest that the soil in Subachoque and Madrid (i) may be less disturbed and more organic than those in Une and Mosquera and (ii) the possible use of organic material rich in nutrients and low C:N ratio that significant affect the abundance of mycophagous nematodes, favoring bacteriophage nematode communities (Atira *et al*., 2025; Berg & Bengtsson, 2007; Pen-Mouratov *et al*., 2010). Our results showed contrasting soil management practices between municipalities in Cundinamarca, which should be analyzed in future studies.

The results showed that indices of abundance and diversity are valuable tools for evaluating soil quality, as nematode community composition reflects soil health (Du Preez *et al*., 2022). An increase in plant-parasitic nematodes may indicate soil degradation. In contrast, a more diverse community with a higher abundance of beneficial free-living nematodes can suggest healthier soil, as observed in Madrid and Mosquera (Ghaderi *et al*., 2025). The indices analyzed in this study can also be used to evaluate and select more effective agronomic practices, including tillage, soil organic matter, crop rotation, and crop intervals, among others (Coutinho *et al*., 2018). In this context, periodically monitoring nematode diversity can support the management of parasitic nematodes in peas in Cundinamarca and other producing regions.

In this study, two statistical analysis models that yielded similar results were applied. In future research, it would be essential when using the spatial distribution of nematodes to use other statistical methods and to compare the results.

Conclusions

Pratylenchus, Meloidogyne, Tylenchus, Helicotylenchus, Nothocriconemoides, Monotrichodorus, *Paratylenchus,* and *Tylenchorhynchus* were the plant-parasitic nematodes found in pea crop areas. *Tylenchus* was the most frequent, followed by *Pratylenchus and Helicotylenchus*. Despite its importance in peas, *Meloidogyne* was found at low densities and prevalence in the studied areas in Cundinamarca. *Nothocriconemoides* and *Monotrichodorus,* previously reported in Mosquera and Une, had not been reported in peas in Colombia; however, molecular techniques must be included in future research to correctly identify the nematodes at the species level. The lowest number of genera of phytoparasitic nematodes was found in plots with the highest abundance of beneficial free-living nematodes and a more diverse cropping history. Therefore, periodic monitoring of the prevalent nematode trophic groups at the plot level must be conducted to determine their population densities and potential risks to quality and yield losses. The results contribute to knowledge of the existing nematode fauna in pea production areas in Colombia and highlight the indices of diversity and dominance as valuable tools for assessing soil biological balance. These indices also provide helpful information for decision-making in crop protection programs aimed at improving soil health in nematode management in sustainable crop systems.

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Conflict of interest statement

The authors declare that there is no conflict of interest regarding the publication of this article.

Author's contributions

Conceptualization: NNC and SGC; Formal data analysis: NNC and SMM; Funding acquisition: SGC; Investigation: NNC and SGC. Methodology: NNC and SGC; Validation: NNC and SGC; Writing - original draft: NN and SGC; Writing – review & editing: SGC, NNC, and SMM; Supervision: NNC and SGC. All authors have read and approved the final version of the manuscript.

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