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Research Article

Community structure and functional diversity of soil nematodes from Udupi district, Karnataka, India

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Abstract
Nematodes constitute the most significant, most numerous, and diversified set of multicellular organisms on the earth. They live in various environments and exhibit a wide range of behavioural patterns. In the soil food web, they can be found at various trophic levels as herbivores (plant parasitic nematodes), bacterivores, fungivores, omnivores, and predators. As there were fewer studies on nematode ecology in the Udupi region, the present study aims to study the community structure and functional diversity of soil nematodes. Soil samples were collected following opportunistic random sampling employing a soil auger and were stored at 4^0C until transported to the laboratory. Nematodes were isolated from soil, killed, fixed, dehydrated, and displayed on a glass slide after isolation. The standard keys were used to identify the individual to genera level. 62 genera of soil nematodes belonging to 26 families and 7 orders were identified. Predator were the most prevalent communities. Various statistical indices for assessing nematode population ecology and nematodes specific indices were also calculated and it indicated a significant abundance of large plant parasitic nematodes. The region exhibits low levels of labile organic carbon and nutrient enrichment (Enrichment Index (EI):14.06 to 21.22). Despite this, the soil food web in the region is well-structured, indicated by Structure Index (SI) (85.51 to 89.74). Prevalence of fungal decomposition dominance and the soil appears to be minimally disturbed, as indicated by high channel index values and low Basal Index (BI) values, respectively

Keywords: c-p values, Maturity Index, Population ecology, Structure Index, Trophic diversity

INTRODUCTION

Nematodes are the most diverse, abundant and umpteen group of multicellular creatures on the planet. They are an indispensable component of the soil food web that integrates plants, bacteria, fungi, and other soil biota and are observed at various trophic levels (Yeates, 2007; Daramola *et al*., 2021; Lazarova *et al*., 2021). Nematodes engage significantly in compound mineralization and soil fertility and perhaps even act as predators to regulate the ecosystems (Gruzdeva and Sushchuk, 2010). Indeed, soil fauna is invaluable for ecosystem functioning through a variety of activities such as primary production and carbon, phosphorus, and nitrogen cycle (Lazarova *et al*., 2021). Nematodes are organisms that inhabit a wide range of environments and have a variety of different life habits (Yeates *et al*., 1993). They are grouped as herbivores (plant parasitic nematodes), bacterivores, fungivores, omnivores, and predators and occupy diverse trophic levels in the soil food web (Bongers and Bongers, 1998; Yang *et al*., 2021). Nematodes are multicellular aquatic animals that live in water films around soil particles, and are among the most frequently employed bioindicator groups of soil ecosystems. (Ferris *et al*., 2001). Nematodes are valuable in monitoring changes in soil function and condition because of their widespread distribution and occupancy of various habitats and their representation of various trophic levels in the soil food web. Responding quickly to environmental and human-caused disruptions can serve as a doorway to changes in terrestrial environments (Yeates and Bongers, 1999; Ferris *et al*., 2001). Comprehending nematode population dynamics is crucial for developing effective approaches to evaluate soil health (Freckman and Ettema, 1993; Gomes et al., 2003; Okada et al., 2004; Baniyamuddin *et al*., 2007). Numerous researchers have investigated the diversity, community ecology, and population dynamics of soil nematodes across various habitat types, including forest soils (Baniyamuddin *et al*., 2007, Pokharel *et al*., 2015; Kouser *et al*., 2021, Wani et al., 2022), grasslands (Viketoft and Sohlenius, 2011; Li *et al*., 2017), agricultural fields (Chandra & Khan, 2011), and soils contaminated with heavy metals (Sánchez-Moreno and Navas, 2007; Gutiérrez *et al*., 2016; Renčo *et al*., 2022). There have been limited studies conducted on the taxonomy of soil nematodes in the Udupi region. No prior attempts have been made to explore the composition and organization of nematode communities, which can provide valuable insights into soil ecology. Hence, the present study was initiated with the objectives: i) To study the diversity of soil-inhabiting nematodes in the region, ii)To assess the community structure and trophic diversity of the soil nematodes from Udupi region of Karnataka.

MATERIALS AND METHODS

Study area

Udupi is a coastal district on the west coast of southern India. It is positioned between 74^0 35' to 75^0 12' E longitudes and 13^0 04' to 13^{0}59'N latitudes, covers a land area of 3575 km^2 and mighty Western Ghats on the east and spectacular Arabian Sea on the west. The region is characterised by three main soil types: yellow loamy soil, sandy soil covering the beaches and the red lateritic soil. The annual rainfall is 4000 mm (Deepika *et al*., 2020; Ramachandra *et al*., 2021). The Udupi district is richly endowed with diverse forest types, including evergreen, semi-evergreen, and moist forests. 1007.58 km^2 out of 3370.86 km^2 total geographical area is covered by forests, which constitute approximately 29.89%. The dense forested areas are predominantly located in the Kundapura and Karkala Taluks. The study area is surrounded by evergreen forests characterised by lush green vegetation and heavy rainfall. Trees like Dalbergia latifolia, Mangifera indica, Syzygium cumini, Artocarpus heterophyllus, Phyllanthus emblica, Mesua ferrea, Albizia saman, Calophyllum inophyllum, Santalum album dominate this area. (https://karenvis.nic.in/Database/KarnatakaForest_8197.aspx).
Rice paddies and areca nut orchards predominantly occupy the agricultural lands in the research area. Additionally, other crops like cashew (*Anacardium occidentale*), rubber (*Hevea brasiliensis*), and coconut (*Cocos nucifera*) are also grown in this region.

Collection of soil samples

105 soil samples were collected in January 2021 from the locations given in (Table 1). Each sampling site is hereafter named as plots. 15 sampling plots were randomly selected from Udupi district's seven taluks (revenue divisions). These taluks are hereafter named M plots (M indicates Main plots). Opportunistic random sampling was employed to sample soil cores (Williams and Brown, 2019). The soil was dug using a hand spade or a soil auger. The soil sample was taken at 10 to 15 cm depth early in the day. Five to six cores of soil surrounding the plant roots were dug, and approximately 1 Kg of soil is gathered and placed in zip lock polythene bags, which were then immediately transferred to a 4^{0}C chiller and carried until further processing in the laboratory (Ravichandra., 2022; Sikora *et al*., 2018).

Isolation of nematodes

The soil in the polythene bags was carefully emptied into a plastic bucket and mixed thoroughly. Stones, pebbles, root samples and other debris are handpicked and separated. Exactly 100 cc of soil was taken for further processing. Nematodes were then isolated from the soil employing Cobb decanting and sieving technique. The murky filtrates thus obtained are then transferred to a Baermann funnel and the setup was left undisturbed for 48 hours to finally collect a clear water sample containing nematodes (Perry *et al*., 2020).

Killing fixing and counting nematodes

The nematodes settled at the base of the rubber tube of the Baermann funnel were carefully transferred to a nematode counting dish (Abebe *et al*., 2006). Excess water was removed with the help of a fine micropipette and a few drops of hot (60^{0}C) 4% Formalin (Bohra, 2011) was added to it which instantly killed and fixed the nematodes and the numbers are recorded. Only the first hundred nematodes (Abebe *et al*., 2006) were randomly selected and identified to their genus level following available literature—and NEMAPLEX website (http://nemaplex.ucdavis.edu/).

