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Soil nematode communities as indicators of forest ecosystem health: A study in Patnitop region of District Udhampur, UT, J&K, India

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Abstract
Nematodes are vital bioindicators of soil health, reflecting ecological conditions and anthropogenic disturbances, such as tourism. This study provides the first comprehensive assessment of nematode diversity in the Patnitop forest (Jammu & Kashmir, India), evaluating their community structure and ecological significance. Soil samples were collected from multiple forest sites, with nematodes identified to genus level and classified by trophic groups and colonizer-persister (c-p) classes. Diversity indices (Shannon Index, Species Evenness, Maturity Index, Plant Parasitic Index) and ecological indices (Enrichment, Structure, Basal) were computed to assess soil food web conditions. Statistical analysis employed the Kruskal-Wallis test. We identified 37 nematode genera, with bacterivores dominating (58.7%), followed by omnivores (20.58%), herbivores (11%), predators (8.9%), and fungivores (2.7%). The c-p classification showed high proportions of opportunistic c-p 1 nematodes (39.0–48.1%) and stable c-p 4 (19.3–27.6%) and c-p 5 (5.8–15.3%) groups. Moderate diversity (Shannon Index: 1.93; Evenness: 0.73) and nutrient-rich conditions (Maturity Index: 2.50; Plant Parasitic Index: 3.20) were observed. High Enrichment (82.59) and Structure (92.48) indices, combined with a low Basal Index (4.17), indicated a stable food web under minimal stress. Trophic group differences were statistically significant (p = 0.00129). The predominance of bacterivores highlights bacterial-mediated decomposition, while nematode metrics demonstrated sensitivity to ecological gradients, underscoring their utility as bioindicators for tourism-linked disturbances. These findings advocate integrating nematode monitoring into forest management frameworks to guide soil conservation in this fragile ecosystem.

Keywords: Colonizer-persister analysis, Ecosystem health, Nematode diversity, Patnitop forest, Soil bio-indicators

INTRODUCTION

Nematodes, members of the phylum Nematoda, represent a major component of subterranean faunal biodiversity. With approximately 27,000 documented species (Hodda, 2022; Hugot *et al*., 2001), these organisms occupy nearly every habitable niche on the planet and account for roughly 80% of the taxonomic and functional diversity of soil-dwelling metazoans (van den Hoogen *et al*., 2019) Soil nematodes, as intact components of soil ecosystems, play a crucial role in nutrient cycling, organic matter decomposition, and the regulation of microbial communities (Porazinska *et al*., 2021; van Bommel *et al*., 2024 Ferris, 2010; Freckman, 1988). Their functional diversity is central for sustaining soil health and ecosystem reliability, particularly in forested environments (Kumar *et al*., 2021; Pajak *et al*., 2016). Nematodes exhibit remarkable ecological adaptability, spanning a spectrum from fast-colonizing *r*-strategists to persistent *K*-strategists, with various intermediate forms existing along the colonizer-persister (c-p) continuum (Bongers, 1990; Kergunteuil *et al*., 2016; Kouser *et al*., 2021). On account of large trophic and functional diversity, nematodes play a leading role in regulating multiple crucial ecosystem processes including nutrient cycling, successional changes, and energy flow (Rueß, 2024; Yeates, 2003; Bakonyi *et al*., 2007; Wan *et al*., 2022). Studies conducted across forest gradients in China (Pang *et al.,* 2024; Shao *et al.,* 2023) have demonstrated that soil attributes, rather than climate variables, are the primary determinants of nematode community structure. Furthermore, nematode-microbe interactions form complex trophic networks that facilitate ecosystem feedback loops essential to soil health (Ruess, 2024). Nematodes are abundant soil metazoans and reliable bioindicators, reflecting ecological shifts through their sensitivity to biotic and abiotic factors (Asif *et al.,* 2021; Van Eekeren *et al*., 2010). Their community structure is shaped more by soil properties—such as pH, moisture, and organic content—than by climatic gradients (Shao *et al.,* 2023; Pang *et al.,* 2024). Nematode-based indices have emerged as effective tools in soil ecological studies, offering insights into ecosystem condition, stress, and sustainability (Du Preez *et al*., 2022). A number of researchers have worked on the nematode diversity in Indian forests such as natural forests of Arunachal Pradesh (Baniyamuddin *et al*. 2007), Sal forests of Dehradun (Rizvi, 2008), and DKG forest of district Poonch, Jammu and Kashmir (Vaid *et al*. 2014). Patnitop (32.99°N, 75.23°E; elevation: 2,024 m), a region within Jammu and Kashmir's Udhampur district, is characterized by alpine meadows and high floristic diversity. Its mixed coniferous and broadleaf vegetation, coupled with its elevation-driven microclimates, renders it ecologically significant for studying Himalayan temperate ecosystems. The region is home to a range of coniferous trees such as *Cedrus deodara*, *Pinus wallichiana*, and *Abies pindrow*. This varied plant life spawns a fitting environment for studying nematode diversity in the region.The aim of the present study was (i) to determine the soil nematode diversity, functional role and community structure (ii) to assess ecosystem health and stability using ecological indices.

