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Original article

Soil Nematodes: Functional Roles and Bioindicator Potential in Ecosystem Health

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ABSTRACT

Soil nematodes are an integral part of terrestrial ecosystems, playing a crucial ecological role and acting as highly sensitive indicators of soil condition. Comprising varied trophic groups namely bacterivores, fungivores, herbivores, omnivores, and predators nematodes play a substantial role in nutrient cycling, decomposition, regulation of microorganisms, and soil structure (Neher, 2001; Ferris *et al*., 2001). Their widespread occurrence, taxonomic richness, and ecological specificity allow them to respond to changes in soil conditions induced by pollution, land-use change, and agricultural management (Bongers & Ferris, 1999). Several ecological indices, such as the Maturity Index and Enrichment Index, are commonly employed to explain nematode community structure and evaluate environmental quality (Ferris *et al*., 2001). This article gives a synopsis of soil nematode functional diversity and the usefulness of nematodes as bioindicators of ecosystem well-being. Through the integration of ecological functions and indicator value, nematodes provide an important tool for sustainable soil management and monitoring under the threat of environmental change.

INTRODUCTION

Soil biodiversity refers to the diversity of life in the soil, including microorganisms (bacteria, fungi, protozoa), mesofauna (nematodes, mites, collembolans), and macrofauna (earthworms, insects). This biological community is rich in diversity and is important for sustaining soil health and ecosystem functioning like nutrient cycling, decomposition of organic matter, soil structure formation, and plant productivity (Wall *et al*., 2012). The interactions among these organisms create complex food webs that maintain ecological balance and resilience. High soil biodiversity enhances soils' ability to resist disturbances, recover from stress, and provide key ecosystem services, such as water filtration, carbon sequestration, and disease suppressio. As such, maintaining soil biodiversity is crucial for sustainable agriculture, climate regulation, and world food security.

Soil nematodes are one of the most diverse and cosmopolitan multicellular animals in the soil biota, found in almost every trophic level of the soil food web. Present in almost every type of soil ranging from deserts, forests, to agricultural fields they are incredibly adaptable and have a varied array of feeding strategies ranging from bacterivory, fungivory, herbivory, predation, and omnivory (Neher, 2001). This trophic richness enables nematodes to play important roles in processes like nutrient mineralization, microbial control, and organic matter decomposition (Ferris *et al*., 2001). Soil nematodes taxonomically represent thousands of species that have diverse morphological and physiological features, although most of them are undescribed because they are microscopic and live cryptically. Their extensive occurrence, ecological specialization, and sensitivity to environmental perturbations make them not only functionally relevant but also ideal biological indicators of soil health and ecosystem functioning.

Soil nematodes are an essential component of the soil food web, playing at several trophic levels and supporting key ecosystem processes. Their varied feeding behaviour bacterivory and fungivory to predation allows them to control microbial communities, increase nutrient cycling, and modify soil structure. Current research emphasizes their function in carbon and nitrogen cycling, especially in peatland ecosystems, where their trophic diversity is reflective of the general structure of the soil food web. Also, nematodes have been found to play a significant role in belowground processes like carbon and energy flux, particularly in high-altitude ecosystems. Their environmental sensitivity and functional diversity render them useful bioindicators to gauge soil fertility and ecosystem stability.

Diversity and Classification of Soil Nematodes

Soil nematodes constitute one of the most functionally diverse and abundant groups of soil fauna, having a broad range of feeding modes and ecological functions. Depending on their feeding habits and position within the soil food web, nematodes can be broadly divided into five trophic categories: bacterivores, fungivores, herbivores (plant-parasitic), omnivores, and predators. Bacterivores and fungivores are regarded as key players in mineralizing nutrients and regulating microbes, while herbivores directly engage with roots of plants and have the potential to serve as agro-pests. Predator nematodes, however, regulate populations of other nematodes and microfauna, ensuring balance of the food web (van den Hoogen *et al*., 2019).

Taxonomically, nematodes are classified under the phylum Nematoda, with thousands of known species and possibly millions still to be discovered. Their diversity is determined by several factors such as soil type, vegetation, moisture, pH, and land use. Nematodes also have specific morphological adaptations like stylets in plant-parasitic species and strong buccal cavities in predatory species. Their morphological and ecological diversity renders them a powerful tool for determining the structure and functioning of soil ecosystems (Ferris *et al*., 2001). New developments in molecular technologies, including DNA barcoding and metagenomics, are facilitating the discovery and identification of nematode species that were hard to morphologically identify earlier, thereby broadening our knowledge of their biodiversity and distribution across various ecosystems (Holterman *et al*., 2017).

Nematode Group	Feeding Type	Ecological Role	Example Genera
Bacterivores	Bacteria	Nutrient mineralization	*Caenorhabditis*
Fungivores	Fungi	Organic matter decomposition	*Aphelenchus*
Herbivores	Plant roots	Crop pests	*Meloidogyne*
Omnivores/Predators	Nematodes, microbes	Soil food web regulation	*Mononchus*

1. Functional Roles in Soil Ecosystem

Soil nematodes have varied but critical functional roles in terrestrial ecosystems, most importantly as regulators of biological and physicochemical processes that underlie soil health. They interact with their environment through their trophic diversity, comprising bacterivores, fungivores, plant-parasitic nematodes, omnivores, and predators. Every group makes a distinct contribution to soil ecosystem services such as nutrient cycling, microbial community regulation, decomposition of organic matter, development of soil structure, and biological control.