Nematode community Analysis

Abundance

Total number of individuals of genera in all plots / Number of plots in which they occurred Eq. 1

Absolute frequency (AF%)

Frequency of the genus × 100/total number of samples counted Eq.2

Density (MD)

Number of nematode specimens of the genus counted in all samples / total number of the samples collected Eq.3

Relative density (RD%)

Mean density of the genus × 100/sum of mean density of all nematode genera Eq. 4

Mean biomass (MB) µg
Biomass of one nematode individual of the genus × absolute density of the genus Eq. 5

Relative biomass (RMB) µg
Mean biomass of the genus) × 100)/sum of biomass of all genera (Tomar and Ahmad, 2009) Eq.6

Shannon-Weaver Index (H')
Σ Pi In Pi (Pi = proportion of individual of taxon *i* in the total population) (Shannon, 1948) Eq. 7

Simpson Dominance (D)
$D = \sum (n / N)^2$ (n = the total number of organisms of a particular species
N = the total number of organisms of all species) (Simpson, 1949) Eq.8

Berger-Parker index (D)
$D = n_{max} / N$ (n = maximum number of identified nematode genera Eq. 9
N=total number of individuals) (Berger and Parker, 1970)

Maturity index (MI)
∑[(c-p)i]vi' Eq.10
Pi represents the proportion of each taxon in the total population; (c-p)i is the c-p value for the free-living nematodes to the i-th nematode genus; vi' indicates the proportion of the genus in the nematode community

Plant-Parasite Index (PPI)
∑[(c-p)i]vi' Eq. 11
Pi represents the proportion of each taxon in the total population; (c-p)i is the c-p value for the free-living nematodes to the i-th nematode genus; vi' indicates the proportion of the genus in the nematode community). This is for plant parasitic nematodes only.

Enrichment Index
100×e/(e+b) Eq.12

Structure Index
100×s/(s+b) Eq.13

Basal Index 100×b/ (e+s+b) Eq.14

Channel Index
100 ×Fu2×W2/(Ba1× W1+Fu2× W2) Eq.15
Where, e, b, and s represent the results of assigned weights by the total number of individuals across all genera). (Ferris *et al*., 2001; Berkelmans *et al*., 2003; Baniyamuddin *et al*., 2007; Zheng *et al*., 2012)

Statistical analysis
Abundance (N), Absolute frequency (AF %), Density (MD), Relative density (RD%), Mean biomass (MB) µg, and Relative biomass (RMB) µg were calculated following Tomar and Ahmad, 2009, in Microsoft Office excel version 2021. Shannon-Weaver Index (H') (Shannon, 1948), Simpson Dominance (Simpson, 1949), and Berger-Parker index (Berger and Parker, 1970) were calculated using PAST software (version 4.01). Nematode specific indices like the Maturity index (MI), Channel Index (CI), Structure Index (SI), Plant Parasitic Index (PPI), and Enrichment Index (EI) (Ferris *et al*., 2001) were calculated using NINJA: Nematode Indicator Joint Analysis accessed on 28/08/2022, (Sieriebriennikov *et al*., 2014). Pie charts were plotted using (https://www.meta-chart.com/pie). Bar chart was plotted in Microsoft office excel (version 2021). Box plots for the Kruskal-Wallis test were plotted using a R-based web tool (http://shiny.chemgrid.org/boxplotr/). Graph for food web analysis and c-p triangle were plotted using NINJA: Nematode Indicator Joint Analysis.

RESULTS AND DISCUSSION

Soil nematode diversity
In the present study, 62 genera of soil nematodes belonging to 27 families and 7 orders were identified and reported (Table 2). The number of individual nematodes isolated from 100cc of the soil ranged between 841 (Plot No. 53) individual and 433 (Plot No. 21), with an average sample size of 400 to 800 individuals per plot. The assessment of the different community compositions of soil nematodes isolated from the soil collected from various geographical locations of Udupi revealed that Predatory nematodes at were the most prevalent communities, accounting for 24.19% of the total genera reported, followed by Herbivores 22.58%, Omnivores at 19.35%, Bacterivores at 19.35%, and Fungivore at 14.51%. In terms of abundance, Herbivores represent 30.81% of all documented individuals, followed by predators 18.35%, bacterivores 18.15%, omnivores 17% and fungivores 15.69%. (Fig. 1). In terms of taxonomic divisions, the order Tylenchida represented the highest proportion, making up 39.1% of the 62 recorded genera, followed by Dorylaimida (30.6%), Rhabditida (14.0%), Mononchida (9.9%), Plectida (2.9%), Monhysterida (1.9%), and Enoplida (1.6%). In terms of abundance, Dorylaimida dominated, accounting for 37.1% of the total, followed by Tylenchida (29.0%), Rhabditida (11.3%), Mononchida (11.3%), Plectida (4.8%), Monhysterida (3.2%), and Enoplida (3.2%) (Fig. 1).
On comparing the per cent composition of genera and Abundance of ordinal and trophic diversity, it was observed that there were subtle differences between the numerical values of different groups. However, the comparative compositions were relatively similar except for the orders Dorylaimida and Tylenchida. In terms of

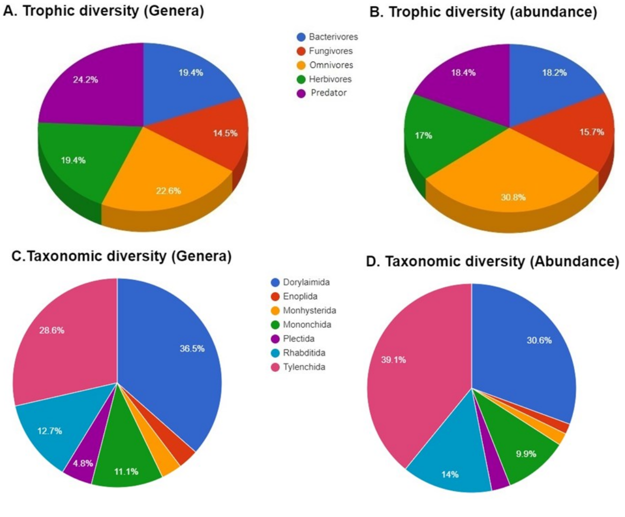

Fig. 1. *Community structure of soil nematodes from Udupi*

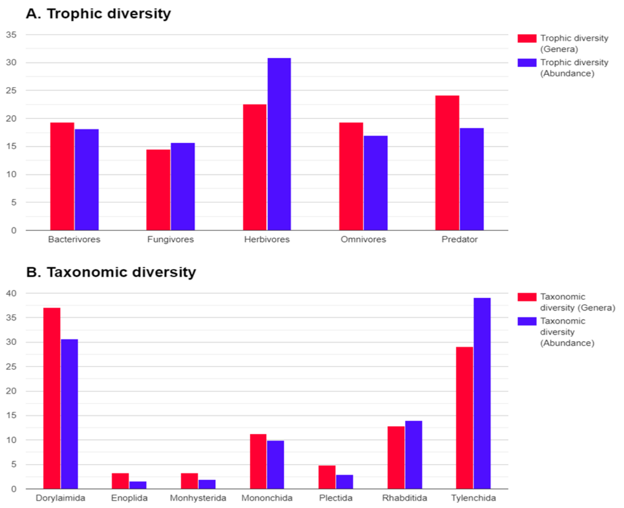

Fig. 2. *Comparison between genera and abundance of trophic and taxonomic diversity of soil nematodes*

abundance, order Tylenchida (39.09%) outnumbers order Dorylaimida (30.59%), whilst order Dorylaimida (37.10%) dominates order Tylenchida (29.03%) (Fig. 2).