MATERIALS AND METHODS

Collection of samples

A survey was conducted in May and June 2023 to examine the diversity and community structure of soil nematodes in Patnitop Forest (33.08°N, 75.33°E). Soil samples were randomly collected using a trowel from various locations within the forest, totalling fifty samples. Each sample was placed in an airtight plastic bag to preserve moisture, labelled with site details, collection dates, and recorded temperatures, and then transported to the laboratory for further analysis.

Nematode extraction and processing

Soil samples were processed using Cobb's sieving-decantation method followed by modified Baermann funnel extraction. Nematodes were fixed in heated (65° C) formalin-acetic acid (4:1), dehydrated through a graded glycerine-ethanol series (5% glycerine in 30% ethanol), and permanently mounted in anhydrous glycerine using established protocols (Seinhorst, 1959). Specimen integrity was verified by phase-contrast microscopy prior to analysis.

Nematode counting

Nematode abundance was quantified by preparing microscopic slides for genus-level identification. Additionally, a Syracuse counting dish was utilized to enhance counting accuracy.

Community analysis: Nematode diversity and ecological distribution were assessed using the following metrics:

Frequency (N): The number of samples in which a specific genus was detected.

Absolute Frequency (AF %): The proportion of samples containing a given genus relative to the total samples analyzed, expressed as:

AF = Genus frequency/ Total number of sample counted ×100 (Eq. 1)

Relative Frequency (RF The occurrence of a genus compared to the cumulative frequency of all genera, calculated as:

RF = Frequency of genus / Total frequency of all genera ×100 (Eq. 2)

Mean density (MD): The average number of individuals of a genus across all samples, determined by:

MD = Total number of individuals of a particular genus counted in all samples / total number of sample counted (Eq. 3)

Relative density (RD %): The mean density of a genus relative to the sum of mean densities for all genera, computed as (Tomar *et al*. 2006):

RD = Mean density of particular genus /Sum of mean density of all nematode genera ×100 (Eq. 4)

Statistical analysis

Frequency (N), Absolute frequency (AF %), Density (MD), Relative density (RD%), were calculated following Tomar and Ahmad, 2009, in Microsoft Office excel version 2021. 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 31/07/2024, (Sieriebriennikov *et al*., 2014). Pie Chart,Shannon diversity (H') and evenness (R software) .Graph for food web analysis and c-p triangle were plotted using NINJA: Nematode Indicator Joint Analysis. A Kruskal-Wallis test followed by Dunn's post-hoc test was carried out to determine if there was any significance in abundance among trophic groups using R software, version 4.4.1 (R Core Team, 2025).

Nematode identification process

Following fixation and dehydration, the nematodes were preserved as permanent slides using the paraffin wax ring method. These slides were then examined under an Olympus BX51 DIC microscope for detailed study. Taxonomic identification of the extracted nematodes was carried out by referencing key taxonomic works (Andrássy, 1983; Jairajpuri and Ahmad, 1992; Ahmad, 1996), enabling classification up to the genus level.

