Nematodes and Earthworms: Their Interaction and Role in Enhancing Soil Fertility

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Abstract — These invertebrates are responsible for the necessary nutrient cycles, microbial regulation and structural improvement of the soil to enable sustainable soil production and a healthy population. Vermitechnologies become a very popular organic farm method, providing alternatives to chemical fertilizers and soil rehabilitation. The biodiversity of nematodes in different substrates used in vermicomposting is evaluated in this study with the determination of nematodes, which were extracted by flotation. Of these specimens we obtained 44% of which were identified: 40% bacterivores, 20% plant feeders, three predatory species, and four fungivorous nematodes. These experiments identified shifts in species composition as well as new taxa which are not detected on the first test run. Interestingly, 35% of nematodes were found in cattle manure before the introduction of earthworm. Earthworm population and food population dynamics were also studied in the context of dieting. Animal husbandry supplemented with hay doubled the populations of *Eisenia fetida* and Georgian red earthworms exhibited gradual increases. On the contrary, earthworms rejected rapeseed substrates, which is probably attributed to its high caloric and lipid contents. Chemical analyses of soil, biohumus and manure were performed in the Institute of Earth Sciences, Ilia State University. These results endorse vermicompost as an environmentally friendly method in restoring fertility in the soil, controlling pests and recycling organic materials.

Keywords — Eisenia fetida, Earthworm, fertility, life activity, Dorylaimida, nematode, soil, vermicompost.

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1 Introduction

Soil fertility is at the basis of sustainable agriculture and the sustainability of soil becomes critical by understanding the essential functions of organisms found on their land. Examples include earthworms and nematodes, which play critical roles in decomposing organic matter, in cycling nutrients, and promoting a healthy ecosystem. Concerning the increasing pressure to cope with soil deterioration and lessen the effect of chemical fertilizer application, vermitechnology has been developed as a feasible candidate. In this paper, the roles and activities of earthworms and nematodes in soil ecology will be investigated, with an emphasis on their collaborative capacity in regulating the fertility of soil and promoting good soil culture for agriculture. From their biological function — burrowing, decomposing themselves and co-mingling with microbes — they control key processes such as nutrient cycling, soil configuration, and the breakdown of organic matter. Of these, annelids, nematodes, centipedes, and micro-arthropods are crucial in compost production and nutrient recovery. Earthworms (e.g., composting species *Eisenia fetida*) boast capabilities such as organic material destruction, microbial community establishment and vermicast enrichment. As natural aerators and as chemical stimulators, they change soil into a biologically activated medium suitable for strong growth of plants. Nematodes, despite their microscopic size, are widely valued in ecology. Their functional range consists of fungal-feeding, bacterial-feeding and predatory species which vary for abundance depending on composting stage. Not only do they signify compost maturity, but they also influence soil biocenosis and nutrient processes. In Georgian land, nematode diversity is consistent with local adjustments which are adaptive to different regions by order, where the population Dorylaimida constitutes a large proportion in that of the population of the Adjara region. All the soil invertebrates together, they represent biological cues, and active contributors to the growth of soil fertility. By understanding their ecological roles, we can design effective vermitechnological solutions that guarantee long-term agricultural sustainability. Nematodes, commonly referred to as roundworms, rank as the second most diverse and abundant class of soil fauna, after protozoa, in terms of species richness. They play a variety of ecological roles, from microbial grazers that control nutrient cycling to plant parasites that inhibit agricultural productivity. These analyses included free-living and entomopathogenic nematodes; here, some of the identified nematodes are shown (see Figs. 1, 2, and 3).

Nematodes exist in almost all habitats and are both free-living and parasitic. Soil nematodes perform key agricultural functions as well as re-fertilizing nutrients and minerals. Nematode biogeochemical communities in compost undergo metamorphosis over time, whereby they continue to form, decay and become degraded. The early phases are often dominated by fungal- and bacterial-feeding nematodes which expedites the degradation of organic materials. With maturing composts, predatory nematodes are becoming more common, signaling the development of a new shift in microbial micro vitality and ecosystem stability.

