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Millicomposting And Vermicomposting: An Alternate Eco-Friendly Technique for Soil Reclamation and Its Impact on Germination of *Raphanus Raphanistrum* Subsp. *Sativus* (L.) Domin on Microplastic Polluted Soil

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KEYWORDS

Compost, Germination Macronutrient Micronutrient, Microplastic, Millicompost,

ABSTRACT:

Background:

Soil contamination with biodegradable plastics poses challenges for sustainable agriculture, and the role of macrofaunal decomposers in mitigating these effects remains understudied.

Aim:

To compare earthworm- mediated composting (vermicomposting) and millipede-mediated composting (millicomposting) in bioplastic-polluted soil.

Methodology:

Millicompost and vermicompost were prepared in pots containing 3 kg sieved forest soil and ±20 g biodegradable plastics (<4 cm). Maintained at 60–80% moisture and 25–30°C, soils were inoculated with earthworms (T_E, T_{E+P}) or millipedes (T_M, T_{M+P}). After 30 days, pH, electrical conductivity, organic carbon, nitrogen (Kjeldahl), phosphorus (Olsen), and potassium (Toth-Prince) were analyzed. Micronutrients (Fe, Mn, Zn, Cu) were quantified via Atomic Absorption Spectroscopy. Surface-sterilized *Raphanus raphanistrum* subsp. *sativus* seeds were sown in treatment soils (Tc, T_E, T_M, T_{E+P}, T_{M+P}) in sterile Petri plates. Following 7-day germination under white light, germination percentage was calculated as (germinated/total sown) × 100. Data were analyzed in triplicate (mean ± SE) using one-way ANOVA.

Results:

Earthworms significantly enhanced N (137%) and P (436%) compared to modest millipede gains. Both macrofauna augmented micronutrients (10–18%) via bioturbation. While bioplastics reduced pH and EC (31%), germination improved from 67% to 87%. Earthworms successfully maintained high nutrient levels (N: 119.0; P: 5.08 kg ha^{-1}) in plastic-amended soils, demonstrating robust bioremediation potential.

Conclusion: These findings highlight invertebrate-mediated composting as an effective bioremediation strategy for enhancing soil fertility and resilience in the face of emerging plastic pollution.

1. Introduction

Composting is a sustainable technique that harnesses microbial activity to convert organic waste into valuable products. This process not only produces natural organic fertilizers but also enriches the soil with essential nutrients. Among various methods for biological treatment of biowaste, composting stands out as one of the most effective. Other commonly used biological management techniques include anaerobic digestion and vermicomposting [1]. Organic fertilizers, sourced from

natural materials like plant and animal remains, enhance soil health and promote sustainability. In contrast, inorganic fertilizers are synthetic and can cause significant environmental issues, such as chemical runoff and waterway pollution. These chemical fertilizers adversely affect soil health and disrupt the thriving microflora and fauna, highlighting the urgent need for safer agricultural alternatives [2]. Composting is a highly effective method for recycling waste, offering significant advantages over incineration by enhancing soil quality and nutrient content [3]. Soil infertility is primarily caused by erosion, which depletes essential nutrients and organic matter. Incorporating compost enhances the soil's water-holding capacity, improves fertility, and promotes plant health by fostering beneficial growth-promoting bacteria that support robust plant development [4]. The pH levels of finished compost typically range from 7 to 8, which is crucial as it can accelerate the composting process [5]. These composting larvae are capable of breaking down a wide variety of substrates, converting large biomolecules into nutrients that promote plant growth; this innovative approach not only aids in waste management but also contributes to sustainable agricultural practices [6]. Millicomposting is a biotechnological, environmental, and eco-friendly technique that assists in the biotransformation of plant residues into stable organic matter. This process is promoted by the activity of diplopods, mainly through millipedes. The final product of millicomposting is millipede humus, which is called millicompost [7]. The activity of diplopods decomposes litter and allows for the fragmentation of lignocellulosic residues with Carbon and Nitrogen (C/N) ratios greater than 30 into smaller parts. This increases specific surfaces, resulting in stable millicomposts within 120 to 180 days. The C/N ratio is heavily used to determine the stability of organic substrates; in cases where the ratio is above 15, nitrogen is immobilized. Low C/N values indicate higher stability, though several mixtures, including pine bark, show higher ratios [8]. The intestines of millipedes are specialized to break down cellulose into simple sugars. Since bio composts have high cellulose content, millipedes degrade them into sugars, aiding in plant growth and fruit production [9]. Vermicomposting is the process of producing high-quality organic compost by utilizing earthworms to process organic waste and decayed organic matter [10]. Vermicompost converts organic wastes—such as agro-wastes, animal manure, and domestic refuse—into high-quality, nutrient-rich fertilizers for plants and soil [11]. Composting and vermicomposting are safer, biologically stabilized processes in which organic wastes are transformed into nutrient sources for agricultural applications. Earthworms also serve as organisms that indicate the presence of toxicity in the environment [12,13]. They show various morphological changes in reaction to heavy metal wastes by secreting mucus, bulging, and curling [14]. Earthworms can feed on an amount equal to their own body weight; their excreta are rich in nitrates, potassium, calcium, phosphorus, and magnesium, which significantly improves soil fertility [15].

