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Investigation of Soil Quality in Lavender Cultivation Using Nematode-Based Biological Indicators

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Abstract

This study was conducted to determine the nematode fauna in lavender cultivation areas in the provinces of Çanakkale and Tekirdağ and to generate distribution maps of the identified species. A total of 35 soil samples were analyzed using the Baermann funnel method, through which 31,327 nematode individuals were identified at the genus level. As a result of the analyses, 7 different orders and 43 different genera were identified. The relative abundance of the orders was expressed using the Prevalence Rate (%), and Tylenchida (35.65%) was determined to be the most prevalent order. While Chromadorida (1.07%) was the least prevalent order. Among the most common genera, *Aphelenchus* (9.15%), *Aphelenchoides* (6.44%), and *Eucephalobus* (6.10%) stood out. In addition, important plant-parasitic nematodes such as *Helicotylencus* (5.25%), *Meloidogyne* (4.46%), and *Pratylenchus* (2.07%) were also detected. Faunal profile and c-p analyses indicated that stress-tolerant species were dominant in both regions. The predominance of the c-p 2 group is consistent with agricultural systems characterized by moderate resource availability and environmental stress. Higher Maturity Index values in Tekirdağ suggest more stable soil conditions, whereas higher Enrichment Index values in Çanakkale indicate more active nutrient inputs and microbial activity. In conclusion, soils in Çanakkale exhibited stronger enrichment signals, while soils in Tekirdağ demonstrated greater structural maturity in certain parameters. The findings highlight that nematode-based biological indicators are effective tools for assessing soil quality in sustainable lavender cultivation systems.

INTRODUCTION

Lavender (*Lavandula* spp.) stands out for its high adaptability and rich essential oil content. A perennial aromatic plant belonging to the mint family (Lamiaceae), lavender is used in the production of pharmaceuticals, cosmetics, soaps, perfumes, and biopesticides (Guenther 1952; Çelik and Yuvalı Çelik 2007). The most economically important species are *L. angustifolia*, *L. intermedia*, and *L. latifolia*, with *L. angustifolia* being particularly notable for its high-quality essential oils (Tucker 1985; Cavanagh and Wilkinson 2002; Arslan et al. 2022). In Türkiye, lavender production is concentrated in Isparta, Afyonkarahisar, Burdur, Denizli, Tekirdağ, and Çanakkale. As of 2024, production reached 9,070 tons across a cultivated area of 49,937 decares (TURKSTAT 2024).

The increasing economic value of lavender cultivation necessitates a closer evaluation of soil-borne risk factors in the agroecosystems where this crop is grown. Particularly in perennial plants such as lavender, which remain in the same field for many years, the accumulation of harmful and beneficial organisms in the soil can directly influence production success. In this context, soil nematodes stand out due to both their direct effects on plant health and their role as indicators of the overall condition of the soil ecosystem.

The presence of nematodes in soil is important not only for plant health but also as an indicator of soil structure, soil pollution, and overall biological soil quality. The population density, species diversity, and distribution of nematodes in soil play a critical role in determining soil health and ecosystem functioning

(Bongers and Ferris 1999; Ferris et al. 2001; Ferris 2010). Nematodes are considered important biological indicators in soil ecosystems (Wilson and Kakouli-Duarte 2009). A high ratio of bacterivorous to fungivorous nematodes indicates that organic matter is predominantly decomposed by bacteria and that nutrient cycling is rapid, whereas the opposite situation suggests a relatively slower nutrient cycle (Ferris et al. 2001). Low population densities of omnivorous and predatory nematodes point to disturbances such as excessive fertilizer inputs, intensive tillage, or the presence of pollutants (Neher 2001). In contrast, a high abundance of omnivores and predators indicates that the soil food web is biologically complex and resilient, with a natural capacity to suppress plant-parasitic nematodes and other soil-borne pathogens (Sánchez-Moreno and Ferris 2018).

Food web analysis, using the Enrichment Index (EI) and Structure Index (SI), is an effective approach for evaluating the distribution of nematode communities within the faunal profile and, accordingly, assessing the condition of the soil food web and overall soil quality. The EI reflects the level of nutrient inputs into the system, whereas the SI provides information about the structural complexity and degree of maturity of the ecosystem. In this study, soil samples collected from lavender cultivation areas in Çanakkale and Tekirdağ provinces were comparatively analyzed based on their EI and SI values (Ferris et al. 2001).

In the biological assessment of soil ecosystems, nematode communities are considered strong bioindicators due to their high diversity, trophic heterogeneity, year-round availability for sampling, and direct contact with the soil solution. Within this framework, Bongers (1990) developed the colonizer-persister (c-p) scale to evaluate environmental disturbance based on nematode community composition, as well as the Maturity Index (MI), which is derived from this scale.

The widely used c-p classification system categorizes free-living nematodes into five distinct groups based on their life-history characteristics, such as life cycle length, reproductive strategies, tolerance to environmental stress, and sensitivity to ecosystem disturbances (Bongers 1990).

Colonizers are characterized by short life cycles, high reproductive capacity, and strong colonization ability. They are tolerant of environmental disturbance, organic enrichment, and even anoxic conditions. They often become numerically dominant in samples, exhibit marked fluctuations in population density, possess relatively large gonads, and produce numerous small eggs; in some species, viviparity is also observed. These traits indicate that colonizers are generally adapted to transient and highly variable habitats. Species belonging to the families Rhabditidae, Panagrolaimidae, Diplogasteridae, and Monhysteridae are typical representatives of this strategy (Zullini 1976; Woombs and Laybourn-Parry 1984).

Persisters comprise species characterized by low reproductive rates and a slow life-history strategy. These nematodes generally have long life cycles, limited colonization capacity, and high sensitivity to environmental disturbances. They rarely become dominant within the community, and their population densities tend to remain relatively stable throughout the year. Their production of relatively few but larger eggs, together with low reproductive rates, reflects an energy investment strategy focused on survival

rather than rapid population growth. Persisters are typically associated with habitats that exhibit long-term environmental stability and are therefore regarded as biological indicators of ecosystem maturity. Certain dorylaimid groups, including Thornematidae, Nygolaimidae, Belondiridae, Discolaimidae, and Actinolaimidae, represent clear examples of this strategy.

Colonizers (c) and persisters (p) represent the two extremes of the c-p scale, which ranges from 1 to 5. Nematodes in the c-p 1 group are opportunistic species with short life cycles and high reproductive capacity, rapidly proliferating in disturbed and organically enriched soils; they are considered indicators of early succession. In contrast, nematodes in the c-p 5 group have long life cycles, low reproductive rates, and high sensitivity to environmental changes, and they are regarded as indicators of stable and minimally disturbed ecosystems.

In natural nematode communities, many taxa exhibit intermediate characteristics and are positioned along this gradient. For example, members of Cephalobidae and Plectidae display colonizer traits; however, they often replace the less efficient Rhabditidae under conditions where food resources decline (Schiemer 1983). This pattern demonstrates that the c-p scale represents a functional continuum rather than a set of sharply defined categories.