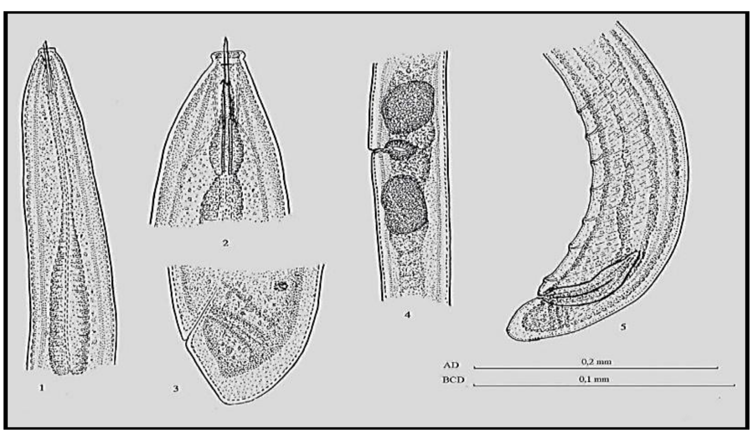

Fig. 1, *Enchodelus georgiensis* Eliava, Tskitishvili, Bagathuria, 2006

1. Female; 2. Head of female; 3. Tail part; 4. Gonads

Necessarily, nematodes are bioindicators of soil health. The rate and presence of worms as well as species indicating biological activity and the level of nutrient availability and maturity of the compost. In mature compost, nematodes feeding on fungi typically predominate, and plant-parasitic species, when found, should not exceed economic impact levels (Figs. 2, 3).