Feeding type composition of nematode assemblage

The feeding type composition of the herbivore nematode assemblage in all M plots is given in (Fig. 3). Among herbivores, 41.96 ± 7.66% of nematodes belong to pp class 3, 29.19 ± 2.96% belong to pp class 2, 25.64 ± 7.85% belong to pp class 5 and only 3.19 ± 1.08% belong to pp class 4. Analysis of the Coloniser-Persister (c-p values were allocated according to Bongers and Bongers, 1998) structure of the free-living nematode assemblage in all M plots it was observed that 46.50 ± 3.44 % of nematodes belong to c-p group 4 . These nematodes are distinguished by a prolonged generation period, permeable cuticle, and high vulnerability to contaminants, followed by Nematodes belonging to c-p category 2 (38.99%±3.45) (These nematodes reproduce quickly and have comparatively high rates of

Table 1. Details of the sampling locations

Name	Revenue divisions of Udupi District/ Sampling locations	Samples
M Plot 1	Udupi	15 Samples (Numbered 1-15)
M Plot 2	Karkala	15 Samples (Numbered 16-30)
M Plot 3	Hebri	15 Samples (Numbered 31-45)
M Plot 4	Kaup	15 Samples (Numbered 46-60)
M Plot 5	Kundapura	15 Samples (Numbered 61-75)
M Plot 6	Byndor	15 Samples (Numbered 76-90)
M Plot 7	Brahmavara	15 Samples (Numbered 91-105)

reproduction; they were also exceedingly resilient to pollution and other disturbances. They consisted of a few predators and bacterial and fungal feeders. 13.19±2.74% of nematodes belonged to c-p class 5 and only 1.34± 0.97% belonged to c-p 3 class, while no nematode belonging to c-p class 1 was documented from the regions (Fig. 4).

Population structure of nematode genera

Nematode population structure from the Udupi is provided in Table 3. *Acrobeles* was found to be the most frequently occurring genus with a frequency of 73.33%, a density of 6.79, a prominence value of 48.04 and mean biomass of 3.39 and the Genus *Tripyla* was the least frequent in the region with only 21.90% frequency of occurrence. Top five genera with highest frequency (A), density(B), Prominence value (C) and Mean Biomass (D) are given in Fig. 5. Among bacterivores *Acrobeles* had a frequency of 73.33%, with a density of 6.79, prominence value 48.04 and Mean biomass of 3.39 and *Wilsonema* was the least frequent with a frequency of 26.67%, with density0.64, prominence value of 3.30 and Mean biomass of 0.05. Among fungivores *Ditylenchus* wss most prevalent with 60.95 % frequency, density of 2.90, prominence value of 22.68 and Mean biomass of 2.42. *Meloidogyne* was the most frequent plant parasitic nematode with a 61.90% density of 4.72, prominence value of 37.17 and Mean biomass of 215.93. *Dorylaimus* was the most frequent omnivore nematode with a 71.43% density 6.79, prominence value of 57.39 and a Mean biomass of 287.26. Among predators, *Cobbonchus* was most prevalent with 60.95 % frequency, density of 1.47, prominence value of 10.90 and mean biomass of 8.24.

Dorylaimus was the most dominant genus with *a* densi-

Table 2. Nematode genera identified from Udupi

Sl.No.	Name	Family	Order
1	*Neoactinolaimus*	Actinolaimidae	Dorylaimida
2	*Axonchium*	Belondiridae	Dorylaimida
3	*Amphidorylaimus*	Dorylaimidae	Dorylaimida
4	*Aporcelaimellus*	Dorylaimidae	Dorylaimida
5	*Aporcelaimus*	Dorylaimidae	Dorylaimida
6	*Dorylaimus*	Dorylaimidae	Dorylaimida
7	*Labronema*	Dorylaimidae	Dorylaimida
8	*Laimydorus*	Dorylaimidae	Dorylaimida
9	*Mesodorylaimus*	Dorylaimidae	Dorylaimida
10	*Longidorus*	Longidoridae	Dorylaimida
11	*Paralongidorus*	Longidoridae	Dorylaimida
12	*Kochinema*	Nordiidae	Dorylaimida
13	*Longidorella*	Nordiidae	Dorylaimida
14	*Oriverutus*	Nordiidae	Dorylaimida
15	*Laevides*	Nygolaimidae	Dorylaimida
16	*Nygellus*	Nygolaimidae	Dorylaimida
17	*Nygolaimus*	Nygolaimidae	Dorylaimida
18	*Discolaimus*	Qudsianematidae	Dorylaimida
19	*Eudorylaimus*	Qudsianematidae	Dorylaimida
20	*Moshajia*	Qudsianematidae	Dorylaimida
21	*Coomansinema*	Thornenematidae	Dorylaimida
22	*Sicaguttur*	Thornenematidae	Dorylaimida
23	*Thornenema*	Thornenematidae	Dorylaimida
24	*Amphidelus*	Amphidelidae	Enoplida
25	*Tripyla*	Tripylidae	Enoplida
26	*Geomonhystera*	Monhysteridae	Monhysterida
27	*Monhystera*	Monhysteridae	Monhysterida
28	*Cobbonchus*	Cobbonchidae	Mononchida
29	*Iotonchus*	Iotonchidae	Mononchida
30	*Parahadronchus*	Iotonchidae	Mononchida
31	*Coomansus*	Mononchidae	Mononchida
32	*Mononchus*	Mononchidae	Mononchida
33	*Prionchulus*	Mononchidae	Mononchida
34	*Mylonchulus*	Mylonchulidae	Mononchida
35	*Anaplectus*	Plectidae	Plectida
36	*Plectus*	Plectidae	Plectida
37	*Wilsonema*	Plectidae	Plectida
38	*Aphelenchoides*	Aphelenchoididae	Rhabditida
39	*Acrobeles*	Cephalobidae	Rhabditida
40	*Acrobeloides*	Cephalobidae	Rhabditida
41	*Cephalobus*	Cephalobidae	Rhabditida
42	*Cervidellus*	Cephalobidae	Rhabditida
43	*Stegelletina*	Cephalobidae	Rhabditida
44	*Zeldia*	Cephalobidae	Rhabditida
45	Paratrophurus	Dolichodoridae	Rhabditida
46	*Ditylenchus*	Anguinidae	Tylenchida
47	*Helicotylenchus*	Hoplolaimidae	Tylenchida
48	*Hoplolaimus*	Hoplolaimidae	Tylenchida
49	*Heterodera*	Meloidogynidae	Tylenchida
50	*Meloidogyne*	Meloidogynidae	Tylenchida
51	*Paratylenchus*	Paratylenchidae	Tylenchida
52	*Pratylenchus*	Pratylenchidae	Tylenchida

Table 2. *Contd.*

53	*Radopholus*	Pratylenchidae	Tylenchida
54	*Tylenchorhynchus*	Telotylenchidae	Tylenchida
55	*Aglenchus*	Tylenchidae	Tylenchida
56	*Basiria*	Tylenchidae	Tylenchida
57	*Boleodorus*	Tylenchidae	Tylenchida
58	*Filenchus*	Tylenchidae	Tylenchida
59	*Psilenchus*	Tylenchidae	Tylenchida
60	*Sakia*	Tylenchidae	Tylenchida
61	*Tylenchus*	Tylenchidae	Tylenchida
62	*Xiphinema*	Xiphinematidae	Tylenchida