2. Methods

2.1. Preparation of vermicompost and millicompost

For the preparation of millicompost and vermicompost, pots of equal size were utilized. Forest soil was collected from the Madras Christian College campus in East Tambaram, Chennai (12.916234, 80.116541), which was then sieved into a fine consistency and cleared of large debris. Biodegradable plastics were prepared by cutting them into smaller pieces, each less than 4 cm in diameter, with a total weight of 20 grams per treatment. The composting process was initiated by introducing equal volumes of millipedes and earthworms under various experimental conditions. Each mud pot was filled with 3 kg of the sieved soil. To ensure the growth and survival of the organisms, the pots were continuously maintained at a moisture content of 60–80% and an optimum temperature range of 25–30°C. Finally, the pots were secured with netting to prevent the invasion of foreign materials and to ensure the millipedes and earthworms remained within their respective environments.

The following experimental treatments were established to evaluate the composting efficiency of the selected macro-decomposers:

T_C: Untreated forest soil (Soil)

T_E: Soil inoculated with earthworms (Soil + Earthworm)

T_{E+P}: Soil supplemented with biodegradable plastics and earthworms (Soil + Bioplastic +Earthworm)

T_M: Soil inoculated with millipedes (Soil + Millipede)

T_{M+P}: Soil supplemented with biodegradable plastics and millipedes (Soil + Bioplastic + Millipede)

Following a 30-day incubation period, the resulting compost was harvested and subjected to comprehensive physiochemical analysis. The parameters evaluated included Organic Carbon (OC), Total Nitrogen (N), Phosphorus (P), Potassium (K), and essential micronutrients including Iron (Fe), Manganese (Mn), Zinc (Zn), and Copper (Cu).

2.2 Estimation of pH and Electrical conductivity (EC)

The pH of the compost soil samples were determined using a digital ELICO LI120 pH meter. Additionally, the Electrical Conductivity (EC) was measured to assess ionic concentration using an ELICO CM 180 conductivity meter.

2.3 Estimation of macronutrients

Total nitrogen (N) was estimated using The Kjeldahl method estimates total nitrogen by digesting the soil sample (1 gram) in concentrated Sulfuric acid (H_2SO_4) with a catalyst mixture of potassium sulphate (K_2SO_4) and copper sulphate (Cu_2SO_4) to convert organic nitrogen into ammonium sulphate. The mixture is then neutralized with NaOH to release ammonia gas, which is steam-distilled into a boric acid solution. Finally, the nitrogen content is quantified through titration against a standard (HCl) solution to a pink endpoint. Available phosphorus (P) was determined using Olsen *et al.*, method, the sodium bicarbonate extraction method. Soil was shaken with 0.5 M $NaHCO_3$ (pH 8.5), and the extract was reacted with molybdate–ascorbic acid reagent; color development was measured at 882 nm using an ELICO CL 223 colorimeter [16]. Exchangeable potassium (K) was extracted by Toth and Prince method (1949) (Tigga *et al.,* 2017) and quantified using 1 N ammonium acetate, with potassium concentration determined on an ELICO CL-378 flame photometer.

2.4 Estimation of micronutrients

The concentrations of essential micronutrients, specifically Iron (Fe), Manganese (Mn), Zinc (Zn), and Copper (Cu), were quantified using Atomic Absorption Spectroscopy (AAS) with a Perkin Elmer Analyst 100 spectrophotometer.