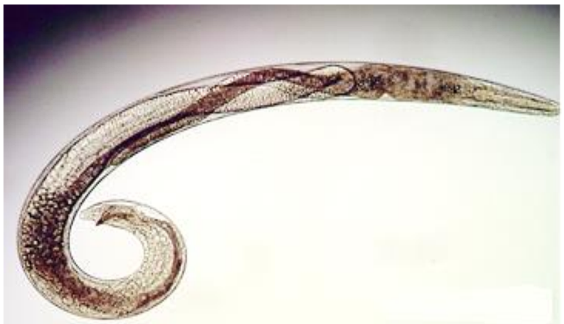

Fig. 2, *Steinernema thesami* Gorgadze, 1988
Male nematode

Fig. 3, *Steinernema thesami* Gorgadze, 1988
Mature female nematode

Research conducted in Georgia shows an excellent nematode biodiversity. For example, in Adjara region, the order Dorylaimida accounts for 37.3% of nematodes recognized, with the most prominent family belonging to the Qutsianematidae family. Other significant orders include Rhabditida (21.4%) and Tylenchida (19.25%), each exhibiting an appropriate adaptation to local soil conditions. Among rarer groups such as Enoplida, Mononchida and Aphelenchida enhance the soil food web by specialized functions. However, not all such nematodes contribute positively to soil ecosystems. Plant-parasitic nematodes, like root-knot nematodes, are serious threats to agricultural crops. They erode roots, inhibit nutrient uptake and lower yields — especially in more underground crops like carrots and potatoes. Knowledge of nematode diversity and its correlation to environmental variables (lifestyle, environment-based variables, such as climate, soil, and biotic associations) is important for the implementation of specific vermitechnological interventions and maintenance of fertility in soils. Earthworm – Nematode Interactions The nature of the interaction between earthworms and nematodes forms an important dynamic ecological relationship with wide-ranging implications for soil health and fertility. Although functionally separated from each other, both organisms also promote biological enrichment of the soil, and together they can create an environment maximizing the benefits of one another. Earthworms affect the populations of nematodes through multiple mechanisms and they do this through burrowing which increases soil porosity and oxygenation which provides environments suitable for nematodes to grow. Digestive processes stimulate microbial growth indirectly increasing food resource for fungal- and bacterial-feeding nematodes. Earthworms may repress harmful plant-parasitic nematodes and promote beneficial ones via the secretion of biologically active compounds. Recent studies indicate that compost generated by vermitechnology has nematode-modulating effects. Vermicompost frequently possesses bioactive compounds that suppress the growth of parasitic nematodes like Meloidogyne spp., but promote beneficial species that contribute to the turnover of nutrients and the suppression of pathogens. Some nematodes have also been found in the body cavities of the earthworm, thus hinting at parasitic or commensal associations. Nematodes of species such as *Dicelis colchicus* and *Dicelis ivericus* have been found in endemic earthworms in Georgia, highlighting the intricate co-evolution of this soil dweller [1]. The earthworms and the nematodes coalesce in an intricate system of biology. Their dynamic interactions regulate the microbial population (microbial regulation), organic tissue degradation and soil resiliency. Understanding these relationships and their use is critical to promote sustainable soil management systems. Some researchers have demonstrated that earthworms represent a potential alternative method for biological control of plant-parasitic species in a variety of crops [2]. Regional Studies in Georgia Georgia offers a context for exploring the different populations of earthworms and nematodes due to its rich biodiversity and diverse soils. Not only do these regional studies emphasize ecological adaptations but they also shed light on the possibility of indigenous species to contribute to improvements in soil fertility through vermitechnology. Soil nematode surveys in the Adjara region showed that the order Dorylaimida comprising 37.3% of the nematode community predominated. Within the family Qutsianematidae was especially prominent for its presence and ecological diversity. Other orders include Rhabditida (21.4%) and Tylenchida (19.25%), which have also played a major role in the soil nematofauna by employing a range of feeding behaviors and life strategies. Less frequent groups—such as Enoplida, Mononchida, Aphelenchida added extra complexities to the regional soil food web [3]. The simultaneous studies on earthworm diversity show an extraordinary richness as a function of the Georgian landscape. Approximately 89 species of earthworms have been discovered, 21 species and subspecies known in the Colchis Lowland -- a biodiversity zone. One of the perennial species for *Eisenia colchidica* and *Allolobophora iverica* have attracted scientific interest owing to the differential interactions they can have with nematodes. Notably, helminthological investigations unveiled parasitic nematodes inhabiting earthworm body cavities, such as newly discovered species *Dicelis colchicus* sp.n. and *Dicelis abchazicus* sp.n. [3]. These results underlined the complexity of soil ecosystems in Georgia, and the intricate web between soil invertebrates. In developing sustainable agricultural management, the findings support the necessity to consider the co-evolution of nematodes and earthworms in the Georgian soils and the importance of regional biodiversity in order to address sustainable agricultural practices. Vermitechnology and Sustainable Farming Vermitechnology —the application of earthworms for organic waste decomposition and soil improvement technology —are being applied in sustainable agriculture systems around the world. This approach tackles a number of ecological challenges, notably nutrient depletion, pollution, soil deterioration and chemical overuse, by converting biodegradable waste into a more efficient organic fertilizer. Vermicompost derived through the digestion processes of composting earthworms contains humic compounds, essential nutrients, and beneficial microbial communities. Relying on it not only increases crop yield, soil fertility but it also lessens the impact of artificial fertilizers, which further builds up nitrate and can contaminate groundwater. Earthworms are also biochemical reactors that secrete cellulase and other enzymes, thus increasing the decomposition rate of plant residues [4, 5]. Their action transforms lignocellulosic waste material into biologically active humus, thus restoring soil structure and better holding onto water. When done properly, vermiculture systems can transform large volumes of organic waste—from agricultural by-products to urban kitchen scraps—into valuable soil amendments. Vermicompost is also shown to kill plant-parasitic nematodes and increase ameliorative ones, and in this way, we establish a more balanced, resilient rhizosphere according to recent studies. This double action improves plant immunity, stimulates root development, and limits yield losses from root pathogens. In areas such as Georgia, vermitechnology provides a scalable example of rural sustainability. Supporting the introduction of this technology to small farmers will promote environmentally sustainable food production and turn waste care into a soil restoration project. Sustainable use of vermicompost can contribute to healthier agroecosystems, allowing "wise" farming to be encouraged – one that respects ecological ethics and can be economically responsible.