(a) Nutrient Cycling and Mineralization

One of the fundamental roles of bacterivorous and fungivorous nematodes is to enable nutrient cycling, particularly nitrogen and phosphorus. The nematodes consume bacteria and fungi, enhancing the turnover of microbial biomass and favoring the release of nutrients in plant-accessible forms. This action is especially critical in nitrogen-starved soils where microbial immobilization may limit nutrient availability to plants. Through their stimulation of microbial turnover, nematodes increase nitrogen mineralization, which is essential for plant growth and yield (Ferris et al., 1998).

(b) Regulation of Microbial Communities

Nematodes also support microbial population balance and diversity. Through selective feeding, they can modulate microbial community structure and activity, with some microbial taxa being favored over others. Top-down control by nematodes aids in microbial succession and resilience to disturbance caused by drought, pollution, and agrochemical application (Geisen *et al*., 2019). Bacterivorous nematodes, for example, can inhibit pathogenic bacteria and favor beneficial microbial communities that ensure plant health.

(c) Organic Matter Decomposition

Fungivorous nematodes indirectly facilitate the decomposition of complex organic matter by feeding on fungal hyphae. This increases fungal turnover and assists in the degradation of plant residues, especially lignin-containing fractions. The combination of activity of nematodes and microbes thus enhances the decomposing process as well as soil organic matter dynamics, which subsequently enhances soil fertility and carbon storage (Neher, 2010).

(d) Soil Structure and Physical Function

By traversing soil pores and consuming microbes within the rhizosphere, nematodes affect porosity and aggregation in the soil. Their movement redistributes microbes and nutrients within the soil matrix. Predatory nematodes can also decrease root-feeding nematode populations, indirectly supporting plant root growth and improving soil structure through more extensive root systems.

(e) Pest Regulation and Biocontrol

Predatory and omnivorous nematodes are important in biological control of pests by controlling plant-parasitic nematodes and other soil microfauna. This biological control facilitates the suppression of damaging populations of nematodes without resorting to chemical nematicides. Additionally, some bacterivorous nematodes have been linked to antagonistic bacterial populations that secrete nematicidal compounds, further aiding plant protection (Liu *et al.*, 2021).

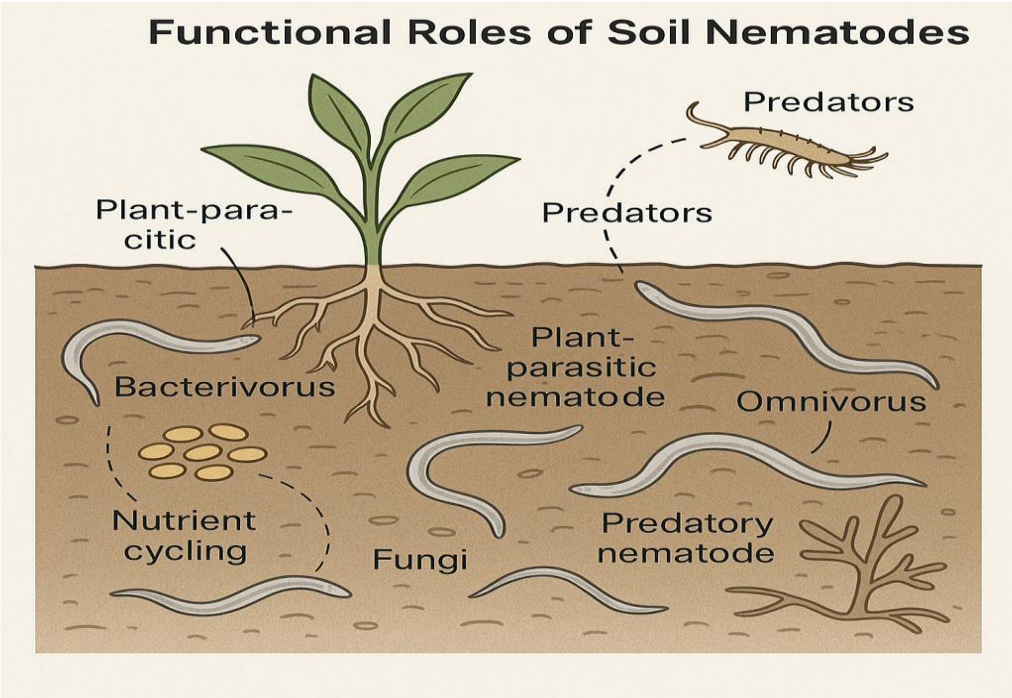

Fig : Functional Roles of Soil Nematodes

2. Nematodes as Bioindicators of Soil Health

Soil health is a complex idea that embodies the ability of soil to maintain biological productivity, enhance plant and animal well-being, and conserve environmental quality. Bioindicators—organisms sensitive to changes in the environment—are a useful method for evaluating soil health. Among them, nematodes are particularly valuable because they are common, trophically diverse, have short generation times, and are responsive to ecological disturbance. Therefore, nematode community structure and functional characteristics are essential to understanding the biological health and ecological processes of soils.