The c-p scale is not merely a taxonomic classification but also forms the basis for the development of various nematode-based ecological indices. In particular, the MI reflects the weighted mean of the c-p values of nematode communities, providing an integrated indicator of the stress level and successional status of the soil ecosystem. Low MI values are generally associated with systems dominated by intensive agricultural practices, chemical inputs, or mechanical soil disturbance, whereas high MI values indicate more stable and less disturbed systems. In this context, the c-p classification serves as a powerful tool in soil health assessment, integrating both functional and indicator-based approaches.

For plant-parasitic nematodes, this approach has been adapted as the plant parasitic-persister (p-p) scale, in which five categories are defined based on similar life-history characteristics (Bongers 1990). The p-p classification considers traits such as host dependency, life cycle duration, and environmental tolerance of plant-parasitic nematodes, thereby contributing to the interpretation of their responses to disturbance and management practices in agricultural systems. The aim of this study is to investigate nematode communities in lavender cultivation areas, to identify plant-parasitic species, to evaluate their ecological roles and impacts on soil, and to provide data on nematode diversity within lavender agroecosystems.

MATERIALS AND METHODS

Survey

In this study, soil sampling was conducted through non-periodic field surveys in lavender cultivation areas located in Çanakkale and Tekirdağ provinces (Fig. 1). Since nematodes generally exhibit aggregated distribution patterns, soil samples must be collected in a manner that represents the entire

field in order to accurately determine population densities (Ferris et al. 1981; Southey 1986). The number of samples taken from each site varied depending on the size of the lavender cultivation area.

The soil samples were preserved under appropriate conditions and transported to the Nematology Laboratory of the Department of Plant Protection, Faculty of Agriculture, Çanakkale Onsekiz Mart University. In total, 35 soil samples were collected (Table 1).

Table 1
Locations and coordinate information of the sampled lavender fields in Çanakkale and Tekirdağ provinces.

Sample Number	Sampling Areas		Coordinates	
	District/Province	Village/Neighborhood	Latitude	Longitude
1	Lapseki/Çanakkale	Merkez	40°20'57.6"N	26°42'03.6"E
2	Gelibolu/Çanakkale	Kavakköy	40°35'55.6"N	26°52'08.7"E
3	Gelibolu/Çanakkale	Kavakköy	40°35'59.1"N	26°52'35.9"E
4	Gelibolu/Çanakkale	Kavakköy	40°36'11.1"N	26°53'22.2"E
5	Gelibolu/Çanakkale	Kavakköy	40°35'58.6"N	26°53'01.5"E
6	Gelibolu/Çanakkale	Kavakköy	40°35'57.7"N	26°53'25.3"E
7	Eceabat/Çanakkale	Bigalı	40°14'49.4"N	26°20'51.8"E
8	Eceabat/Çanakkale	Bigalı	40°14'48.4"N	26°20'54.2"E
9	Eceabat/Çanakkale	Kocadere	40°12'04.2"N	26°19'57.0"E
Continued from Table 1.				
10	Eceabat/Çanakkale	Kocadere	40°12'05.8"N	26°19'57.6"E
11	Süleymanpaşa/Tekirdağ	Esentepe	40°57'47.5"N	27°22'17.3"E
12	Süleymanpaşa/Tekirdağ	Esentepe	40°57'44.3"N	27°22'06.7"E
13	Süleymanpaşa/Tekirdağ	Yazır	40°55'40.4"N	27°25'26.2"E
14	Ergene/Tekirdağ	Velimeşe	41°12'39.4"N	27°53'33.4"E
15	Çerkezköy/Tekirdağ	Namık Kemal	41°14'01.4"N	27°58'51.8"E
16	Saray/Tekirdağ	Pazarcık	41°27'41.1"N	27°56'46.0"E
17	Saray/Tekirdağ	Ayvacık	41°29'06.6"N	27°56'35.9"E
18	Saray/Tekirdağ	Yeni	41°28'03.1"N	27°54'13.5"E
19	Saray/Tekirdağ	Sofular	41°24'33.6"N	27°39'04.5"E
20	Muratlı/Tekirdağ	Ballıhoca	41°13'00.5"N	27°30'42.0"E
21	Süleymanpaşa/Tekirdağ	Karacakılavuz	41°08'11.1"N	27°23'22.6"E
22	Süleymanpaşa/Tekirdağ	Karacakılavuz	41°08'17.3"N	27°23'58.0"E
23	Süleymanpaşa/Tekirdağ	Köseilyas	41°00'56.2"N	27°34'39.6"E
24	Süleymanpaşa/Tekirdağ	Karadeniz	40°59'39.3"N	27°29'13.3"E

Sample Number	Sampling Areas		Coordinates	
	District/Province	Village/Neighborhood	Latitude	Longitude
25	Süleymanpaşa/Tekirdağ	Otmanlı	40°56'38.7"N	27°13'60.0"E
26	Merkez/Çanakkale	Kumkale	39°59'17.0"N	26°14'42.6"E
27	Merkez/Çanakkale	Çıplak	39°57'15.9"N	26°16'14.8"E
28	Merkez/Çanakkale	Gökçalı	39°56'58.6"N	26°17'34.1"E
29	Merkez/Çanakkale	Gökçalı	39°56'38.3"N	26°17'17.7"E
48	Merkez/Çanakkale	Esenler	40°10'05.5"N	26°24'48.7"E
65	Bayramiç/Çanakkale	Camicedit	39°48'37.1"N	26°36'15.0"E
66	Bayramiç/Çanakkale	Külcüler	39°47'58.1"N	26°47'02.1"E
67	Bayramiç/Çanakkale	Külcüler	39°48'19.8"N	26°47'45.6"E
68	Bayramiç/Çanakkale	Gedik	39°49'23.1"N	26°46'06.1"E
69	Bayramiç/Çanakkale	Gedik	39°49'38.4"N	26°46'21.1"E

Extraction of nematodes from soil samples

The modified Baermann funnel method was used to extract motile nematodes from the soil samples (Hooper 1986). In this method, plastic Petri dishes measuring 12 cm in diameter and 2 cm in depth were used. For each sample, a sieve was placed inside the Petri dish and covered with filter paper, after which 100 g of soil was added. The Petri dishes were placed in containers filled with water, allowing the motile nematodes to migrate into the water. After 48 hours, the water was transferred into 100 ml graduated cylinders and left undisturbed for 24 hours to allow the nematodes to settle at the bottom. Subsequently, the remaining 10 ml water–nematode suspension at the bottom was transferred into tubes and preserved for identification procedures.

Identification of nematodes at the genus level using morphological methods

The preserved suspension in the glass tubes was concentrated to 1 ml to obtain a dense nematode population. For identification, the samples were first mixed using a vortex device to ensure homogeneity, and 100 µl was taken with a micropipette and placed between a slide and coverslip. To immobilize the nematodes, facilitate identification, and ensure accurate morphological characterization, the prepared slides were subjected to controlled heat treatment on a heating table for a specific temperature and duration. Genus-level identification of the nematodes was performed using a Leica DM1000 light

microscope equipped with a Leica DFC 290 HD digital camera and Leica Application Suite v4 software. Identification was carried out with the aid of diagnostic keys (Siddiqi 2000; Mai 2018).

Analysis of nematode communities

In this classification process, taxonomic keys were used as the primary reference. In particular De Ley P, Blaxter M (2002), De Ley P, Blaxter ML (2004), Plant-Parasitic Nematodes: A Pictorial Key to Genera (Mai 2018) and Siddiqi (2000) were consulted.