RESULTS AND DISCUSSION

Nematode community patterns and ecological distribution

In the nematode community diversity study conducted in Patnitop, 37 nematode genera were identified. Bacterivores were the most prevalent, representing 58.7% of the total genera, followed by omnivores (20.58%), herbivores (11%), predators (8.9%), and fungivores (2.7%) (Fig 1 and 2). This outcome aligns with the findings of previous studies (Dong *et al*.,2017; Kashyap *et al*., 2022). This suggests that a faster, bacteria-driven decomposition process is dominant in the study area (Sushchuk and Matveeva, 2021; Vaid *et al*., 2014; Nisa *et al*., 2021). Herbivorous nematodes varied based on parasitism type, with migratory endoparasites (e.g., *Pratylenchus* spp.),ectoparasites (e.g., *Longidorus* spp.), sedentary parasites (e.g., *Heterodera* spp.), and root hair feeders (e.g., *Tylenchus* spp.) present across all sampled localities.

Nematodes were categorized using colonizer-persister (c-p) values for free-living forms (Table 1). C-p 1 nematodes dominated (39.0%–48.1%), indicating a high proportion of opportunistic species, which are often associated with disturbed or enriched environments (Ettema and Bongers, 1993; Kemenju *et al*., 2009) (Fig. 2). C-p 2 nematodes were less abundant (9.9%–16.1%), while c-p 3 nematodes showed moderate presence (7.7%–11.4%). Higher c-p groups (c-p 4 and c-p 5) were also recorded, with c-p 4 nematodes representing 19.3%–27.6% and c-p 5 nematodes comprising 5.8%–15.3% of the community (Fig. 2). The presence of higher c-p groups suggests some level of ecosystem stability, as these groups are associated with slower growth rates and longer life cycles, often indicating a more resilient and balanced ecosystem (Ettema and Bongers, 1993; Preez *et al*., 2022).

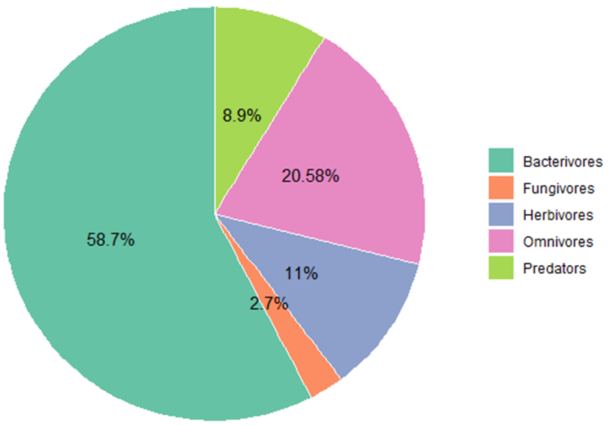

Fig.1. *Nematode generic diversity*

Population structure of nematode genera

Among bacterivorous nematodes, *Mesorhabditis* was the most frequent genus (Absolute Frequency, AF = 21.06%), followed by *Acrobeles* (AF = 14.99%) and *Diplogasteriana* (AF = 14.85%). *Eucephalobus* was the least frequent (AF = 0.69%). For omnivorous nematodes, *Dorylaimus* (AF = 14.85%) and *Aporcelaimus* (AF = 17.81%) were the most frequent, while *Mosh ajia* was the least frequent (AF = 0.77%). Among plant-parasitic nematodes, *Pratylenchus* had the highest AF (3.89%), and *Tylenchus* was the least frequent (AF = 0.52%). Predatory nematodes were dominated by *Mononchus* (AF = 3.82%), with *Crassolabium* being the least frequent (AF = 0.58%). Among fungivorous nematodes, Aphelenchus was the most frequent (AF = 1.21%), while *Doryllium* and *Nothotylenchus* were the least frequent (AF = 0.77% and 0.37%, respectively) (Table 1).