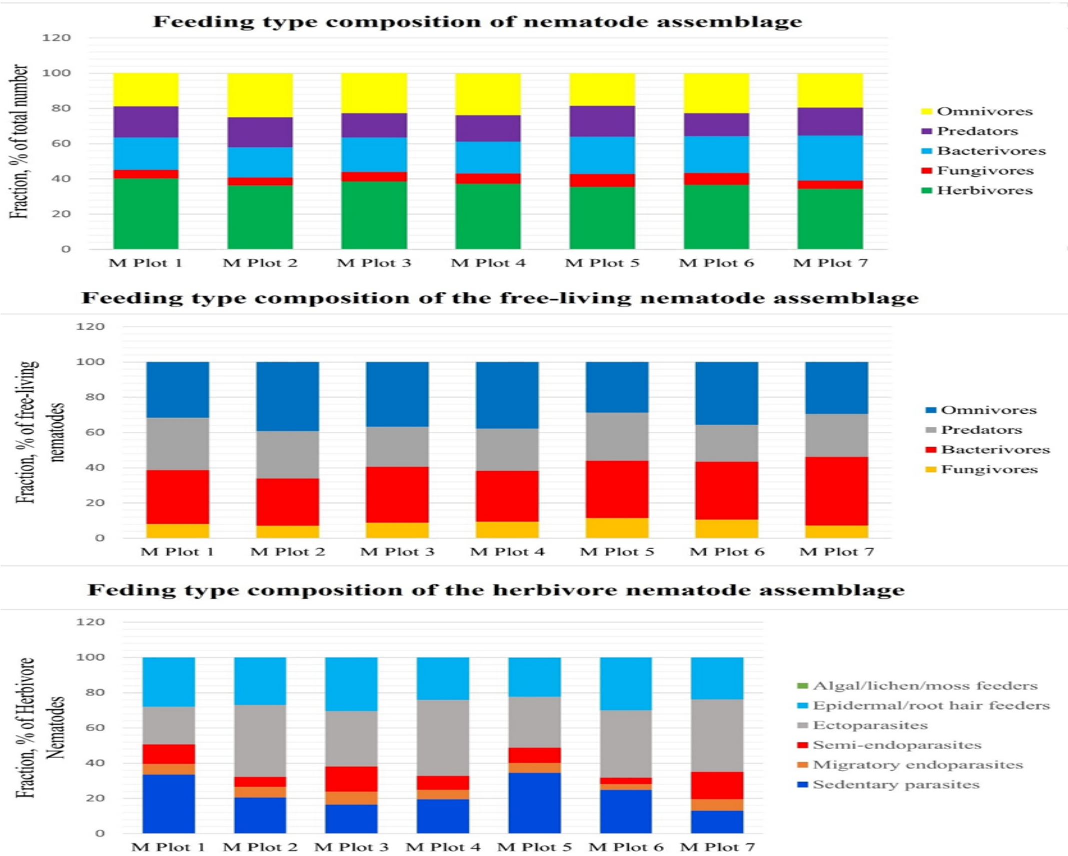

Fig. 3. *Different Nematode assemblages*

ty of 6.79 and RD 6.79% among all the Nematodes collected and *Tylenchorhynchus* was the least dominant genus with a density of 0.40 and RD 0.40%. Among the bacterivores, *Acrobeles* is the most dominant genus with 5.61 and RD 5.61% and *Wilsonema* is the least prevalent with 0.64 and RD 0.64%. *Ditylenchus* was the most dominant with a density of 2.90, RD 2.90%, and *Filenchus* was the least prevalent genus among the fungivores. *Meloidogyne* was the most dominant genus among the Plant parasitic nematodes with a density of 4.72 and RD 4.72% and *Tylenchorhynchus* was the least dominant genus with a density of 0.40 and RD 0.40%. *Dorylaimus* was the most dominant omnivore genus with *a* density of 6.79 and RD 6.79% and *Oriverutus* was the least dominant with a density of 0.51 and RD 0.51%. *Mononchus* was the most dominant predator with density of 3.19 and 3.19% RD and the least density was recorded for *Nygolaimus* with *a* density of 0.50 and RD 0.50%.

Population structure of trophic groups

Nematodes were categorised into five trophic groups: herbivores (plant parasitic nematodes), bacterivores, fungivores, omnivores, and predators. Detailed population structure of different Nematode trophic groups is given in Table 4. Fungivore nematodes were the most frequently observed community with an absolute frequency of 44.02 ± 10.03 (CV 14.86%) and N 1647. In contrast, predators were the least frequent communities with an absolute frequency of 37.27 ± 10.76 (CV 30.69%) and N 1927. Among all the nematodes scored, maximum density was observed in herbivores with MD 1.94 ± 1.43 (CV 73.61), whereas predators were the least dominant with MD 1.24 ± 0.77 (CV 62.40). The