(a) Sensitivity to Environmental Change

Nematodes hold every trophic position in the soil food web, from feeding on microorganisms to top carnivores, thus their community patterns mirror large-scale soil ecological alteration. Nematodes show an immediate reaction to different stress factors like chemical pollutants, tillage, organic fertilizer, heavy metals, and nutrient imbalances (Neher, 2001; Sánchez-Moreno *et al*., 2010). For example, bacterivorous and fungivorous nematodes grow well in response to organic input, but in traditionally cultivated or degraded soil, their population would decrease.

(b) Nematode-Based Indices for Soil Assessment

Over the past two decades, a suite of nematode-based indices has been developed to quantitatively assess soil ecological status. The most commonly used among these are:

- **Maturity Index (MI):** Bongers (1990) suggested this index, which is derived from the colonizer-persister (c–p) scale that classifies nematodes by life-history characteristics. The more organized, undisturbed soils have higher MI values, while disturbed or enriched conditions have lower values.
- **Structure and Enrichment Indices (SI and EI):** These were introduced by Ferris et al. (2001) as indices that have a graphical basis (faunal profile) to interpret the community structure and functioning of the nematode assemblage. SI is indicative of food web complexity, while EI is representative of nutrient enrichment and microbial activity.
- **Channel Index (CI)**: CI determines whether decomposition is bacterial or fungal dominated. A high CI suggests fungal-driven processes, while a low CI indicates bacterial dominance.

(c) Indicators of Land Use and Management Practices

Communities of nematodes are also responsive to land use change. Diverse, well-organized nematode communities have been found in natural or organically cultivated systems, whereas lower diversity and opportunistic taxon dominance correlate with conventional or intensively farmed agriculture (Song *et al*., 2020). Organic farming strategies, for example, enrich the population density of omnivores and predators, which reflects more complex soil food web structure and ecosystem function.

In restored or reclaimed soil, nematode communities may be employed to monitor ecological succession and determine if recovery is toward a more stable, mature ecosystem of the soil (Liang et al., 2021). Their incorporation into monitoring schemes improves our capacity to identify gradual changes in ecosystem health over time.

3. Methods for Nematode Analysis

Accurate assessment of nematode communities requires standardized methods for **extraction, identification, and quantification**. These techniques are critical for evaluating soil health and interpreting ecological functions.

(a) Nematode Extraction Techniques

The most widely applied nematode extraction technique is the Baermann funnel method, which takes advantage of nematodes' active movement from soil when suspended in water over tissue paper or mesh. Modified forms such as the Oostenbrink elutriator and centrifugal flotation are also used, particularly for quantitative recovery in different soil types (Barker, 1985). Each of these techniques differs in efficiency with soil texture, moisture levels, and nematode mobility.

(b) Morphological Identification

When removed, nematodes are slide-mounted and viewed under compound microscopes. Identification is made using morphological characters e.g., stylet shape, shape of the esophagus, and tail structure—up to genus or family level with the help of taxonomic keys (Siddiqi, 2000). This, though, needs specialization and is tedious.

Future Perspectives and Applications

As there is an increased focus on sustainable agriculture and ecological restoration, soil nematodes are ready to contribute much more to environmental monitoring, assessment of soil health, and biocontrol measures. Future studies will be able to utilize molecular biology, remote sensing, and data science advancements to improve and broaden the use of nematodes as reliable and sensitive indicators of soil ecological status. In agricultural systems, diagnostics based on nematodes can be incorporated into precision farm equipment for in real-time monitoring soil biological health. In addition, improved understanding of nematode-microbiome-plant interactions will pave the way for new biocontrol and soil amendment practices, such as the utilization of beneficial nematodes or microbial communities to inhibit pathogens and improve nutrient cycling. Finally, a transdisciplinary strategy integrating nematology, ecology, genomics, and agronomy will be necessary to realize the full potential of nematodes to enhance soil resilience and support sustainable land management.

CONCLUSION

Soil nematodes, with their ecological richness, trophic plasticity, and responsiveness to environmental perturbation, provide an exclusive window onto the functional integrity and biological quality of soils. As part of the soil food web, they play a pivotal role in processes such as nutrient cycling, decomposition of organic matter, and control of pests and thereby contribute to vital ecosystem processes. Their structural indices and composition provide excellent measurements for evaluating land use effects, management practices, and environmental impacts on soil systems.

With advances in molecular diagnostics and data analytics, the use of nematodes as bioindicators becomes increasingly robust and scalable. These advancements hold great promise for integrating nematode-based tools into sustainable agriculture, ecological restoration, and global soil monitoring programs. By combining nematode analysis with comprehensive biodiversity and soil function measurements, scientists and land managers are able to more fully understand, conserve, and enhance the biological integrity of terrestrial ecosystems in the context of continued global change.

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