In terms of dominance, *Mesorhabditis* (Mean Density, MD = 21.06%; Relative Density, RD = 10.93%) was the most dominant bacterivorous genus, while *Eucephalobus* (MD = 0.69%; RD = 0.36%) was the least dominant. Among omnivores, *Aporcelaimus* (MD = 17.81%; RD = 9.25%) was the most dominant, and *Moshajia* (MD = 0.77%; RD = 0.40%) was the least dominant. For plant-parasitic nematodes, *Pratylenchus* (MD = 3.89%; RD = 2.02%) was the most dominant, while *Tylenchus* (MD = 0.52%; RD = 0.27%)was the least dominant. Among predators, *Mononchus* (MD = 3.82%; RD = 1.98%) was the most dominant, and *Crassolabium* (MD = 0.58%; RD = 0.30%) was the least dominant. For fungivores, *Aphelenchus* (MD = 1.21%; RD = 0.63%) was the most dominant (Table 1).

Functional Indices

Functional indices provided insight into the health and functional dynamics of the soil ecosystem (Table 2, Fig. 4). The Shannon Diversity Index was 1.93, with a Species Evenness of 0.73, indicating a moderately diverse and evenly distributed nematode community. This suggests a well-distributed variety of species,

Table 1. Population structure of soil-inhabiting nematodes in Patnitop forest

Nematode Genera	C-p value	F	AF	RF	MD	RD
Bacterivores						
Acrobeles	2	21	56.7568	3.79747	8.66	4.49637
Bursilla	1	11	29.7297	1.98915	12.69	6.58879
Cephalobus	2	16	43.2432	2.89331	4.4	2.28453
Diplogasteriana	1	21	56.7568	3.79747	14.99	7.78297
Eucephalobus	2	9	24.3243	1.62749	0.69	0.35826
Mesorhabditis	1	17	45.9459	3.07414	21.06	10.9346
Panagrolaimus	1	7	18.9189	1.26582	2.52	1.30841
Plectus	2	12	32.4324	2.16998	4.41	2.28972
Protorhabditis	1	12	32.4324	2.16998	12.97	6.73416
Rhabditis	1	19	51.3514	3.4358	13.06	6.78089
Teratocephalus	3	14	37.8378	2.53165	17.16	8.90966
Omnivores						
Aporcelaimus	5	19	51.3514	3.4358	17.81	9.24714
Dorylaimus	4	16	43.2432	2.89331	14.85	7.71028
Mesodorylaimus	4	18	48.6486	3.25497	3.53	1.83281
Metaporcelaimus	5	8	21.6216	1.44665	1.97	1.02285
Moshajia	4	14	37.8378	2.53165	0.77	0.39979
Herbivores						
Helicotylenchus	0	20	54.0541	3.61664	3.8	1.973
Hemicriconemoides	0	20	54.0541	3.61664	1.45	0.75286
Mesocriconema	0	19	51.3514	3.4358	3.06	1.58879
Paralongidorus	0	15	40.5405	2.71248	3.13	1.62513
Pratylenchus	0	19	51.3514	3.4358	3.89	2.01973
Psilenchus	0	19	51.3514	3.4358	1.85	0.96054
Rotylenchus	0	15	40.5405	2.71248	1.13	0.58671
Tylenchus	0	11	29.7297	1.98915	0.52	0.26999
Xiphinema	0	15	40.5405	2.71248	3.2	1.66147
Predators						
Crassolabium	4	12	32.4324	2.16998	0.58	0.30114
Discolaimus	4	8	21.6216	1.44665	2.29	1.18899
Eudorylaimus	4	19	51.3514	3.4358	2.51	1.30322
Labronema	4	10	27.027	1.80832	0.6	0.31153
Microdorylaimus	4	14	37.8378	2.53165	0.86	0.44652
Mononchus	4	18	48.6486	3.25497	3.82	1.98339
Nygolaimoides	5	18	48.6486	3.25497	2.24	1.16303
Prionchulus	4	19	51.3514	3.4358	2.6	1.34995
Fungivores						
Aphelenchus	2	14	37.8378	2.53165	1.21	0.62825
Doryllium	4	11	29.7297	1.98915	0.77	0.39979
Nothotylenchus	2	11	29.7297	1.98915	0.37	0.19211
Tylencholaimus	4	12	32.4324	2.16998	1.18	0.61267