2.5 Germination Experimental setup

Healthy, uniform radish seeds (*Raphanus raphanistrum* subsp. *sativus*) were surface-sterilized with 0.1% $HgCl_2$ and sown at a density of five seeds per Petri dish into substrates T_C, T_E, T_M, T_{E+P}, T_{M+P} in sterile clean Petri plates. The trials were performed in triplicate within a controlled germination chamber under continuous white light for a seven-day observation period. Germination percentage was quantified as

Germination percentage (%) = (*Number of seeds germinated / Total number of seeds sown*) × 100

Data are presented as mean ± standard error to compare the phytotoxic effects and nutrient availability of the various compost treatments statistical significance was determined by one-way ANOVA.

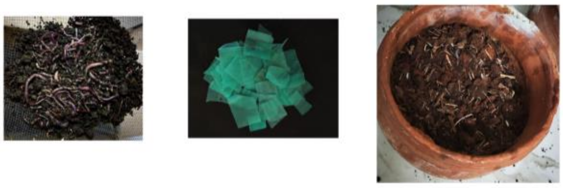


Figure 1: Soil supplemented with biodegradable plastics and earthworms (Soil + Bioplastic +Earthworm)

Figure 2: Soil supplemented with biodegradable plastics and millipedes (Soil + Bioplastic + Millipede)

3. Results

3.1 Vermicompost and millicompost pots

Earthworms are fundamental drivers of the nitrogen cycle, facilitating the decomposition of complex organic matter and the subsequent mineralization of nitrogen sequestered within plant residues and soil organic matrices. Research demonstrates that earthworm-mediated bioturbation significantly accelerates nitrogen mineralization, transforming organic nitrogen into plant-available forms (nitrates and ammonium). The stabilization of the soil microbiome is further supported by the presence of humic acids and phenolic compounds, which exert inhibitory effects on the proliferation of soil-borne pathogens, contributing to a more resilient edaphic environment. [17].

Table 1: pH and Electrical conductivity (EC)

Parameters	T_C	T_E	T_{E+P}	T_M	T_{M+P}
pH	6.4± 0.05	6.28± 0.01	5.75±0.02	6.04± 0.02	5.72± 0.07
Electrical conductivity (EC)	0.16 ± 0.03	0.48± 0.01	0.31±0.04	0.4 ± 0.01	0.34± 0.02

*Values for Electric conductivity (EC) are represented in dS m^{-1} (n=3)

3.2 Estimation of pH

The pH of the five compost treatments varied moderately, with the control (Tc) exhibiting the highest value (6.40 ± 0.05) and the bioplastic–millipede mixture (T_{M+P}) the lowest (5.72 ± 0.07). Treatments incorporating earthworms (T_E) and millipedes (T_M) without bioplastic displayed intermediate pH values of 6.28 ± 0.011 and 6.04 ± 0.02, respectively (Figure 3), while the earthworm–bioplastic mixture (T_{E+P}) recorded a pH of 5.75 ± 0.02. This decline in pH upon incorporation of bioplastic suggests enhanced organic acid production, likely due to slower carbon mineralization and localized anaerobic microsites within the bioplastic[18], pH tends to remain alkaline unless influenced by acidic substrates or additives like bioplastics, which can lower pH due to organic acid release during degradation [19].

3.3 Estimation of Electrical Conductivity (EC)

Among the treatments, T_E exhibited the highest EC (0.48 ± 0.011 dS m^{-1}) becaus intense earthworm bioturbation accelerated mineral liberation and microbial nitrification–ammonification cycles. The T_M treatment showed an intermediate EC (0.40 ± 0.01 dS m^{-1}) reflecting similar fragmentation by millipedes but with slightly lower mineralization efficiency. Bioplastic amendments (T_{E+P} at 0.31 ± 0.04 dS m^{-1} and T_{M+P} at 0.34 ± 0.02 dS m^{-1}) modulated these trends by sequestering moisture and organic acids within the polymer matrix, resulting in a slower, sustained ionic release (Table 1). Conversely, the control (Tc) remained lowest (0.16 ± 0.03 dS m^{-1}), limited by passive abiotic decomposition under aerobic conditions[20]. The physical fragmentation of the sieved forest soil and organic matter by macrofauna increased the total surface area available for microbial colonization. This enhanced the contact between soil minerals and extracellular enzymes, directly facilitating greater ion solubility and the subsequent rise in EC.