The c-p classification of nematodes based on life-history traits (scale 1–5) was determined in accordance with Bongers (1990) and Bongers and Ferris (1999). The feeding type classification of nematodes was further supported by the studies of Yeates et al. (1993) and Du Preez et al. (2022).

In addition, the MI was used to evaluate the responses of nematode communities to ecosystem disturbances (Ferris and Bongers 2009). MI calculations were performed using the Nematode Indicator Joint Analysis (NINJA) tool, an online analytical platform (Sieriebriennikov et al. 2014).

RESULTS

Within the scope of the study, nematodes were extracted from 35 soil samples collected from lavender cultivation areas in Çanakkale and Tekirdağ provinces. Among a total of 31,327 examined nematodes, 7 different orders and 43 different genera were identified (Table 2).

In the examined samples, the relative prevalence of nematode orders was expressed as Prevalence Rate (%). Accordingly, the order Tylenchida had the highest prevalence at 35.65%, followed by Rhabditida (28.58%), Aphelenchida (15.59%), and Dorylaimida (13.83%). Plectida (3.77%) and Mononchida (1.51%) were represented at lower rates, while Chromadorida showed the lowest prevalence at 1.07%.

Additionally, when evaluated according to feeding types, herbivores showed the highest prevalence rate at 37.38%, followed by bacterivores (33.39%) and fungivores (18.25%). Predators (6.22%) and omnivores (4.75%) exhibited comparatively lower prevalence rates.

Table 2
The prevalence rates, cp series, feeding types, and taxonomic information (Genus name, Order, and Family) of nematode communities

Genus Name	Order: Family	Prevalence Rate (%)	c-p Class	p-p Class	Feeding Type
Achromadora Cobb, 1913	Chromadorida: Achromadoridae	1.07	3	0	Predators
Acrobeles von Linstow, 1877	Rhabditida: Cephalobidae	3.62	2	0	Bacterivores
Acrobeloides Cobb, 1928	Rhabditida: Cephalobidae	4.81	2	0	Bacterivores
Aglenchus Andrassy, 1954	Tylenchida: Tylenchidae	1.51	0	2	Herbivores
Alaimus de Man, 1880	Dorylaimida: Alaimidae	1.04	4	0	Bacterivores
Aphelenchoides Fischer, 1894	Aphelenchida: Aphelenchoididae	6.44	2	0	Fungivores
Aphelenchus Bastian, 1865	Aphelenchida: Aphelenchidae	9.15	2	0	Fungivores
Continued from Table 2.					
Boleodorus Thorne, 1941	Tylenchida: Tylenchidae	0.25	0	2	Herbivores
Cephalobus Bastian, 1865	Rhabditida: Cephalobidae	2.70	2	0	Bacterivores
Cervidellus Thorne, 1937	Rhabditida: Cephalobidae	4.21	2	0	Bacterivores
Chiloplacus Thorne, 1937	Rhabditida: Cephalobidae	1.73	2	0	Bacterivores
Coslenchus Siddiqi, 1978	Tylenchida: Tylenchidae	2.36	0	2	Herbivores
Diphtherophora de Man, 1880	Dorylaimida: Diphterophoridae	0.28	3	0	Fungivores
Diplogaster Schultze, 1857	Rhabditida: Diplogastridae	0.85	1	0	Bacterivores
Discolaimoides Heyns, 1963	Dorylaimida: Qudsianematidae	1.13	4	0	Predators
Ditylenchus Filipjev, 1936	Tylenchida: Anguinidae	1.57	2	0	Fungivores

Genus Name	Order: Family	Prevalence Rate (%)	c-p Class	p-p Class	Feeding Type
Dorylaimus Dujardin, 1845	Dorylaimida: Dorylaimidae	4.75	4	0	Omnivores
Ecumenicus Thorne, 1974	Dorylaimida: Qudsianematidae	1.10	4	0	Predators
Eucephalobus Steiner, 1936	Rhabditida: Cephalobidae	6.10	2	0	Bacterivores
Euteratocephalus Andrassy, 1958	Plectida: Teratocephalidae	0.97	3	0	Bacterivores
Filenchus Andrassy, 1954	Tylenchida: Tylenchidae	0.75	2	0	Fungivores
Continued from Table 2.					
Helicotylenchus Steiner, 1945	Tylenchida: Hoplolaimidae	5.25	0	3	Herbivores
Hoplolaimus von Daday, 1905	Tylenchida: Hoplolaimidae	0.06	0	3	Herbivores
Malenchus Andrassy, 1968	Tylenchida: Tylenchidae	1.45	0	2	Herbivores
Meloidogyne Goeldi, 1892	Tylenchida: Meloidogynidae	4.46	0	3	Herbivores
Merlinius Siddiqi, 1970	Tylenchida: Dolichodoridae	5.38	0	3	Herbivores
Mononchus Bastian, 1865	Mononchida: Mononchoidea	1.51	4	0	Predators
Nygolaimus Cobb, 1913	Dorylaimida: Nygolaimidae	1.41	5	0	Predators
Panagrolaimus Fuchs, 1930	Rhabditida: Panagrolaimidae	3.52	1	0	Bacterivores
Paratrichodorus Siddiqi, 1973	Dorylaimida: Trichodoridae	0.22	0	4	Herbivores
Paratylenchus Micoletzky, 1922	Tylenchida: Tylenchulidae	2.51	0	2	Herbivores
Pratylenchus Filipjev, 1936	Tylenchida: Pratylenchidae	2.07	0	3	Herbivores
Psilenchus de Man, 1921	Tylenchida: Psilenchidae	0.47	0	2	Herbivores

Genus Name	Order: Family	Prevalence Rate (%)	c-p Class	p-p Class	Feeding Type
Rhabditis Dujardin, 1844	Rhabditida: Rhabditidae	1.04	1	0	Bacterivores
Rhabdolaimus De Man, 1880	Plectida: Rhabdolaimidae	1.23	3	0	Bacterivores
Continued from Table 2.					
Rotylenchus Filipjev, 1936	Tylenchida: Hoplolaimidae	0.28	0	3	Herbivores
Telotylenchus Siddiqi, 1960	Tylenchida: Tylenchidae	1.67	0	3	Herbivores
Trophurus Loof, 1956	Tylenchida: Telotylenchidae	0.22	0	3	Herbivores
Tylencholaimus De Man, 1876	Dorylaimida: Tylencholaimoidea	0.06	4	0	Fungivores
Tylenchorhynchus Cobb, 1913	Tylenchida: Telotylenchidae	1.01	0	3	Herbivores
Tylenchus Bastian, 1865	Tylenchida: Tylenchidae	4.37	0	2	Herbivores
Wilsonema Cobb, 1913	Plectida: Plectidae	1.57	2	0	Bacterivores
Xiphinema Cobb, 1913	Dorylaimida: Longidoridae	3.84	0	5	Herbivores

Classification of nematodes according to feeding types

The percentage distribution of nematode communities according to feeding types in Çanakkale and Tekirdağ provinces is presented in Fig. 2. In Çanakkale, herbivorous nematodes were identified as the dominant trophic group at 39.96%, followed by bacterivores (33.99%) and fungivores (16.02%). Predatory (5.54%) and omnivorous (4.49%) nematodes were represented at lower proportions. In Tekirdağ, bacterivorous nematodes constituted the most prevalent group at 36.65%, followed by herbivores (31.46%) and fungivores (16.26%). The proportion of predatory nematodes (10.07%) was higher than in Çanakkale, while omnivores accounted for 4.94%. In both provinces, no nematode groups feeding on unicellular eukaryotes were detected (Fig. 2).