C-p value = Colonizer-persister value, N = Frequency, AF = Absolute frequency, RF = Relative frequency, MD = Mean density, RD = Relative density

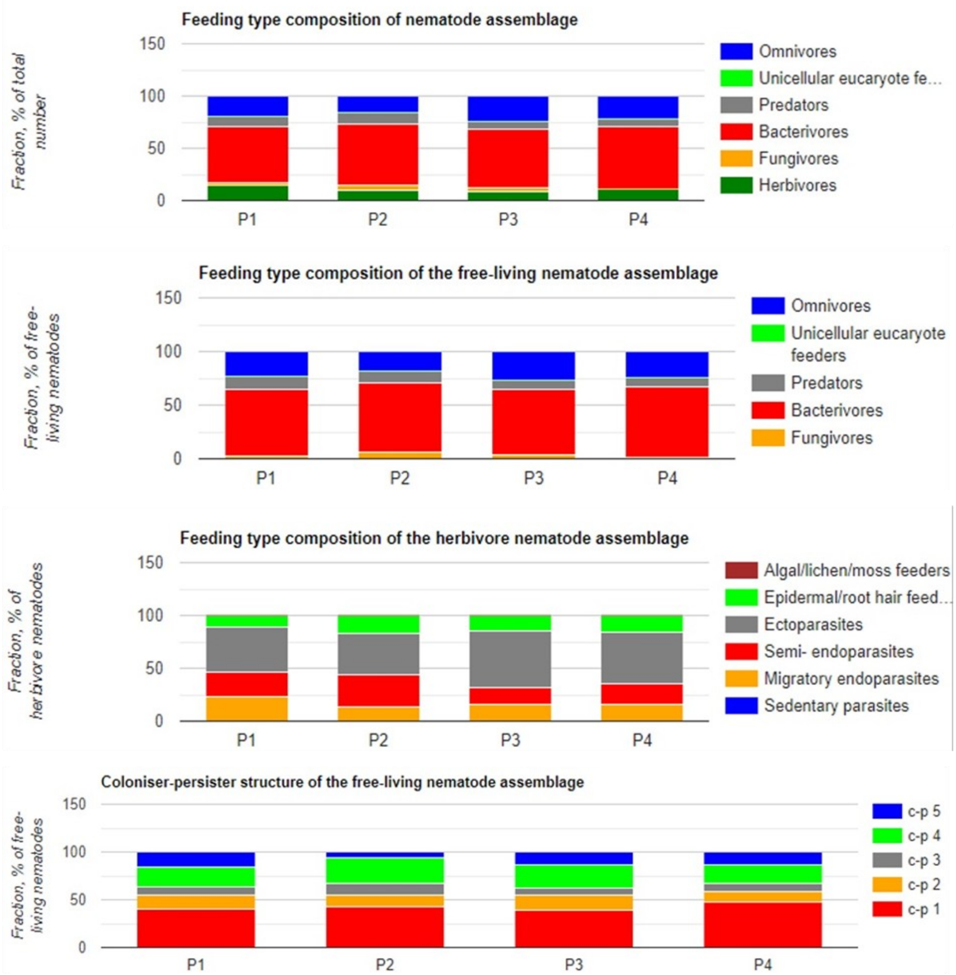

Fig 2. *Proportion of soil nematode communities that occurred in Patnitop forest of district Udhampur*