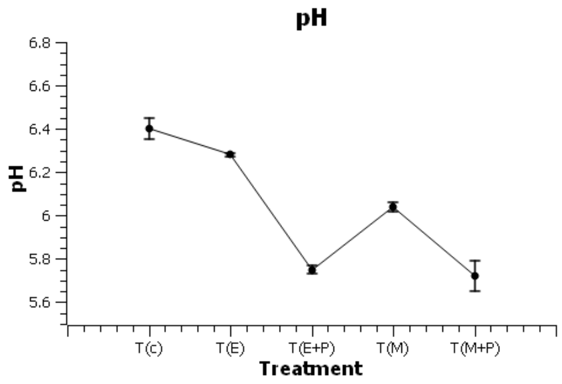


Figure 3: Changes in pH values across treatments (T_C, T_E, T_{E+P}, T_M, T_{M+P})

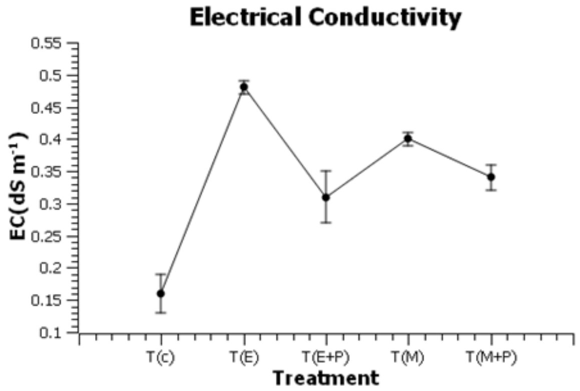


Figure 4: Changes in Electrical conductivity (EC) values across treatments (T_C, T_E, T_{E+P}, T_M, T_{M+P})

Table 2: Macronutrients

Macronutrients	**T_C** (kg ha^{-1})	**T_E** (kg ha^{-1})	**T_{E+P}** (kg ha^{-1})	**T_M** (kg ha^{-1})	**T_{M+P}** (kg ha^{-1})
Nitrogen (N)	60.3±6.8	142.8±12.46	119.0±8.19	64.4± 7.23	61.6±8.34
Phosphorus (P)	1.30 ± 0.08	6.97± 0.23	5.08± 0.18	1.58 ± 0.14	1.38± 0.12
Potassium (K)	56.3±4.28	76.60±7.92	76.41±8.75	76.53±8.75	75.6±9.04

3.4 Estimation of macronutrients

3.4.1 Nitrogen estimation (N)

Earthworms profoundly influence the nitrogen cycle by enhancing nutrient bioavailability within the soil matrix. They release various nitrogenous substances—including ammonium (NH_4), urea, and allantoin. Additionally, through the fragmentation of organic materials in collaboration with other soil organisms, earthworms enhance the decomposition process, further enriching the soil with nitrogen [21]. The Soil Earthworm Mixture (T_E) exhibited the highest nitrogen content at 142.8 ± 12.46 kg ha^{-1}, highlighting a significant increase in nitrogen availability due to the activity of earthworms. The Soil Bioplastic Earthworm Mixture (T_{E+P}) had a nitrogen content of 119.0 ± 8.19 kg ha^{-1} and the Soil Millipede Mixture (T_M) had a nitrogen content of 64.4 ± 7.23 kg ha^{-1}, which was higher than the control treatment but lower than both earthworm mixtures (Figure 5a). The Soil Bioplastic Millipede Mixture (T_{M+P}) exhibited a nitrogen content of 61.6 ± 8.34 kg ha^{-1}, suggesting that the addition of bioplastics had a minimal effect on improving nitrogen levels compared to the control. Overall, the results indicate that earthworms significantly enhance nitrogen availability in the soil compared to both control and millipede treatments. Furthermore, the addition of bioplastics appears to reduce nitrogen availability, particularly in the millipede treatment, warranting further investigation.