Overall, trophic groups associated with plant- and microbe-based food resources were dominant in both locations; however, regional differences were observed in the proportional distribution of predatory and herbivorous groups. These variations in feeding type composition are likely related to regional differences in soil properties, vegetation cover, and management practices.

The findings indicate that, in the studied areas, soil organic matter cycling and biological diversity may be closely associated with the dominant herbivorous, bacterivorous, and fungivorous nematode groups.

When free-living nematode communities were evaluated separately, bacterivorous nematodes were found to be the dominant trophic group in both locations. In Çanakkale, bacterivores had the highest proportion at 56.62%, followed by fungivores (26.68%), predators (9.22%), and omnivores (7.48%). A similar distribution was observed in Tekirdağ; bacterivorous nematodes remained dominant at 53.46%, while fungivores accounted for 23.72%. However, the proportion of predatory nematodes (15.61%) was higher in Tekirdağ compared to Çanakkale. In Tekirdağ, omnivores showed the lowest prevalence at 7.21%. In both locations, no nematode groups feeding on unicellular eukaryotes were detected (Fig. 3).

These distributions indicate the dominance of bacterivorous and fungivorous groups among free-living nematodes, suggesting that bacterial and fungal activity varies between the regions and that the soils of these provinces may support relatively high biological diversity.

When the distribution of the herbivorous nematode community was evaluated according to feeding strategies, marked differences were observed between the two locations. In Çanakkale, ectoparasitic nematodes were identified as the dominant group at 36.96%, followed by epidermal/root-hair feeders (25.94%) and semi-endoparasites (19.11%). The proportion of sedentary parasites was recorded at 15.04%, while migratory endoparasites were represented at a limited level of 2.94%. No herbivorous nematodes feeding on algae, lichens, or mosses were detected at this location.

In Tekirdağ, ectoparasitic nematodes were clearly dominant at 52.11%, while epidermal/root-hair feeders accounted for 34.00%. In contrast, the proportion of semi-endoparasites (3.78%) was considerably lower than in Çanakkale. Migratory endoparasites (8.85%) and sedentary parasites (1.26%) were observed at low levels, and no herbivorous nematode groups feeding on algae, lichens, or mosses were detected in either location.

There are marked differences between Çanakkale and Tekirdağ in terms of the feeding strategies of herbivorous nematode communities (Fig. 4). Tekirdağ, the proportion of ectoparasitic nematodes is higher compared to Çanakkale, whereas in Çanakkale, epidermal/root-hair feeders, semi-endoparasites, and sedentary parasitic groups are represented at higher rates. In contrast, migratory endoparasites are more prevalent in Tekirdağ than in Çanakkale.

Food web analysis evaluates the position of nematode fauna within the faunal profile based on the Enrichment and Structure indices, thereby revealing the condition of the soil food web and associated soil quality (Ferris et al. 2001). The EI reflects the intensity of nutrient enrichment (particularly resource inputs), whereas the SI is associated with the maturity level of an ecosystem. Within the scope of this study, soil samples collected from lavender cultivation areas in different regions (Çanakkale and Tekirdağ provinces) were evaluated based on their Enrichment and Structure Index values.

The results of the nematode-based food web analysis revealed marked differences between the soils of Çanakkale and Tekirdağ (Fig. 5). A large proportion of the Çanakkale samples were concentrated in areas characterized by high SI values and moderate to high EI levels. This indicates that the soil food web is structurally well-developed, trophically more complex, and in a relatively advanced stage of maturation. In particular, samples located in the upper-right and lower-right quadrants suggest soil conditions in which bacterial and fungal decomposition channels operate simultaneously, reflecting regulated and partially suppressive soil environments.

In contrast, the Tekirdağ samples exhibited a broader distribution along the SI and EI axes, with a notable concentration in regions characterized by low SI values, reflecting more heterogeneous and locally disturbed food web conditions. This pattern observed in Tekirdağ soils suggests lower structural stability of the food web and indicates that, in some areas, disturbed or early-stage systems may be predominant. Overall, while Çanakkale soils display a more mature and balanced nematode-based food web structure, Tekirdağ soils appear to exhibit more variable food web dynamics under environmental and management influences.

Maturity index analysis and classification according to c-p series

According to the MI analysis, values showed significant differences between the provinces (Fig. 6). The average MI value indicated the highest maturity level in Tekirdağ (MI = 2.56), whereas Çanakkale exhibited a lower maturity level (MI = 2.34). Based on the MI 2–5 analysis, the highest average maturity level was again observed in Tekirdağ (MI = 2.66), while Çanakkale showed a comparatively lower maturity level (MI = 2.49).

According to the Sigma Maturity Index analysis, the average values showed slight differences: the highest maturity level was observed in Tekirdağ (Sigma MI = 2.69), while Çanakkale exhibited a lower maturity level (Sigma MI = 2.50). The Plant Parasitic Index (PPI) analysis also indicated that the highest average PPI values were recorded in Tekirdağ (PPI = 2.91), whereas Çanakkale showed a comparatively lower average PPI value (PPI = 2.84).

The EI analysis indicated that the highest enrichment level was observed in Çanakkale (EI = 47.19), while Tekirdağ exhibited a lower enrichment index value (EI = 41.54). According to the SI analysis, the highest structural level was recorded in Tekirdağ (SI = 61.60), whereas Çanakkale showed a comparatively lower structure index value (SI = 50.06).

The faunal profile diagram, based on the proportional distribution of c-p 1, c-p 2, and c-p 3–5 nematode groups, shows that samples from both Çanakkale and Tekirdağ are primarily positioned in the stress-dominated region. This indicates that the examined free-living nematode communities are composed mainly of stress-tolerant species adapted to environmental disturbances.

The low representation of nematodes in the c-p 1 group indicates that opportunistic species, which rapidly respond to short-term nutrient enrichment, are not dominant in these soils. This finding suggests

that easily decomposable organic matter or sudden nutrient inputs are not among the primary factors shaping the nematode community structure.

In contrast, the limited contribution of the c-p 2 group indicates that conditions suitable for species sensitive to moderate nutrient levels and preferring more balanced environments are restricted. The dominance of c-p 3–5 groups suggests that the nematode community structure is largely shaped by environmental stress factors rather than nutrient enrichment. Such a structure is typically associated with soils subjected to long-term stress or disturbance, where food web complexity is limited.

The similar placement of the Çanakkale and Tekirdağ samples in the faunal profile diagram suggests that the soils in both provinces have largely comparable ecological conditions and soil food web structures. Nevertheless, the slight shifts of certain samples toward the stress axis indicate localized differences, likely resulting from land-use practices or site-specific environmental pressures.

Overall, the faunal profile analysis indicates that the studied soils are characterized by nematode communities with weak enrichment signals and a stress-focused structure. This pattern suggests that ecological maturity and functional complexity are limited in these soil ecosystems, with nematode community composition primarily shaped by stress tolerance.