2 Materials & Methods

With technology such as vermitechnology only making its first steps in Georgia, any research conducted this way is incredibly important. This study aimed to assess the species composition of nematodes in cow manure and biohumus, considering its structure and food composition. The study was conducted in a laboratory. A conventional procedure was utilized for vermicomposting: the initial number of earthworms consisted of - *Lumbricus rubellus* - 60 and *Eisenia fetida* - 25 per container and the earthworms were put into plastic containers of $0.2m^2$ and basic substrate for feeding worms was cow dung with no impurities. Cow dung and hay were from private farms and cow dung was not fresh. All specimens obtained from the test tubes were maintained at 24-28°C and in the laboratory. Evaluating the presence of nematodes in the earthworm casts, repeated tests were performed after 3 months. The materials for the experiments were collected in the following areas of Georgia: Avchala (41°49´07.56´´N, 44°46´40.22´´E, altitude =503.5 m asl), Krtsanisi (41°36´28.50´´N, 44°54´01.26´´E, alt = 420 m asl), and Dighomi (41°47´11.30´´N, 44°44´08.71´´E, alt = 503 m asl). *Eisenia fetida*, (Savigny, 1826), Krtsanisi *Aporrectodea caliginosa* (Savigny, 1826), and *E. fetida* were identified in the samples from Avchala and Dighomi districts. Meanwhile, the other purpose of this study was to contrast the breeding rates of the earthworm among 2 different populations; local red earthworm (*Lumbricus rubellus* Hoffmeister 1843) and California Red Wigglers (*Eisenia fetida*, Savigny 1826). These populations were leveraged to evaluate in vitro organic waste recycling and vermicomposting. The cow dung was added the hay to observe the breeding rate of earthworms as well as the dependence of their vital activity on fodder. To compare breeding rates, earthworms were counted manually. The boxes were suspended in the open air at a temperature of 30-35°C during this period. The observations were made within 6 months from May to October. We tested rape cake as a fodder for the earthworm feeding in our experiments. The nematofauna of biohumus and cow manure, the primary feeding substrate for earthworms, were investigated. The maximum total number and species composition of the nematode population were determined via three composite (mixed) samples taken from biohumus and cow manure (Earthworm feeding substrate). Composite samples ranged in weight from 100 to 150 grams and consisted of 10 primary samples. Baermann's funnel technique [6, 7] was then employed to extract nematodes from substrates. We relied on the monographs by, e.g. [8, 9, 10, 11, 12]. The average number and frequency of detection of nematodes were counted. The purpose of our study has not been to document the variability of the nematode number. All the methods employed to control nematodes, the chemical and the environmental, cannot lead to total destruction for them, but also reduce their population to an extent which ensures that any damage becomes negligible. However, even if this procedure turns out successfully, that does not equate well with resting in our laurels. Just one has only to disrupt farming technology, or to make a mistake, as nematodes multiplied severalfold instantly. Ecological Implications: The interactions between soil invertebrates, especially among earthworms and nematodes, provide deep insights into the ecological processes associated with soil fertility. They are the main axis of sustainable agriculture through their decomposition, nutrient cycling, and biological regulation. Earthworms improve soil structure, promote microbial life, and convert organic wastes into nutrient-rich compost. Different functional nematodes regulate the microbiome and act as indicators for soil health. Collectively, their synergistic interactions—tackled in both global and regional Georgian ecosystems—show the effectiveness of biologically driven soil rehabilitation strategies. Vermitechnology becomes not just a composting solution, but an ecological philosophy, one that addresses urgent problems: chemical overuse, waste deposit in the soil, and declining soil productivity. And once we address these concerns, farming practices can move toward greater resilience — yield ecologically clean crops, avoid toxic land-mines, regenerate ruined soils and reduce ecological impact. All in all, to care for the Earth's soils is to care for the biological integrity in them. That understanding of the interrelation and leverage between the soils organisms is a privilege and a necessity in the name of food security, environmental health and scientific progress of the future.