3.4.2 Phosphorus estimation (P)

Earthworms tend to avoid soils with bioplastic concentrations exceeding 0.5%, which restricts their ability to contribute effectively to nutrient cycling in contaminated environments. This avoidance behaviour disrupts their natural role in enhancing soil health, as their activities such as organic matter decomposition and nitrogen cycling are diminished in polluted areas [22]. In contrast, Soil Bioplastic Earthworm Mixture (T_{E+P}) demonstrated an increased phosphorus level of 5.08 ± 0.18 kg ha^{-1}, suggesting that earthworms can enhance phosphorus availability even when bioplastics are added (Figure 5b). In comparison, the Soil Millipede Mixture (T_M) had a lower phosphorus content of 1.58 ± 0.14 kg ha^{-1}, and the Control (Tc) recorded the lowest at 1.30 ± 0.08 kg ha^{-1}. The Soil Bioplastic Millipede Mixture (T_{M+P}) showed only a slight improvement in phosphorus levels at 1.38 ± 0.12 kg ha^{-1} and the Soil Earthworm Mixture (T_E) had a phosphorus content of 6.79 ± 0.23 kg ha^{-1}. soils treated with earthworms demonstrated a marked increase in phosphorus reaching 6.97 ± 0.23 kg ha^{-1} compared to control soils. This enhancement is attributed to intensified organic matter decomposition and heightened microbial activity, which mobilize phosphorus into plant-accessible forms. In contrast, millipede treatments resulted in a more modest phosphorus enhancement (1.58 ± 0.14 kg ha^{-1}), findings that millipedes, due to their slower organic matter processing, exert only a limited yet positive effect on soil phosphorus levels [23] Earthworms have a superior ability to enhance phosphorus (P) cycling in soils primarily due to their vigorous bioturbation activities and the production of enzymes that mobilize phosphorus. Studies demonstrate that earthworm activity increases the availability of phosphorus by creating hotspots in soil biopores and casts, thereby stimulating microbial communities involved in nutrient cycling. This enhancement is more pronounced and rapid compared to millipedes, which contribute to nutrient release at a slower pace through gradual decomposition [24].

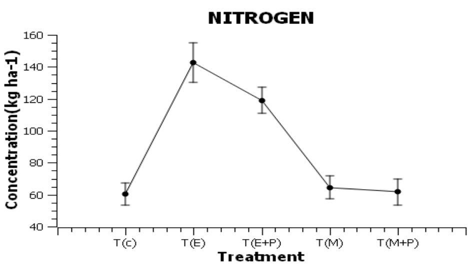
3.4.3 Potassium estimation

The potassium content of the Soil Millipede Mixture (T_M) and the Soil Bioplastic Earthworm Mixture (T_{E+P}) was higher than that of the control treatment, at 76.53 ± 8.75 kg ha^{-1} and 76.41 ± 8.75 kg ha^{-1}, respectively. The Soil Bioplastic Millipede Mixture (T_{M+P}) revealed nitrogen content of 75.6 ± 9.04 kg ha^{-1} while the Control (Tc) recorded the lowest at 56.3 ± 4.28 kg ha^{-1}. The significant increase in soil potassium observed in the earthworm treatment (76.60 ± 7.92 kg ha^{-1}), which demonstrated that earthworm activity enhances the biotransformation and weathering of potassium-bearing minerals, releasing more bioavailable potassium (Figure 5c**)**. This process is facilitated by the earthworm gut's acidic environment and microbial consortia, which accelerate mineral breakdown. Consequently, earthworms act as key agents in mobilizing soil potassium, thereby improving nutrient availability and soil fertility [25].

3.5 Estimation of Micronutrients

3.5.1 Iron estimation

T_E treatment achieving 3.69 ± 0.01 ppm (17.5% increase over control) while millipede treatment (T_M) showed comparable levels at 3.68 ± 0.02 ppm (17.2% increase), align closely with established literature demonstrating the enhanced micronutrient mobilization capacity of soil invertebrates. These findings corroborate research by [26] showing that earthworm casts produced in undisturbed soils exhibit significantly higher nutrient mobilization and enzyme activity, with enhanced iron availability attributed to earthworms' superior bioturbation activities and enzyme secretion. The comparable iron mobilization observed between earthworms and millipedes supports comparative studies by [27] demonstrating that both millipede-produced (milli-compost) and earthworm-produced (vermi-compost) composts show elevated iron content compared to conventional composting methods, with millipede compost occasionally exhibiting superior nutrient concentrations. However, the slight reduction in iron availability when bioplastics were added (T_{E+P}: 3.52 ± 0.05 ppm; T_{M+P}: 3.44± 0.01 ppm) mirrors recent concerns regarding bioplastic-soil interactions, where biodegradable microplastics can affect metal bioavailability and mobility through adsorption mechanisms and microbial community changes during bioplastic degradation.