which is essential for fostering ecosystem functions such as nutrient cycling and the stability of food webs. Studies have shown that nematode diversity and abundance can vary significantly with elevation. For instance, in the subtropical forests of Huangshan Mountain, nematode diversity increased with elevation, likely due to increased soil moisture (Ding *et al*., 2024). The Species Evenness of 0.73 indicates a relatively even distribution of species, which is consistent with findings from the Mezin National Nature Park, where nematode communities showed varied distribution across different habitats (Жиліна and Шевченко, 2024). The Maturity Index (MI), recorded at 2.50, reflects a community skewed toward colonizer (r-strategist) nematodes, suggesting moderate environmental disturbance and a low successional status (Bongers and Ferris, 1999). Complementing this, the Enrichment Index (EI = 82.59) indicates a highly enriched system, likely influenced by recent organic inputs or nutrient flushes, which tend to promote bacterial-feeding nematodes (Shaw *et al.,* 2019; Tomar and Ahmad, 2009). Despite signs of enrichment, the Structure Index (SI = 92.48) indicates a well-developed, complex food web, characteristic of a functionally stable and structured community, a pattern consistent with old-growth or mature forest soils (Förster *et al.,* 2024; Kitagami and Matsuda, 2024). The Plant Parasitic Index (PPI = 3.20) indicates a moderate herbivorous load, characterized by 11% herbivorous nematode abundance, a level typically observed in stable forest ecosystems (Neher, 2001; Ferris, 2010). Furthermore, the low Basal Index (BI = 4.17) and Channel

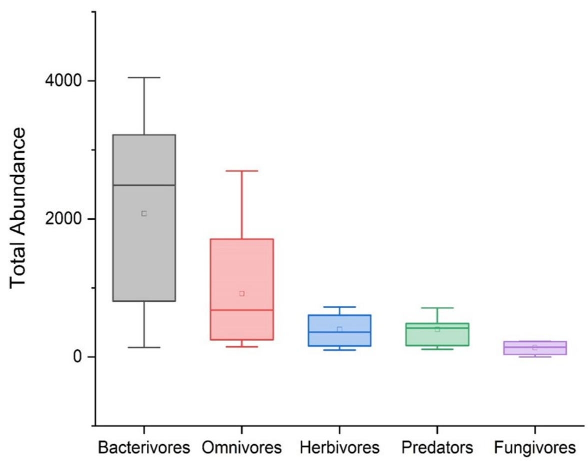

Fig. 3. *Total mean abundance of different trophic groups studied in Patnitop forest*