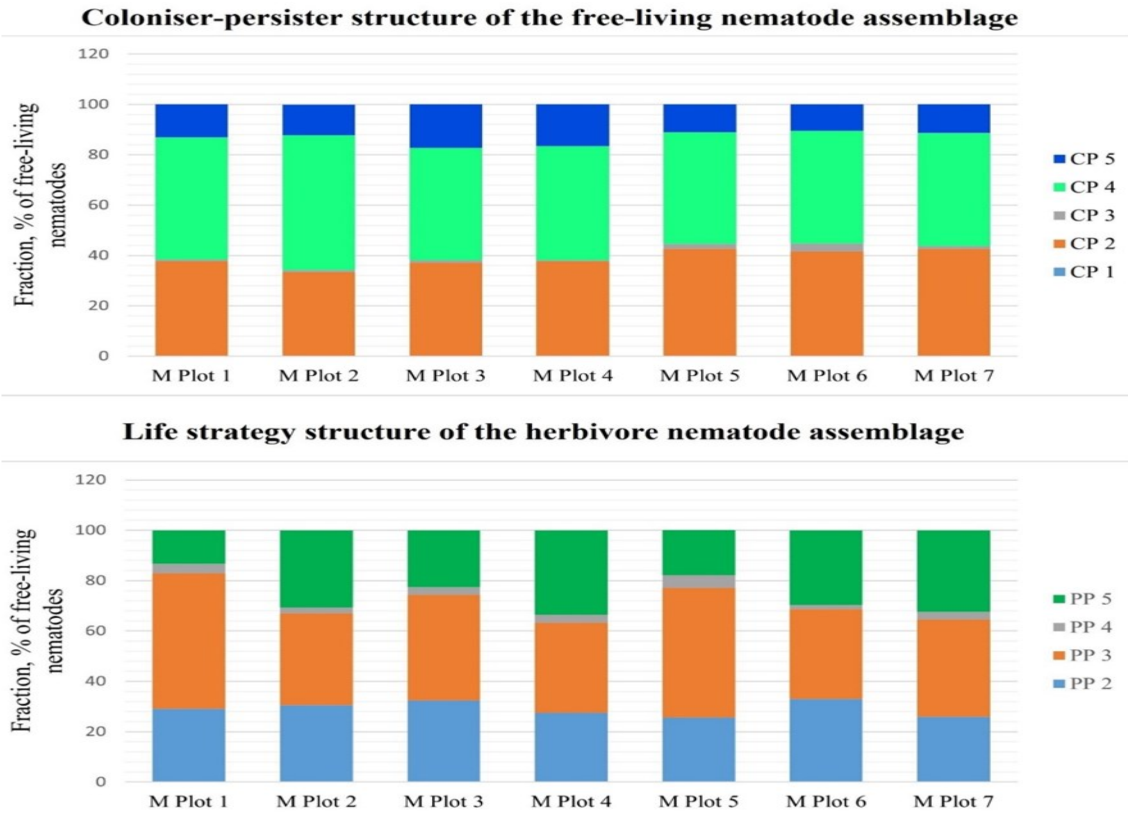

Fig. 4. *Fraction of nematodes belonging to their respective c-p and p-p class*

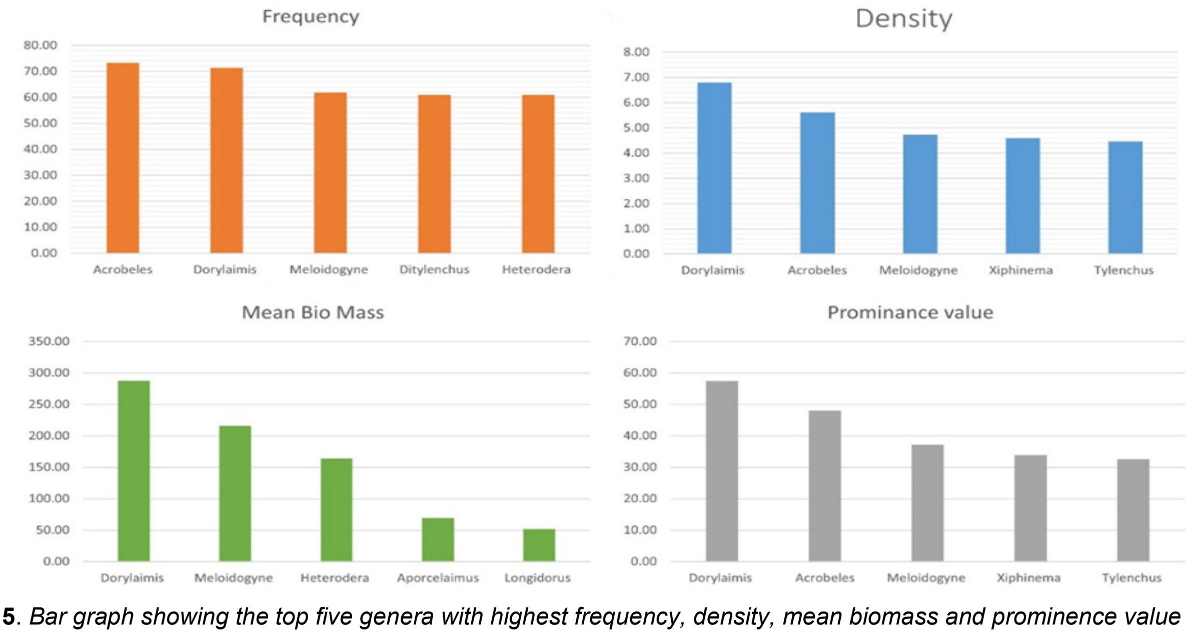

Fig. 5. *Bar graph showing the top five genera with highest frequency, density, mean biomass and prominence value*

maximum mean biomass in the entire population was recorded for Omnivores with MB 24.81µg ± 69.68 (CV 280.87) and Bacterivores with MB of 0.83 µg ±1.03 (CV124.17) is the smallest community documented.

Nematode population dynamics

The nematode population in all the seven main plots was highly diverse (Maximum Simpson -1-D value observed in M plot 3 0.97), with all the plots having Simpson 1-D value < 0.95 (Table 5). Most of the nematodes were evenly distributed in all seven M plots, with a maximum evenness value of 0.79 in M plot 3. M Plot 3 has the maximum Shannon Weaver index value (3.901) and the least value was observed in M Plot 6 (3.583). However, the Shannon Weaver index of all seven plots ranges from 3.583 to 3.901, indicating a fairly significant rich diversity. The genera composition in terms of richness across all seven was high, with a

Table 3. Population structure of nematode genera documented from Udupi

Genera	c-p value	N	AF%	Density	RD%	PV	RPV%	MB	RMB%
Bacterivores									
Acrobeles	2	589	73.33	5.61	5.61	48.04	6.93	3.39	0.34
Acrobeloides	2	249	56.19	2.37	2.37	17.78	2.56	0.53	0.05
Plectus	2	109	53.33	3.05	3.05	22.26	3.21	0.1	0.01
Cephalobus	2	194	48.57	1.85	1.85	12.88	1.86	0.59	0.06
Cervidellus	2	114	43.81	1.09	1.09	7.19	1.04	0.17	0.02
Amphidelus	4	75	40.95	0.71	0.71	4.57	0.66	0.79	0.08
Anaplectus,	2	131	37.14	1.25	1.25	7.6	1.1	2.44	0.25
Geomonhystera	2	107	34.29	1.02	1.02	5.97	0.86	0.36	0.04
Zeldia	2	103	34.29	0.98	0.98	5.74	0.83	0.42	0.04
Monhystera	2	91	33.33	0.87	0.87	5	0.72	0.94	0.1
Stegelletina	2	77	28.57	0.73	0.73	3.92	0.57	0.2	0.02
Wilsonema	2	67	26.67	0.64	0.64	3.3	0.48	0.05	
Fungivores									
Aphelenchoides	2	148	43.81	1.41	1.41	9.33	1.35	0.21	0.02
Ditylenchus	2	305	60.95	2.9	2.9	22.68	3.27	2.42	0.25
Filenchus	2	143	46.67	1.36	1.36	9.3	1.34	0.14	0.01
Aglenchus	2	98	41.9	0.93	0.93	6.04	0.87	0.08	0.01
Basiria	2	153	44.76	1.46	1.46	9.75	1.41	0.22	0.02
Psilenchus	2	93	32.38	1	1	5.69	0.82	7.74	0.79
Boleodorus	2	167	47.62	1.59	1.59	10.98	1.58	0.29	0.03
Sakia	2	72	24.76	0.69	0.69	3.41	0.49	0.18	0.02
Tylenchus	2	468	53.33	4.46	4.46	32.55	4.69	1.54	0.16
Herbivores									
Tylenchorhynchus	3	42	23.81	0.4	0.4	1.95	0.28	0.09	0.01
Paralongidorus	5	76	28.57	0.72	0.72	3.87	0.56	14.78	1.5
Pratylenchus	3	320	33.33	0.91	0.91	5.28	0.76	2.55	0.26
Axonchium	5	98	41.9	0.93	0.93	6.04	0.87	3.21	0.33
Paratylenchus	2	265	35.24	1.04	1.04	6.16	0.89	0.81	0.08
Radopholus	3	114	37.14	1.09	1.09	6.62	0.95	0.3	0.03
Longidorella	4	124	39.05	1.18	1.18	7.38	1.06	1.52	0.15
Hoplolaimus	3	176	49.52	1.68	1.68	11.8	1.7	2.47	0.25
Helicotylenchus	3	193	44.76	1.84	1.84	12.3	1.77	0.53	0.05
Paratrophurus	3	105	45.71	2.52	2.52	17.06	2.46	0.54	0.06
Longidorus	5	332	55.24	3.16	3.16	23.5	3.39	51.6	5.24
Heterodera	3	412	60.95	3.92	3.92	30.63	4.42	164.16	16.67
Xiphinema	5	482	54.29	4.59	4.59	33.82	4.88	24.54	2.49
Meloidogyne	3	496	61.9	4.72	4.72	37.17	5.36	215.93	21.93
Omnivores									
Oriverutus	4	54	28.57	0.51	0.51	2.75	0.4	0.57	0.06
Sicaguttur	5	62	28.57	0.59	0.59	3.16	0.46	0.26	0.03
Laimydorus	4	86	30.48	0.82	0.82	4.52	0.65	3.33	0.34

Table 3. Contd.