3 Results and Discussion

Soil is most important for food security. Before even considering the fertility and productivity of the soil, these two concepts can be combined and therefore, soil can only be completely evaluated to decide how and what it needs to be developed and enriched with something. With these two characteristic features of soil the soil invertebrates have a role in making the soil better and more enriching. Especially interesting to find out about how they all contribute to the improvement of the soil combined. What is soil fertility? Soil Fertility - It also indicates the levels of available nutrients for the plants, it is an essential attribute of the soil and can be studied in the laboratory, it is the potential status of the soil for crop production. Soil productivity is a wider term used to refer to yields from crops, which can be measured under certain climatic conditions. Nematodes and Earthworms have interacted several researchers studied [13, 14, 15]. There are available data on the potential influence of vermicompost on plant pest resistance, not least to soil nematodes [16]. The majority of the researchers reported an arrest effect of homely pest worms by nematodes with invader earthworms' effect. Although not caused by a direct effect on the parasite and the leaves of the genes responsible for its enzymes (lipoxygenase, phospholipase D, and cysteine protease) expressed expression significantly lowers the parasite. Following the application of vermicompost, a remarkable decrease of pathogenic microorganisms, nematodes and insect pests was observed. In the presence of earthworms, the nematodial lesion of rice was reduced to 82% [17, 18, 19]. Crop productivity increases by 30-70% at a time of vermicompost application. It further enhances germination and development of different crops and protects them from diseases and pest [20]. Trophic relations as well as allocation of ecological groups are important ecological features of nematodes as we have known. The investigations revealed that the nature of nematodes in the earthworms' casts were significantly more diverse than in cattle manure and are primarily represented by the bacteria feeder of 24 species, omnivores of 13 species, including the other ecological groups: two families of fungus feeder nematodes belonging to the Tylenchidae and Leptonchidae, 3 species of predator nematodes and 9 species of the plant feeder nematodes. It should also be kept in mind that nematodes have not been found in the guts of earthworms. We achieved remarkable results in experimental studies investigating the diversity of nematode representatives in vermicompost. Notably, no nematodes were detected in the compost derived from earthworms fed grape leaves. Whereas four nematode families were identified in the substrate obtained from earthworms fed cattle manure: Aporcelaimellus, Eudorilaimus, Mesodorilaimus and Paraxonchium. Some other investigators observed that various microorganisms in the different feed substrates prior to the ingestion by the earthworms were not in the casts [16]. The second time in our experiments the replication tests of vermicompost indicated that nematode species composition has slightly changed and also some other nematodes were identified that were not detected at initial period of test. Particularly, all predatory species were detected during repeat experiment and only one species of predator nematodes - Coomansus parvus - was detected later in the food (cattle manure) of earthworms. Nematode species composition is diverse in other ecological groups. Noteworthy is the observation that fungus feeder species (as opposed to predatory forms of nematode fungi) were detected only in the first test and have not been registered on the repeated experiment. Similar to the case with the predatory this is also only one species of nematodes - *Filenchus* sp. in the cattle manure, which are the predominant food sources for earthworms. Based on a study of the fauna, it could reasonably be inferred that the morphological structure of taxonomic nematodes did not differ significantly among different samples. We know earthworms have a lot of predators including: mites, centipedes, earwigs and more - with nematodes, but here only three predacious species of nematodes were identified. The observation of other species of free-living nematodes during retesting of vermicompost is likely due to direct consumption and consequent impacts on the vigor, viability and germination of cysts found in casts. Compost is useful because we receive fertilized plants that are incredibly resistant to pests and diseases. The disease resistance in part comes from the microscopic fungi that live in the compost, which make and take antibiotics. They inhibit the growth of pathogenic microbes in the soil. Antibiotics that are absorbed by roots go into the above ground part and protect it from infection. It has been experimentally evident that, even minor added application of the vermicompost fertilizer in the soil in plants significantly enhances and hastens the germination, growth, flowering and ripening of the crop irrespective of the nutrient storage plants [18]. The static activity of vermicompost-induced fungi was also demonstrated in the experiments [21, 22]. The compost lends itself to mushroom predators that possess durable long chains of stuck fibers, which can tear down the depth of compost and trap the nematodes. The filaments create rings that contain the falling nematodes and digest them progressively. Thus, the compost is considered by nematod scientist as the best means. Predacious fungi, fully encapsulated with adherent hyphaes nutrients and predatory nematodes, can greatly decrease the generation of phytohelminthes because we are able to conclude that the faulty closed humus (long-term) and open (short-term) ground area can be used [23]. The research found that, with the application of organic fertilizer to soil, much more predatory fungi were found, than for mineral fertilizers. Sadly, the investigation of predation of fungi in biohumus was not the purpose of our study. Considering the former nematodes are phytophagic and carnivorous. Carnivore nematodes feed on their kin — herbivorous nematodes, and even though they are not destroyed out of all proportion, they greatly limit their numbers. On beds fertilized with compost, you cannot be afraid of strong root damage by nematodes. Among the top ecological factors that phytonematodes need to adapt in natural conditions are: climate, weather, soil type and composition including soil biocenose and terminal points of plants which are both temporary or permanent habitations or sources of food for the worms, composition of fodder and quality are also important. There are known influences of all these factors on the vital activity of earthworms [21]. This will lead to the results of the analysis of ecological groups by substrate, represented in Figure 1, whereby the ratio of ecological groups of nematodes to each other is shown. The study found 24 bacterial feeding nematodes to be present in cattle manure and vermicompost, accounting for 37.5% and 79% of nematodes in manure and vermicompost, respectively, and about 22% were omnivorous, 72% in vermicompost and 27.3% in cattle manure. Predatory forms of nematodes and nematodes feeding on fungi were in the minority, only 7.4%; each group is found almost equally in both manure and vermicompost. Regarding plant-feeding nematodes, about 18% were noted in both manure and vermicompost equally (see Fig. 4).