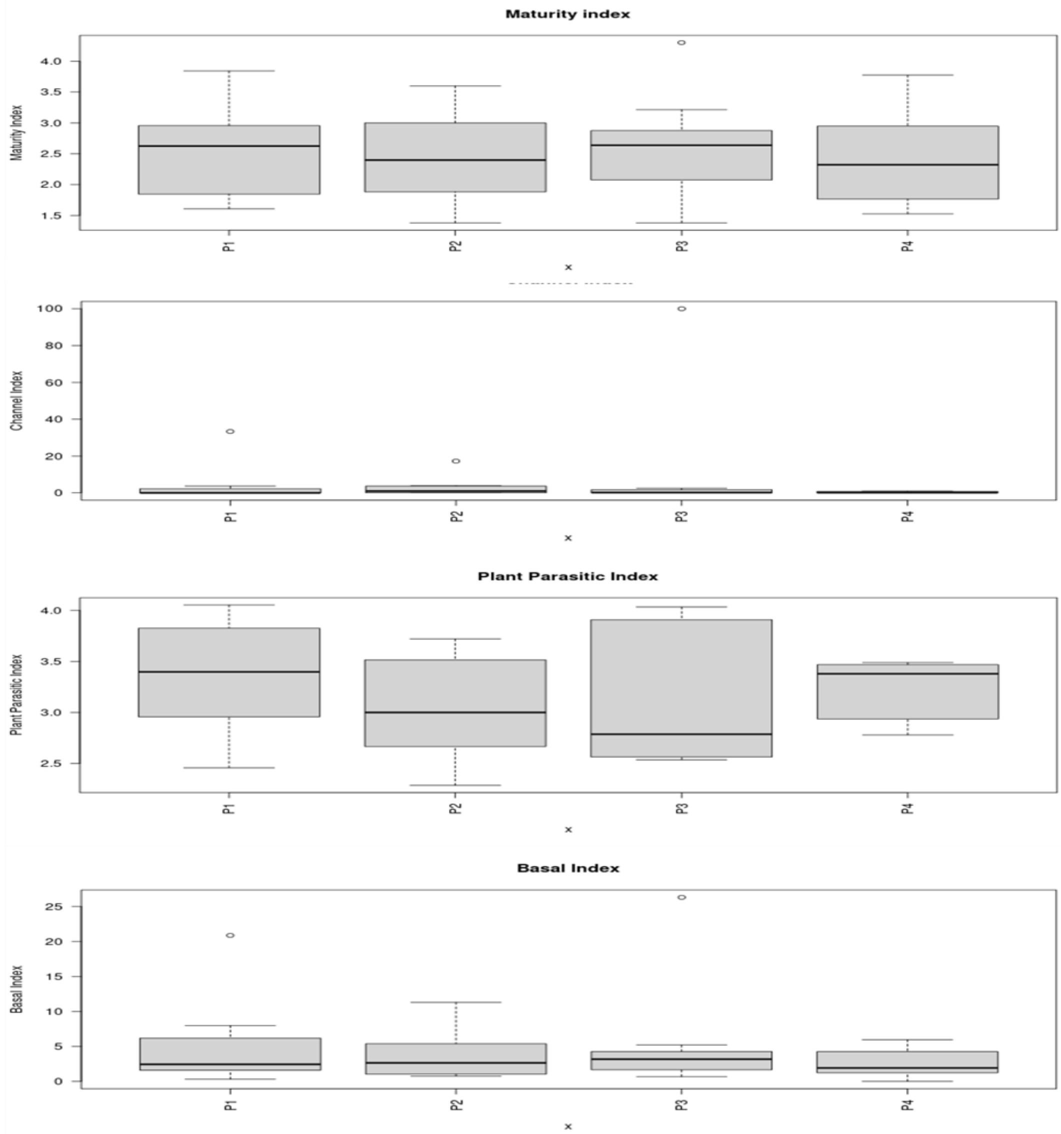

Fig. 4. *Soil nematode Functional indices in Patnitop forest (MI (Maturity Index), CI (channel Index), PPI (Plant Parasitic Index), BI (Basal index)*

Index (CI = 4.57) denote a minimal presence of stress-tolerant taxa and a dominant bacterial decomposition pathway, respectively. Collectively, these indices confirm that while nutrient enrichment is evident, the nematode community retains structural integrity and functional resilience, highlighting a balanced yet dynamic forest soil environment (Fig. 4). A Kruskal-Wallis test revealed significant differences among trophic groups (Kruskal-Wallis chi-squared = 17.902, df = 4, p-value = 0.00129). Dunn's post-hoc test showed that bacterivores differed significantly in abundance compared to fungivores, herbivores, and predators (Fig. 3). This highlights the functional diversity within the nematode community and their roles in nutrient cycling and ecosystem stability.

Nematodes as potential soil bio-indicators

Nematodes were assessed as bioindicators of soil health using food web diagnostics (Fig. 6). Over 80% of the samples were characterized by fertile or suppressive soils with moderate C:N ratios and bacterial-fungal properties. A c-p triangle analysis (Fig. 5) indicated that most soil samples were close to enrichment (c-p 1) and stability conditions (c-p 3–5). The predominance of c-p 1 nematodes suggests a soil environment undergoing disturbance or enrichment, potentially due to human activities, such as tourism, or natural disturbances. In contrast, cp-4 represents stress-tolerant persisters, characterized by slower growth rates and longer life cycles, which often suggest a more resilient and balanced ecosystem. The present findings indicate that the prevalence of cp-1 nematodes suggests a soil environment experiencing either disturbance or enrichment. This may be attributed to human activities, particularly tourism, given that Patnitop is recognized as a prime tourist destination, or it could be a result of natural dis-