Kochinema	4	88	38.1	0.84	0.84	5.17	0.75	0.4	0.04
Moshajia	4	91	32.38	0.87	0.87	4.93	0.71	1.34	0.14
Thornenema	5	95	30.48	0.9	0.9	4.99	0.72	1.09	0.11
Labronema	4	96	33.33	0.91	0.91	5.28	0.76	7.38	0.75
Coomansinema	5	114	41.9	1.09	1.09	7.03	1.01	3.27	0.33
Eudorylaimus	4	118	52.38	1.12	1.12	8.13	1.17	3.45	0.35
Amphidorylaimus	4	119	38.1	1.13	1.13	7	1.01	1.32	0.13
Mesodorylaimus	4	149	34.29	1.42	1.42	8.31	1.2	1.79	0.18
Dorylaimus	4	713	71.43	6.79	6.79	57.39	8.27	287.26	29.17
Predators									
Nygolaimus	5	53	22.86	0.5	0.5	2.41	0.35	2.91	0.3
Parahadronchus	4	55	24.76	0.52	0.52	2.61	0.38	7.51	0.76
Mylonchulus	4	73	29.52	0.7	0.7	3.78	0.54	1.22	0.12
Tripyla	3	89	21.9	0.85	0.85	3.97	0.57	4.24	0.43
Prionchulus	4	96	32.38	0.89	0.89	5.04	0.73	0.29	0.03
Laevides	5	94	37.14	0.9	0.9	5.46	0.79	16.03	1.63
Coomansus	4	141	47.62	1.34	1.34	9.27	1.34	8.7	0.88
Cobbonchus	4	154	55.24	1.47	1.47	10.9	1.57	8.24	0.84
Nygellus	5	156	36.19	1.49	1.49	8.94	1.29	6.3	0.64
Iotonchus	4	187	48.57	1.78	1.78	12.41	1.79	12.65	1.28
Mononchus	4	335	50.48	3.19	3.19	22.67	3.27	13.84	1.41
Discolaimus	4	199	52.38	1.9	1.9	13.72	1.98	4.82	0.49
Neoactinolaimus	5	91	28.57	0.87	0.87	4.63	0.67	2.28	0.23
Aporcelaimellus	5	106	33.33	1.01	1.01	5.83	0.84	9.01	0.92
Aporcelaimus	5	98	38.1	0.93	0.93	5.76	0.83	69.4	7.05

c-p Value – colonizer-persistor scale (Bongers, 1990); N, Abundance ; AF, absolute frequency; RD, relative density; PV, prominence value; RPV, relative prominence value; MB, mean biomass; RMB, relative biomass

Table 4. Population structure of nematode trophic groups documented from Udupi

	Bacteri-vores	CV	Fungivores	CV	Herbivores	CV	Omnivores	CV	Predators	CV
N	272.29±28.2	10.39	85.14±16.12	18.93	612.29±45.79	7.48	325.57±38.17	11.72	204.71±27.31	13.34
AF	42.54±12.87	30.26	50.48±7.50	14.86	42.81±10.88	25.42	38.27±11.22	29.31	36.97±11.35	30.69
MD	1.68±1.44	85.80	1.89 ± 0.88	46.37	1.94 ± 1.43	73.61	1.36±1.44	105.92	1.24±0.77	62.40
MB	0.83±1.03	124.17	0.93 ± 1.30	140.21	24.65±58.49	237.23	24.81±69.68	280.87	7.45±5.16	69.23
RMB%	0.09 ± 0.11	116.57	0.09 ± 0.13	140.1	2.50 ± 5.94	237.23	2.52±7.08	280.87	0.76±0.52	69.23

N, frequency; AF, absolute frequency; MD, Mean density; MB, mean biomass; RMB, relative biomass; CV, Coefficient of variation.

400 to 800 individuals per plot, the number of individual nematodes isolated from 100cc3 of soil in the present study varied from 841 (plot no. 53) to 433 (plot no. 21). In the present study 62 genera (Table 3) of soil nematodes were isolated, identified, and reported, with herbivores being the most prominent and fungivores being the least dominant (Fig.1).

Several studies from various parts of India have been reported. Baniyamuddin *et al.*, 2007 reported soil nematodes representing 85 genera from forests of Arunachal Pradesh; the fungal feeders were the most dominant group (29%), and omnivores (10%) were the least dominant, 47 genera were reported from Himalayan Mountain ranges (Kouser *et al*, 2021), Kouser *et al*, 2022 reported 77 genera, different vegetations of Jammu division of Jammu and Kashmir, India, 58 genera of nematodes have been reported from the soils extracted from different elevations of Gangotri National Park and

Table 5. Different nematode diversity indices of Udupi district

	M plot 1	M plot 2	M plot 3	M plot 4	M plot 5	M plot 6	M plot 7
Taxa_S	62	62	62	62	61	62	62
Individuals	1500	1500	1500	1500	1500	1500	1500
Simpson-1-D	0.9696	0.9647	0.975	0.9715	0.9709	0.9596	0.9691
Shannon Weaver index	3.8	3.757	3.901	3.835	3.789	3.583	3.786
Evenness_e^H/S	0.7207	0.6906	0.7977	0.747	0.7247	0.5801	0.7109
Margalef	8.341	8.341	8.341	8.341	8.204	8.341	8.341

Table 6. Environmental indices based on nematode diversity of Udupi district

Index name	M Plot 1	M Plot 2	M Plot 3	M Plot 4	M Plot 5	M Plot 6	M Plot 7
Maturity Index	3.37	3.45	3.42	3.41	3.24	3.24	3.25
Maturity Index 2-5	3.37	3.45	3.42	3.41	3.24	3.24	3.25
Sigma Maturity Index	3.22	3.4	3.32	3.41	3.21	3.26	3.31
Plant Parasitic Index	3.01	3.33	3.16	3.43	3.15	3.28	3.42
Channel Index	100	100	100	100	100	100	100
Basal Index	11.68	10.04	11.12	11.32	13.94	13.69	14.12
Enrichment Index	17.76	17.57	19.29	20.05	21.22	20.36	14.6
Structure Index	88.02	89.74	88.58	88.35	85.51	85.81	85.53

value of 8.341 in all M plots except M plot 5, which had a relatively lower value of 8.204.

Nematode diversity and soil ecosystem

Based on the analysis of various environmental indices based on nematode diversity, it was inferred that soil type indicates certain soil food web maturity. The Maturity Index MI of all plots ranges from 3.24 to 3.45 (Table 6), which suggests a complex and well-organized soil food web that likely has connection and energy transfer between trophic levels (Bongers, 1990). The plots' Maturity Index MI 2-5 ranged from 3.24 to 3.45 (Table 6), indicating higher maturity with little or no influence from perturbations.