The c-p classification is based on the life-history characteristics of nematodes. Nematodes in the c-p 1 group are defined as opportunistic species that respond rapidly to enrichment; due to their short life cycles, they tend to dominate in disturbed or stressed environments. In contrast, c-p 5 nematodes have long life cycles and are associated with structurally stable and mature ecosystems. The c-p values of plant-parasitic nematodes are evaluated in the literature under the p-p classification.

The c-p structure of free-living nematodes in both provinces shows that the c-p 2 group is dominant (Fig. 7). In Çanakkale, the c-p 2 group accounted for the highest proportion at 65.90%, while in Tekirdağ, it represented 59.86%.

In Tekirdağ, the c-p 4 group (25.92%) was higher compared to Çanakkale (14.36%). This increase suggests that the soil conditions in Tekirdağ support a more stable and mature free-living nematode community. In contrast, the c-p 1 group in Çanakkale (10.65%) was higher than in Tekirdağ (5.69%), indicating that opportunistic and fast-reproducing species are relatively more dominant in Çanakkale.

In both provinces, the c-p 3 group was present at similar proportions (6–7%), while the c-p 5 group was represented at very low levels in both regions (< 3%). These results indicate that long-lived, environmentally sensitive species are limited in both areas.

Nematodes in the c-p 2 group typically represent species that develop in nutrient-rich but environmentally stressed conditions, whereas c-p 3–5 groups reflect species found in soils with lower nutrient levels but reduced environmental stress and more stable conditions. In this study, the dominance of the c-p 2 group in both provinces indicates that the examined nematode communities are

adapted to high-stress conditions and environmental fluctuations. In contrast, the lower representation of c-p 3–5 groups reveals that long-lived, stress-sensitive species are limited in these areas.

These results suggest that the soils in Çanakkale and Tekirdağ exhibit ecosystem characteristics that are prone to instability but have relatively high nutrient inputs. Overall, the nematode community in Tekirdağ appears more balanced and stable compared to Çanakkale, whereas Çanakkale shows a structure more susceptible to disturbance, dominated by opportunistic species.

When the life-history strategy of the herbivorous nematode community was examined, the p-p 3 group was found to be dominant in both provinces (Fig. 8). In Çanakkale, the p-p 3 group accounted for the highest proportion at 57.67%, while in Tekirdağ, it represented 49.88%. This indicates that, in both regions, plant-feeding nematode communities are primarily composed of species with moderate environmental tolerance and relatively rapid reproductive capacity.

The proportion of the p-p 2 group was similar in Tekirdağ (35.62%) and Çanakkale (35.04%), reflecting agricultural conditions in both regions where food resources are available but environmental stress remains significant. In contrast, the higher proportion of the p-p 5 group in Tekirdağ (13.52%) compared to Çanakkale (6.28%) suggests that some areas in Tekirdağ support longer-term, more stable plant–soil interactions.

The low representation of the p-p 4 group in both provinces (Çanakkale 1.02%; Tekirdağ 0.99%) indicates that highly stable, minimally disturbed systems are limited. Overall, the structure of the herbivorous nematode communities reflects soil conditions in both regions that are shaped by agricultural activities, characterized by moderate stress and relatively continuous resource availability.

DISCUSSION

This study provides important data on nematode fauna in lavender agroecosystems in Türkiye by revealing the diversity of nematode communities and the presence of plant-parasitic species in lavender cultivation areas in Çanakkale and Tekirdağ provinces. The high number of individuals and taxonomic diversity observed in the samples indicate that the lavender rhizosphere offers a favorable and complex microhabitat for nematodes. The 43 genera across 7 orders identified suggest that both free-living and plant-parasitic nematodes coexist in these fields, reflecting a soil food web that is trophically rich.

The fact that field sampling was conducted during the summer period should also be considered when interpreting the observed community structure. Summer is generally regarded as a period when temperature, soil moisture, and biological activity create more favorable conditions for nematode activity (Yeates and Bird 1994; Stamou et al. 2005). These conditions may have supported the relative abundance of certain trophic groups. It is well known that some plant-parasitic nematodes possess advanced survival strategies that enable them to withstand adverse environmental conditions (Perry and Gaur 1996; Perry 1999, 2002). Such traits may explain the persistence of particular phytoparasitic species in agricultural fields despite environmental fluctuations.

A substantial proportion of the identified genera (e.g., *Cephalobus*, *Acrobeloides*, *Rhabditis*, *Panagrolaimus*) are bacterivorous or fungivorous, representing functional groups involved in organic matter decomposition and nutrient cycling. This indicates that microbial activity and organic matter turnover processes are active in soils cultivated with lavender. The presence of these functional groups can be considered a positive indicator of biological functionality and nutrient cycling within the soil ecosystem. Moreover, the apparent absence of previous studies in the literature reporting the percentage distribution of nematode communities according to feeding types in lavender cultivation areas of Çanakkale and Tekirdağ highlights the originality of the present findings and their contribution at a regional scale. On the other hand, the presence of plant-parasitic genera such as *Pratylenchus, Helicotylenchus, Paratylenchus, Tylenchorhynchus, Xiphinema*, and *Meloidogyne* indicates that potential phytoparasitic pressure in lavender production areas should not be overlooked.

In addition, nematodes belonging to the genera *Boleodorus* and *Filenchus* which were also detected, are characterized by short life cycles, high reproductive potential, and feeding on root hairs. These taxa are known for their widespread global distribution (Munawar et al. 2021; Munawar et al. 2022).

Members of the order Dorylaimida are known to exhibit predominantly omnivorous feeding behavior and are widely distributed in terrestrial ecosystems (Yeates et al. 1993). The presence of this group in our study indicates that higher trophic levels are functioning within the soil food web.

The genera identified in this study *Cephalobus, Acrobeloides, Chiloplacus, Acrobeles, Ditylenchus, Alaimus, Rhabditis, Filenchus, Pratylenchus, Panagrolaimus, Eucephalobus*, and *Aphelenchus* are consistent with those previously reported from lavender cultivation areas in Uzbekistan (Aramova 2024).

Other studies conducted in different lavender-growing areas have reported several important plant-parasitic nematodes, including *Paratylenchus sarissus* (Tarjan 1960*), Aphelenchoides ritzemabosi* (Schwartz 1911), *Ditylenchus dipsaci* (Kühn 1857) Filipjev 1936, and *Meloidogyne javanica* (Treub) Chitwood 1949 (Junges 1938; Kirjanova 1939; Minz 1956; Tarjan 1960).

In New Zealand, *Aphelenchoides fragariae* was detected in the roots of *Lavandula dentata*, and *Aphelenchoides ritzemabosi* was reported in *Lavandula angustifolia* (Dale 1971; Knight et al. 1997). In southern Bulgaria, nematodes belonging to the genera *Meloidogyne, Pratylenchus, Pratylenchoides*, and *Tylenchorhynchus* were identified in lavender cultivation areas (Lazarova et al. 2019).