Table 2. Summary of nematode diversity indices in Patnitop forest

S.No.	Ecological Indices	Values
1	Shannon Diversity	1.93
2	Species Evenness	0.73
3	Maturity Index	2.50
4	Plant Parasitic Index	3.20
5	Channel Index	4.57
6	Basal Index	4.17
7	Enrichment Index	82.59
8	Structure Index	92.48

turbances. Supporting this, recent studies have shown that tourist trampling in forest ecosystems significantly alters soil microbial communities, often promoting bacterial growth and shifting community composition toward human-associated taxa (Shang *et al*., 2022; Li *et al*., 2022). Such microbial shifts have been linked to increased nitrogen mineralization and nutrient cycling, potentially creating favorable conditions for colonizer–persister group 1 (c-p 1) nematodes. These microbial and nutrient changes, induced by tourism-driven disturbance, may partially explain the observed nematode community structure. Conversely, the presence of cp-4 nematodes suggests a more stable and mature ecosystem, characterized by a balanced nutrient cycle and strong soil health (Ettema and Bongers, 1993; Du Preez *et al*., 2022).

Conclusion

The study highlights the dominance of bacterivorous nematodes in the Patnitop forest, suggesting that bacteria play a significant role in decomposing organic matter. The presence of both opportunistic (c-p 1) and stable (c-p 4–5) nematode groups suggests a dynamic soil environment influenced by natural and anthropogenic factors. The functional indices, including the Shannon Diversity Index, Maturity Index, and Enrichment Index, offer valuable insights into the health and stability of the soil ecosystem. Nematodes serve as effective bio-indicators of soil health, reflecting the impacts of disturbances and nutrient dynamics. These findings underscore the importance of sustainable forest management and long-term monitoring to maintain ecosystem stability and biodiversity. Future research should integrate nematode-based indicators with other soil health metrics to enhance conservation strategies and promote the sustainability of forest ecosystems.

Conflict of interest

The authors declare that they have no conflict of interest.

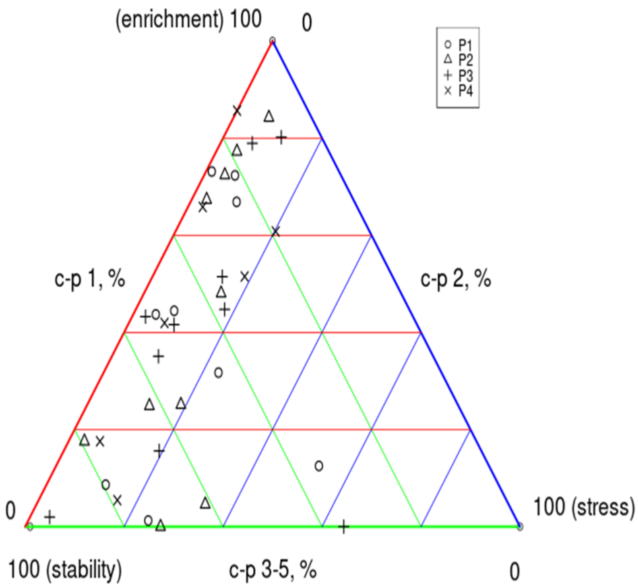

Fig. 5. *c-p (colonizer-persister) triangle depicting soil status regarding nematode c-p groups' evolution in Patnitop forest*

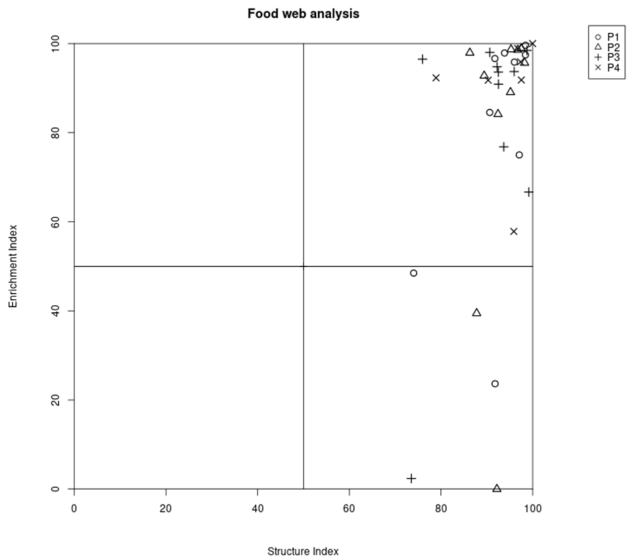

Fig. 6. *Food web diagnostic profile*

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