Plots were dominated by relatively high numbers of large plant parasitic nematodes, evident after analysing the Plant parasitic index PPI (3.01 to 3.43) (Table 6). Labile organic carbon and nutrient enrichment in the region was low in all seven regions (Table 6), with Enrichment Index (EI) value ranging between 14.06 to 21.22, Structure Index (SI) values of all the plots range between 85.51 and 89.74, indicating a structured food web in the region and Channel Index (CI) values were 100 in all plots which indicates increasing decomposition dominance by fungi. Low Basal Index (BI) indicated the soil was least disturbed, between 10.04 and 14.12 (Table 6). Analysis of these parameters gives a comprehensive idea of the status of the soil in all the sampled areas.

Kruskal-Wallis H test was conducted to determine if there was a significant difference in species composition and distribution between the seven M plots. The test did not find a significant difference between the groups, with a p-value of 0.373. This means no evidence suggested that the genera composition and distribution were different between the seven plots. The mean rank score for plot M was 217.4, consistent with species' overall distribution (Fig. 6).

The succession of free-living nematodes belonging to different c-p groups documented from different Udupi shall be a useful index of status soil in this region. A c-p triangle was constructed for all nematodes after assigning them to their respective c-p classes following Bongers and Bongers (1998). It was observed that the values of all seven M plots were concentrated towards c-p 3-5 %, which showed that the region had stable soils (Fig. 7). Food web of the region was analysed after plotting the enrichment index (EI parallels the intensity of nutrient enrichment) and structure index (SI correlates with the degree of maturity of an ecosystem). The graph clearly describes all M plots (Sampled locations) were characterized by fertile, suppressive soils with a moderate C:N ratio (Carbon: Nitrogen) and bacterial-fungal combination propriety (Fig. 8).

Diversity of soil nematodes

Nematodes, comprised of over 30,000 described species, exists in almost all possible environment on the planet and account for more than 80% of metazoan taxonomic and functional diversity in soils (Nisa *et al.*, 2021). Soil nematode abundances were highly variable within and across terrestrial biomes. On average, the number of nematodes per 100 g dry soil is in the few hundred to thousand range (median = 859, mean = 2,671), although the highest recorded abundances exceed 20,000 nematodes per 100 g dry soil. Across biomes, bacterivores were the most abundant trophic group and predatory nematodes were the least abundant (Hoogen 2020). With an average sample size of

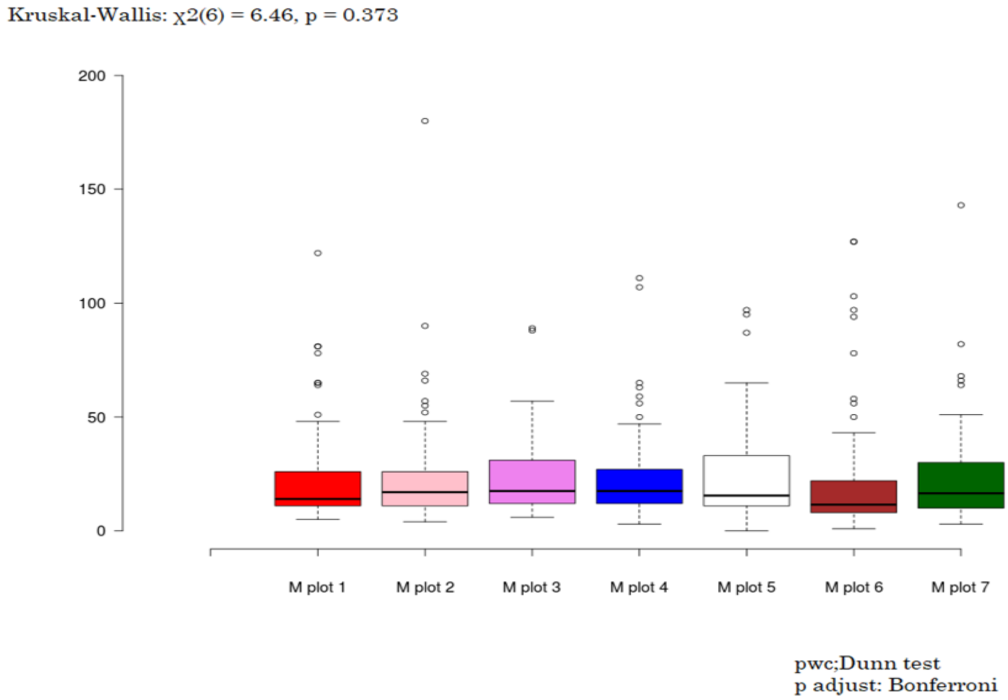

Fig. 6. *Box plot showing the species composition of all M plots from Udupi district*

maximum abundance was observed in Bacterivores (Uttarakhand), India, (Kashyap *et al*., 2022), 30 nematode genera with bacterivore nematodes being most dominant were recorded from Lower Forest Area of Gulmarg of District Baramulla, Jammu and Kashmir, India (Wani *et al*., 2022). Forty-seven nematode genera were documented from 10 different sites in Kashmir Valley India. Bacterivores constituted the highest abundance (Nisa *et al*., 2021). Although bacterivore diversity is highest in the majority of studies, the present study, herbivorous nematodes were found to be more abundant (Fig.1). This is mostly because sampling sites were limited to agricultural fields and forest areas bordering agricultural fields. Thus, the present findings support past observations that indicated more diversified populations of herbivore nematodes in habitats with less varied flora (Eisenhauer *et al*., 2011; Cortois *et al*., 2017; Dietrich *et al*., 2021).

Nematode population dynamics

Species richness is perhaps the most basic approach to assess community and regional biodiversity (Gotelli and Colwell, 2001). Population dynamics is a section of ecology that mainly focuses on change in the community structure of one more species across geographical regions and time (Begon *et al*., 2006). The Shannon Weiner index (H') bases its hypothesis on the notion that heterogeneity is a function of the number of species and their relative individual distribution. The measure of the overall distribution of richness is the total number of individuals of each species present in a given area (Kumar *et al*., 2022), and its value ranges between 1.99 or below and 3.50 or above, where lower values indicate less diversity and higher values indicate high diversity (Baliton *et al*., 2020). The Shannon Weiner index (H') of the present study of all seven plots ranged from 3.583 to 3.901 (Table 5), portraying a very high diversity of soil nematodes in the region. Simpson's diversity index is the most straightforward way to assess a community's character while accounting for species richness and abundance patterns (Begon *et al*., 2006). All seven M plots of the present study showed exuberant diversity with values greater than 0.95 (Table 5).