The presence of *Meloidogyne* spp. in lavender-growing areas worldwide has been documented in various studies (Gorustovich et al. 1997; Carneiro et al. 2000; Pauletti and Echeverrigaray 2000; Ibrahim and Mokbel 2009; Carneiro et al. 2014; Gonçalves et al. 2020; Sarkar 2020; Oliveira et al. 2022). Similarly, the occurrence of *Meloidogyne* spp. has also been reported in Türkiye (Özalp et al. 2020; Özdemir 2022). Studies on soil nematode fauna in the Marmara Region under different crops (Öztürk 2023; Çakmak 2024) have likewise identified similar taxa, supporting the consistency of these findings.

This study demonstrates that the nematode community structure in lavender agroecosystems of Çanakkale and Tekirdağ differs both taxonomically and functionally. The dominance of Tylenchida in both provinces indicates the widespread presence of plant-parasitic nematodes in agricultural systems, while differences in the distribution of orders and trophic groups suggest the influence of local soil conditions and management practices. Indeed, Schnürer et al. (1986) and Yeates (2007) emphasized soil organic matter, texture, structure, chemical properties, moisture, and environmental disturbances as key factors shaping nematode communities. It is also well established that nematodes with short life cycles may exhibit population patterns that fluctuate seasonally. While some studies have reported pronounced annual fluctuations (Fisher 1968; Palomares-Rius et al. 2015) others have documented more limited variation (Strayer 1985).

The dominance of bacterivorous nematodes among free-living groups in both locations indicates that bacterial decomposition channels are active. The relatively higher proportion of fungivores in Çanakkale suggests a greater importance of the fungal energy channel, pointing to possible regional differences in organic matter turnover processes. In Tekirdağ, the higher abundance of predatory nematodes indicates that trophic regulation may be stronger in certain areas.

The high proportion of herbivorous nematodes indicates that the lavender rhizosphere constitutes an important food resource. The dominance of ectoparasites in Tekirdağ may be associated with the greater availability of accessible resources on the root surface, whereas the relatively higher presence of semi-endoparasites and sedentary parasites in Çanakkale suggests more established plant-nematode interactions.

Faunal profile and c-p analyses showed that stress-tolerant species are dominant in both regions. The prevalence of the c-p 2 group is consistent with agricultural systems characterized by moderate resource availability combined with environmental stress. Higher MI) values in Tekirdağ indicate relatively more stable conditions in certain areas, whereas higher EI) values in Çanakkale suggest more active nutrient inputs and enhanced microbial activity.

Overall, Çanakkale soils exhibit stronger enrichment signals, whereas Tekirdağ soils demonstrate greater structural maturity in certain parameters. However, the dominance of stress-tolerant nematodes in both regions indicates that lavender production systems are sensitive to management practices. These findings support the use of nematode-based biological indicators as effective tools for assessing soil quality in sustainable lavender cultivation systems.

This study demonstrates that the structure of nematode communities in lavender cultivation areas should be evaluated not only in terms of species richness but also with regard to their potential effects on agroecosystem functioning and plant health. The findings indicate that soils under lavender cultivation are biologically dynamic systems, in which nematode communities function as key components of the ecosystem.

The composition of the nematode fauna suggests that soil biota in lavender agroecosystems may play a dual role in terms of both productivity and plant health. On the one hand, the presence of free-living nematode groups supports the continuity of essential soil processes. On the other hand, the detection of plant-parasitic nematodes reveals the existence of potential biotic stress factors that may remain unnoticed in lavender production. This highlights the need to monitor not only agronomic practices but also soil biota in lavender cultivation systems.

In conclusion, this study highlights the importance of addressing nematode fauna in lavender agroecosystems from a holistic perspective. It provides a solid foundation for future research focusing on ecologically based nematode management, soil health monitoring programs, and studies targeting lavender nematode interactions.

Future studies focusing on long-term population dynamics, more detailed species-level identification, and modeling the relationships between environmental variables and nematode communities will contribute significantly to the development of sustainable production systems.

DECLARATIONS

AUTHOR CONTRIBUTIONS

All authors critically reviewed and commented on drafts of the manuscript. All authors read and approved the final manuscript. The authors declare that they have contributed equally to the article.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the