The results of laboratory analyses of the chemical composition of soil, biohumus and cattle manure showed that the humus content in vermicompost is much higher than in soil and cattle manure [25]. The organic matter in vermicompost is about five times more than its content in the soil and five per cent higher than in manure. The nitrogen content is approximately three times higher and the phosphate content is 4.5 times higher than in the manure. The results clearly indicate the importance of earthworms' role in enriching vermicompost. Both are strongly influenced by the activities of soil invertebrates, such as earthworms and nematodes. An insight into their ecological roles and interactions is essential in the design of sustainable soil management practices. Effects of Vermicompost on Soil Health and Plant Resistance Several studies [13–19] have investigated nematode and earthworm interactions and the effect of vermicompost on pest resistance, especially against soil-borne nematodes. Vermicompost application has been observed to suppress pathogenic microorganisms and insect pests, decrease nematode damage to crops (including rice by 82%). Its protective effect is not straightforward but involves systemic responses in plants – increasing expression of defensive genes associated with the enzymes: lipoxygenase, phospholipase D and cysteine protease. Furthermore, the performance of plants is also improved by vermicompost: increased production of plants by up to 30–70%, faster seed germination, and stronger growth. This puts it in good condition as an organic alternative to synthetic fertilizers and pest control agents. Nematode diversity in some substrates Experimental data showed the number of different ecological groups of nematodes in the substrates treated by earthworms was high. Nematodes were found in 24 species of bacterial-feeding nematodes, 13 species of omnivores, 2 families of fungal-feeding nematodes (Tylenchidae, Leptonchidae), 3 species of predatory nematodes, and 9 species of plant feeding nematodes in earthworm casts compared to cattle manure. Moreover, nematodes were not identified in the intestinal tract of the earthworms, indicating that the nematode populations are maintained outside of the stomach or in the substrate environment rather than by ingestion. Interestingly, grape leaf-fed vermicompost revealed no nematode presence, whereas cattle manure-fed vermicompost hosted multiple families including Aporcelaimellus, Eudorilaimus, Mesodorilaimus, and Paraxonchium. Multiple tests suggested that species compositions shifted in the late detection of predatory nematodes like Coomansus parvus and later in fungal-feeding nematodes. Vermicompost, Fungal Activity and Nematode Suppression Vermicompost is a known nematode suppressing medium used to host fungi. These fungi synthesize antibiotics that eliminate soil pathogens, and create sticky hyphal traps that trap and kill nematode species. This biological antagonism decreases populations of phytoparasitic nematodes, acting as a potent biological control. Experiments also verified the fungistatic activity of vermicompost [27, 28] and revealed that organic fertilizers promote predatory fungi much more efficiently than mineral fertilizers. This mechanism enhances the compost protective capability against nematode-induced crop damage. Ecological Adaptation and Nematode Group Distribution Nematodes are able to adapt to ecological conditions e.g., climate, soil type, plant hosts, and biocenosis. Such factors also affect earthworm activity and compost diversity. This work investigates the comparative distribution of nematode ecological groups of manure and vermicompost substrates. The main comparative studies were based on the distributions of natural nematodes and their ecological groups in raw manure and vermicomposted. Ecological groups breakdown was assessed (see Fig. 4) showed:

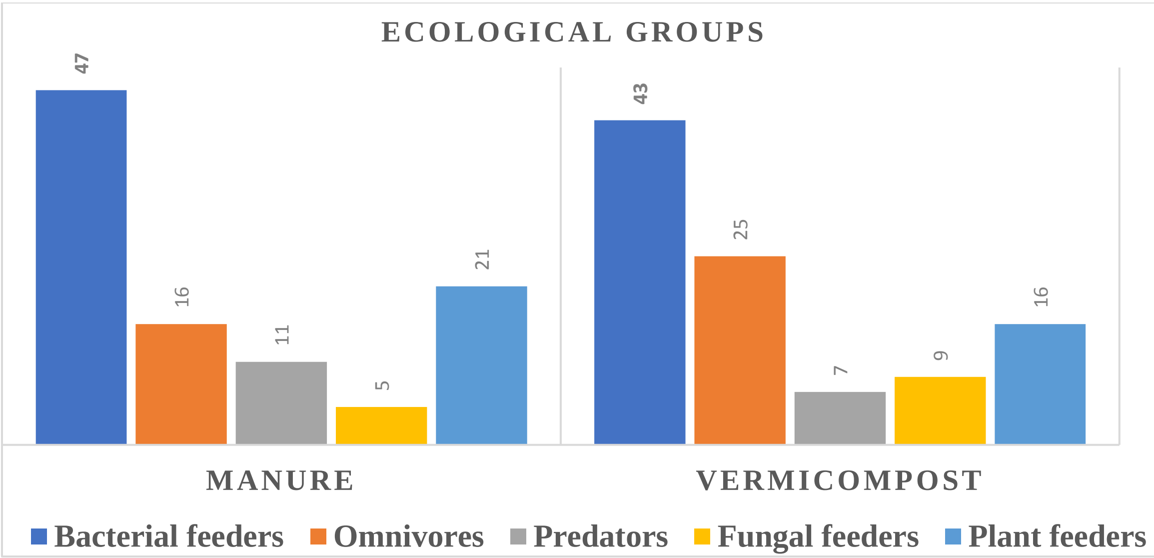

Fig. 4, Relative abundance of nematode ecological groups in manure and vermicompost

This distribution illustrates vermicompost's enrichment effect on microbial grazers as well as its stability to keep harmful nematodes to a minimum.

4 Conclusion

Earthworms represent important sources of soil enrichment, not only by biological activity but also as hosts to various soil organisms, including over forty nematode species from the families of Dioctophymidae, Capillaridae, Subuliridae, Rhabditidae and Drilonematidae [24]. Over 54 nematode forms have been described, of which 32 species have been identified. Of these bacterivores represent approximately 45%, while plant-feeders (10 species) and fungal-feeders (4 species) follow. The large geographic distribution of these species' points to their ecological ubiquity in all habitats. Faunal studies reveal little difference in nematode taxonomic structures across the sample sites, compared to other research sites. Biochemical analysis supports the finding that organic matter concentration in biohumus is five times more than in untreated soil and 5% greater than that in raw manure, with a clear indication of how composted waste would add value. Well-matured compost effectively reduces nematode spread, and it is known that mature compost is a very viable soil remedy for the prevention of nematode growth. Earthworm casts and organic mulch also provide similar benefits. The power and strength of earthworm populations, including the Californian Red Wigglers, had doubled after hay was added to manure — an essential dietary product, laboratory experiments showed. Whereas, earthworms refrained from using rapeseed substrates, probably influenced by its high caloric content (419.16) and oil content (15.32%). These assays validate earthworms' primary contribution to enriching organic fertilizers and have practical implications for the farming community. Increasing the use of vermicompost will also result in better soil quality, higher crop performance and less reliance on chemical inputs into soil. Choosing the most productive worm populations for local use makes it cost-effective and sustainable as a model for biohumus production and organic waste recycling. The significance of this study is given credence to increasing the exposure of Georgian farmers and agricultural stakeholders to vermitechnologies and their ecological and economic advantages. Taking soil biology as a regenerative resource, vermitechnology offers a way of moving towards recovery, environmental preservation and food security.

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