Nematode diversity as soil health indicator

The status of the soil ecosystem and the consequences of anthropogenic and natural processes on soil were evaluated using nematode-based indexes. (Du Preez *et al*., 2022). Analysis of Nematode fauna offers a potent diagnostic tool for determining the intricacy and condition of soil food webs (Ferris *et al*., 2001). The present study observed that herbivores were the dominant communities of soil nematodes and the fungivores were least dominant in the Udupi region. Regarding taxonomic divisions, Tylenchida was most abundant while Enoplida was least. Among herbivores the highest proportion of nematodes belonged to pp class 3; the lowest number was recorded for pp class 5 (Fig 4). Allocation of c-p classes following Bongers and Bongers, (1998), the maximum diversity of nematodes represented c-p class 4 and minimum to c-p class 3 (Fig 4). Interestingly, no nematodes belonging to c-p class 1 were recorded. Nematodes belonging to c-p

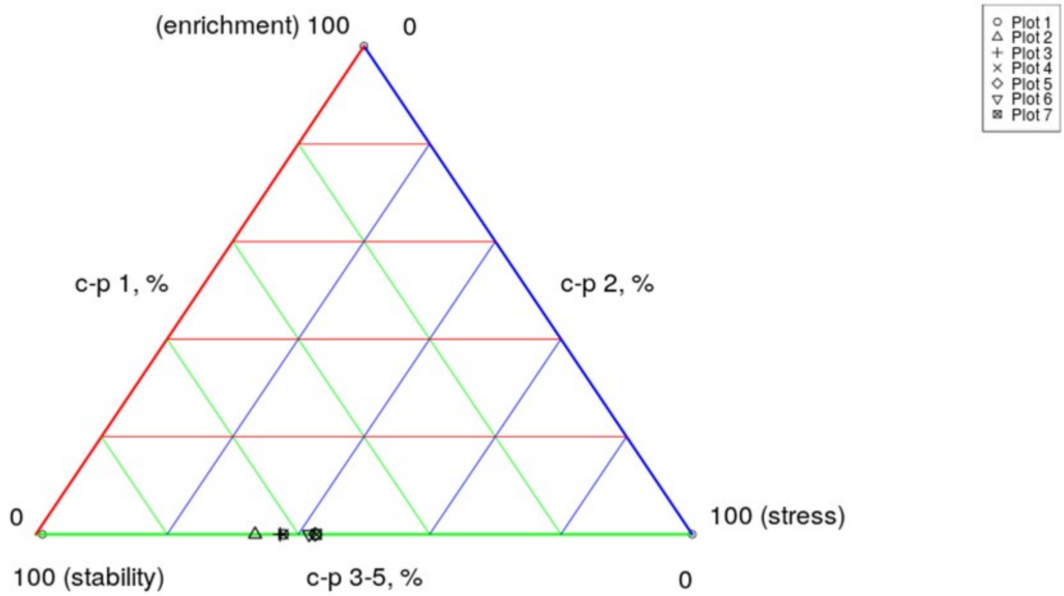

Fig. 7. *c-p triangle showing assemblage of nematodes of all M plots from Udupi district*

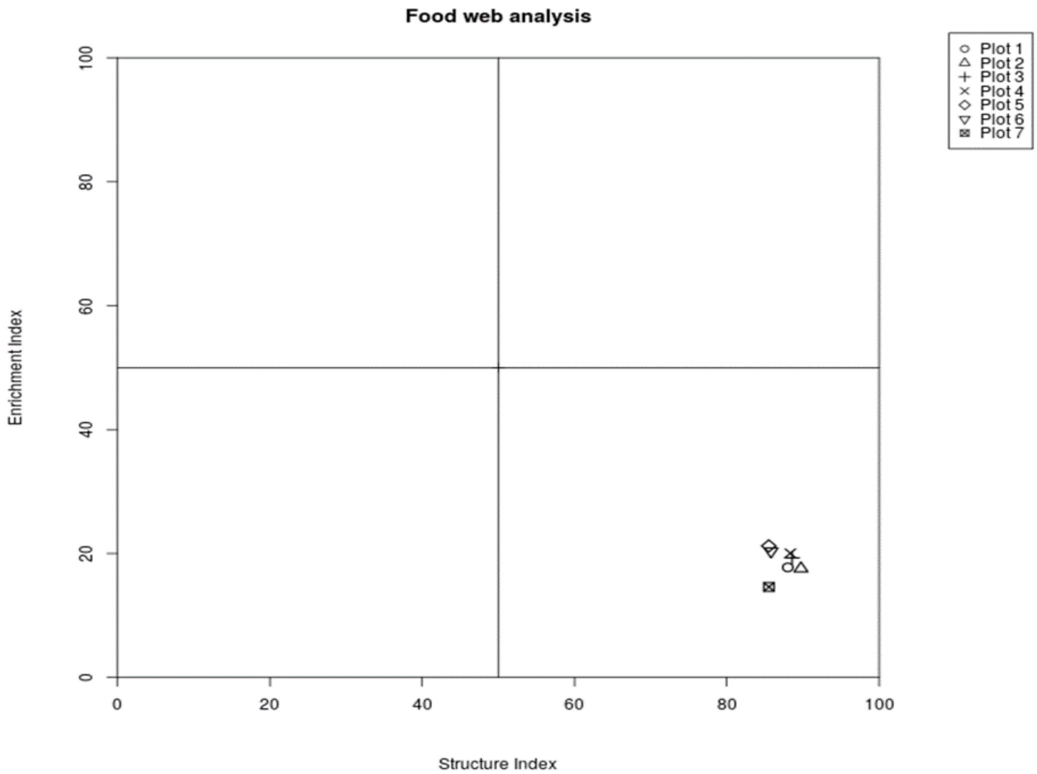

Fig. 8. *Food web analysis of all M plots from Udupi district*

class 4 were distinguished by a prolonged generation period, permeable cuticle, and high vulnerability to contaminants (Bongers and Bongers, 1998; Ferris *et al*., 2001) and thrive in soils that were rich in resources and mostly free from anthropogenic perturbances.

The maturity index (MI) is a nematode species-based ecological indicator of environmental perturbation. MI represents the state of the soil system and any soil disturbances (Bongers, 1990). Lower MI values demonstrated that the use of fertilisers and pesticides had increased the amount of soil disturbance. The MI of all seven plots ranged from 3.24 to 3.45, portraying less disturbed soils (Table 6). Nisa *et al*., 2021 reported MI in alpine soil (3.70) and in rice field soil (1.50), Baniyamuddin *et al.* (2007) reported 3.37 MI from forests of Arunachal Pradesh. Many workers have reported that soil pollution or other soil perturbations result in lower MI values (Bongers, 1990; Nisa *et al*., 2021; Niu *et al*., 2022).

The Plant parasite index (PPI) in the present study

(3.01 to 3.43) reveals that plots were dominated by relatively significant populations of large plant parasitic nematodes. All plots had Enrichment Index (EI) values ranging from 14.06 to 21.22, Structure Index (SI) values ranging from 85.51 to 89.74, suggesting a structured food web in the region, and Channel Index (CI) values of 100, indicating an increasing dominance of fungi in decomposition. The basal index (BI) values between 10.04 and 14.12 signify the least disturbed soil (Table 6). It was evident that the assessment of soil nematode diversity offers a comprehensive idea of the health and status of the soil. Hence, regular monitoring of soil nematode diversity may help design soil conservation strategies.

Conclusion

This study focused on soil nematodes in the Udupi region and reported 62 genera of soil nematodes. The soil in the study region had low levels of labile organic carbon and nutrient enrichment. However, the soil food web was well-structured. Fungal decomposition dominance was prevalent, and the soil appeared minimally disturbed, as suggested by high channel index values and low Basal Index (BI) values. This study provided valuable insights into the community structure and functional diversity of soil nematodes in the Udupi region, shedding light on their ecological roles and the overall health of the soil ecosystem. Nematodes are essential components of soil ecosystems, significantly impacting soil properties and functions. Understanding the interactions between nematodes and soil properties is crucial for assessing soil health, ecosystem dynamics, and agricultural productivity.

Conflict of interest

The authors declare that they have no conflict of interest.

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