current study

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Figures

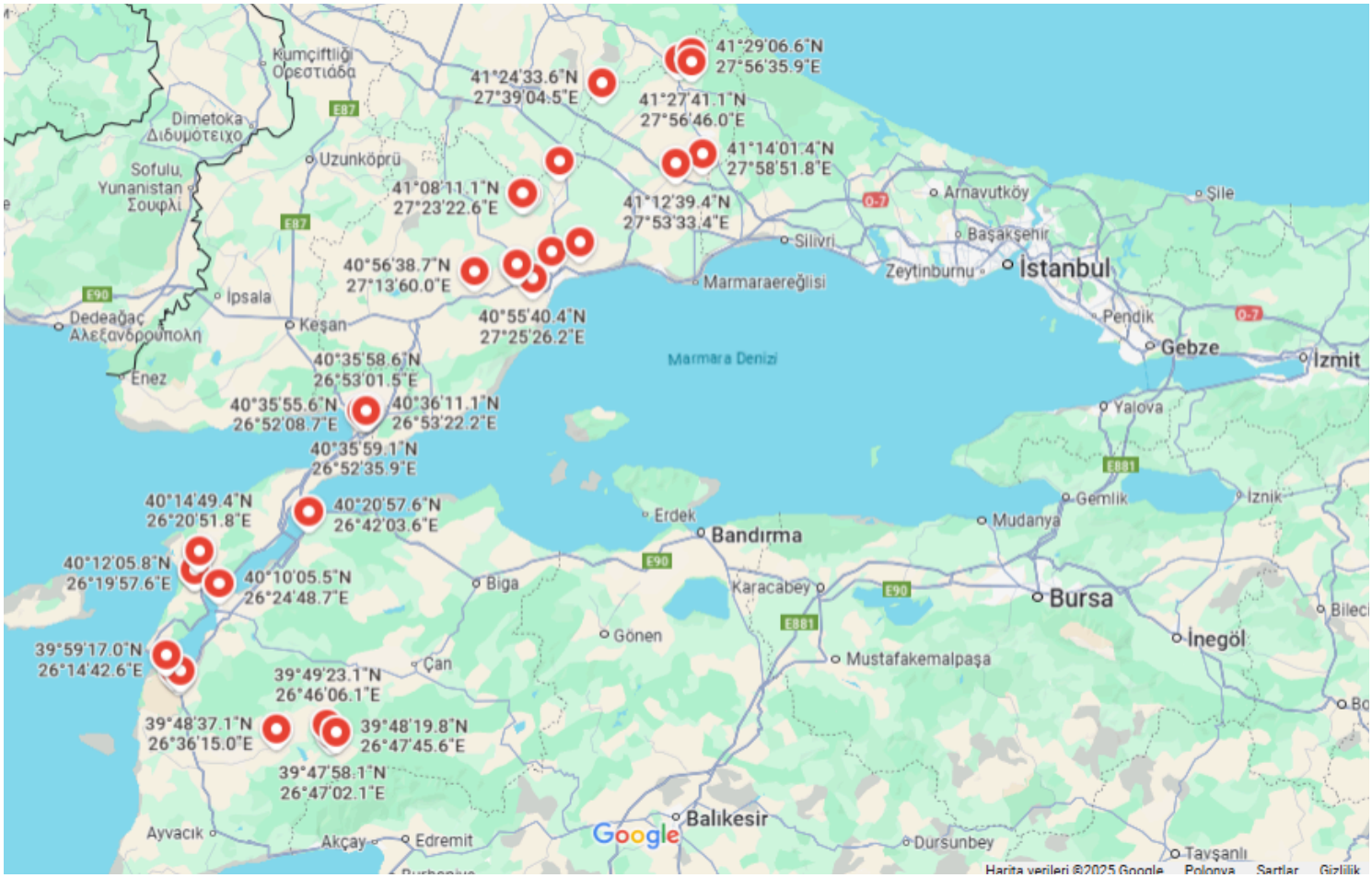


Figure 1

Distribution of the GPS coordinates of the sampling locations on the map

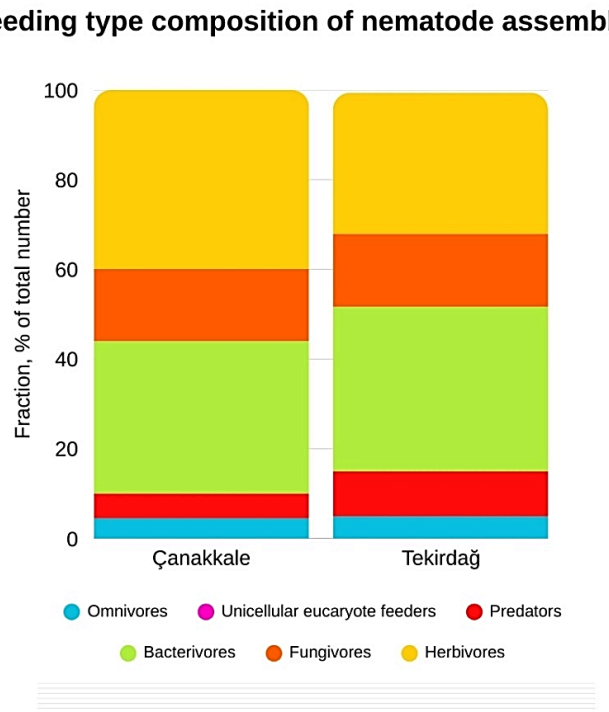


Figure 2

Feeding types and relative abundance of nematode communities in lavender fields in Çanakkale and Tekirdağ, Türkiye

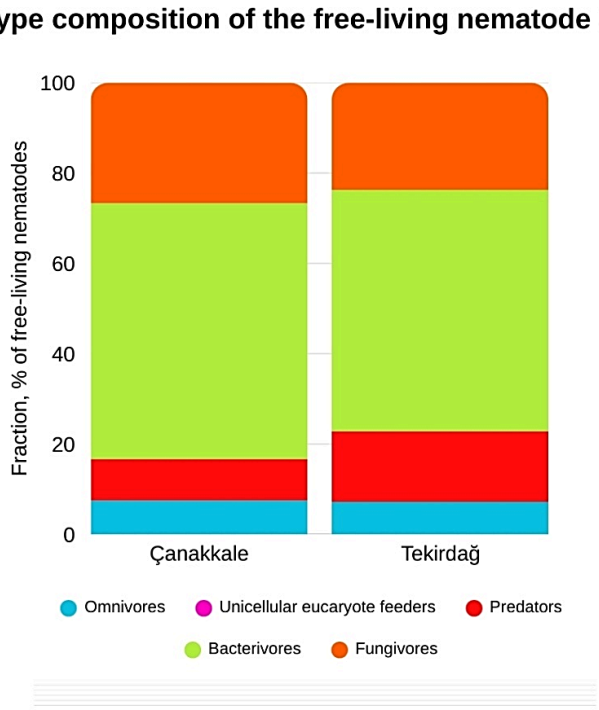


Figure 3

Distribution (%) of feeding types within the free-living nematodes from lavender fields in Çanakkale and Tekirdağ, Türkiye

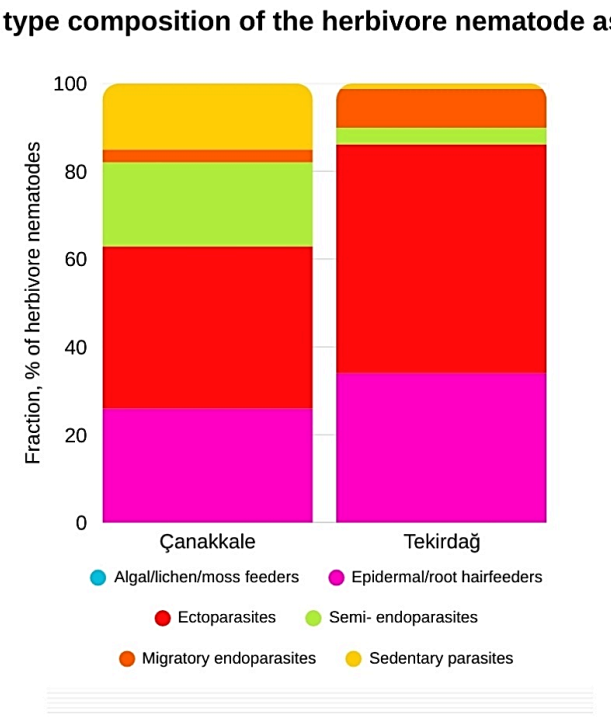


Figure 4

Distribution (%) of feeding types within the plant-parasitic nematodes from lavender fields in Çanakkale and Tekirdağ, Türkiye

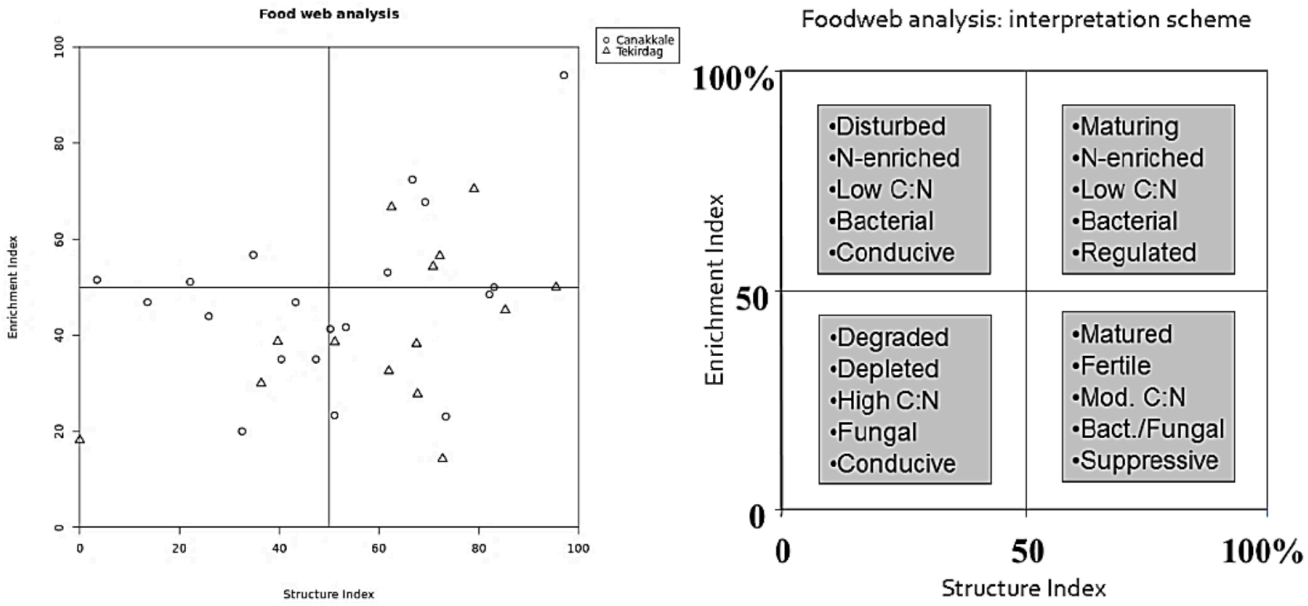


Figure 5

Food web analysis (Enrichment/Structure indices) from lavender fields in Çanakkale and Tekirdağ, Türkiye

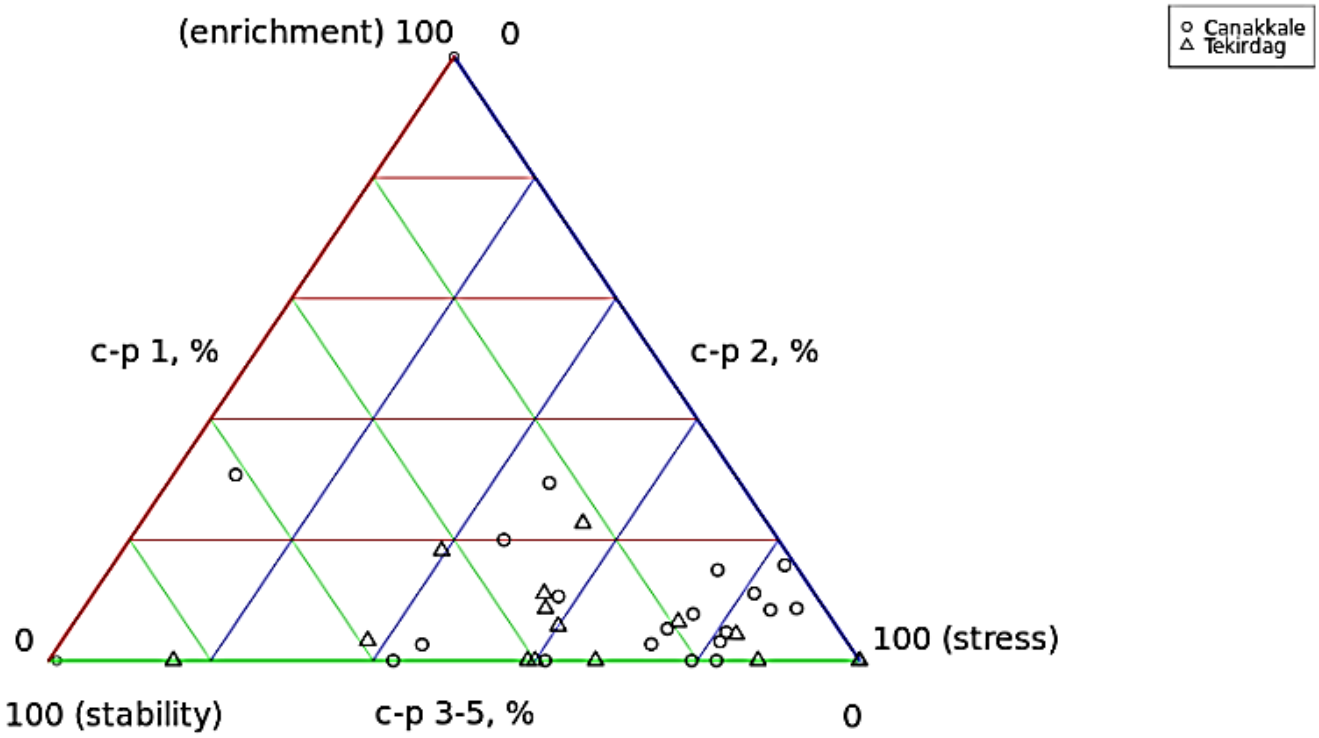


Figure 6

Comparative maturity index analysis of nematode c-p classification in lavender fields in Çanakkale and Tekirdağ, Türkiye

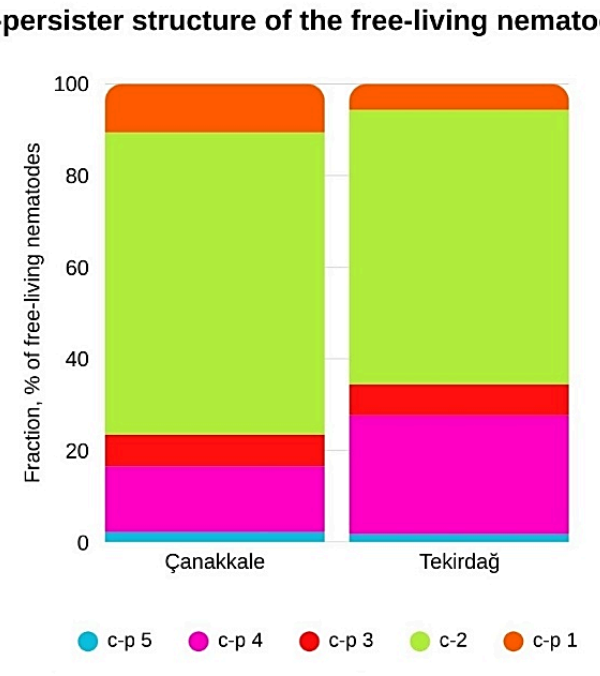


Figure 7

Free-living nematode c-p classification from lavender fields in Çanakkale and Tekirdağ, Türkiye

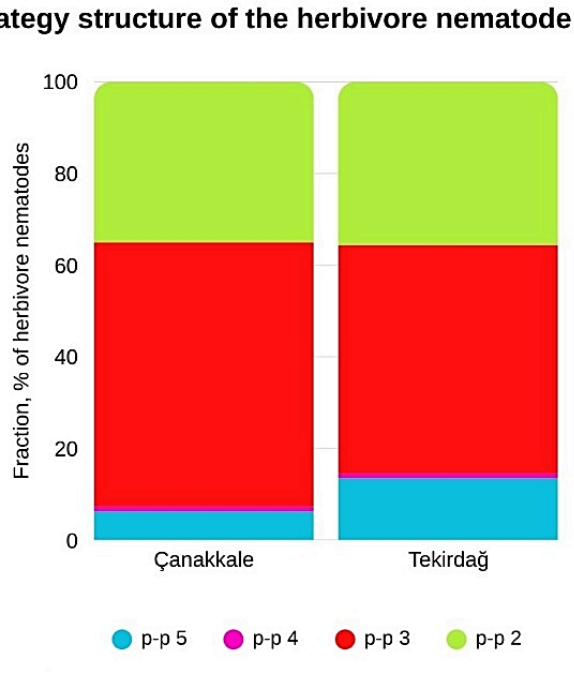


Figure 8

Plant parasitic nematode c-p classification from lavender fields in Çanakkale and Tekirdağ, Türkiye