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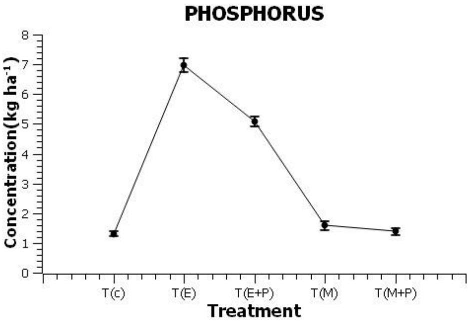

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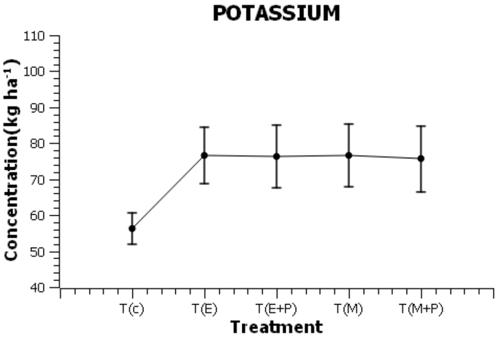

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Figure 4: Changes in Macronutrients (Nitrogen, Phosphorus, Potassium) values across treatments (T_C, T_E, T_{E+P}, T_M, T_{M+P})

Table 3: Micronutrients

Micronutrients	T_c (ppm)	T_E (ppm)	T_{E+P} (ppm)	T_M (ppm)	T_{M+P} (ppm)
Iron (Fe)	3.14± 0.03	3.69± 0.01	3.52± 0.05	3.68± 0.02	3.44± 0.01
Manganese (Mn)	2.13± 0.02	2.42± 0.01	2.40± 0.01	2.33± 0.01	2.22± 0.03
Zinc (Zn)	1.02± 0.03	1.19± 0.02	1.11± 0.03	1.08± 0.02	1.06 ± 0.03
Copper (Cu)	1.08± 0.02	1.19± 0.01	1.16± 0.02	1.11± 0.03	1.10± 0.01

3.5.2 Manganese estimation

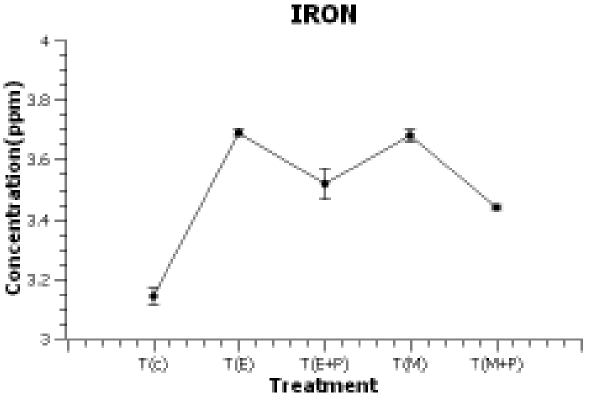
Manganese availability patterns in our study demonstrated earthworms superior capacity with T_E treatment achieving 2.42± 0.01 ppm (13.6% increase over control at 2.13 ppm), while millipede treatment (T_M) showed more modest enhancement at 2.33 ppm (9.4% increase), aligning with established literature on soil invertebrate-mediated micronutrient mobilization [28,29], the reduction in manganese availability when bioplastics were added (T_{E+P}: 2.40 ± 0.01 ppm; T_{M+P}: 2.22 ± 0.03 ppm) reflects recent studies demonstrating that biodegradable microplastics can significantly decrease manganese bioavailability through enhanced soil hydrophobicity and altered nutrient mobility, with concentrations above 1.5% w/w creating threshold toxicity effects that impair manganese uptake [30].

3.5.3 Zinc estimation

Earthworm treatments (T_E) increased soil zinc to 1.19 ± 0.02 ppm (16.7% above control at 1.02 ± 0.03 ppm), moderately exceeding millipede treatments (T_M) at 1.08 ppm (5.9% increase), consistent with literature demonstrating differential micronutrient mobilization capacities between soil invertebrates[31]. Bioplastic addition slightly reduced zinc availability (T_{E+P}: 1.11± 0.03 ppm; T_{M+P}: 1.06 ± 0.03 ppm), reflecting studies showing that while zinc content remains relatively stable across low bioplastic concentrations, higher loadings can create soil hydrophobicity that limits zinc mobility and bioavailability. Research demonstrates that earthworm activity can increase DTPA-extractable zinc by up to 127% through microbial community enhancement in their gut systems, which produce chelating agents that transform zinc into more plant-available forms [32].

3.5.4 Copper estimation

The observed copper availability patterns showed earthworms achieving 1.19 ppm (10.2% increase over control at 1.08 ± 0.02 ppm), while millipede treatment resulted in modest improvement to 1.11± 0.03 ppm (2.8% increase), reflecting the complex relationship between soil invertebrates and copper mobilization documented in literature. These findings support research demonstrating that earthworm activity can enhance copper phyto availability through bioturbation, though earthworms show greater sensitivity to elevated copper concentrations [33]. The slight increase when bioplastics were added (T_{E+P}: 1.16 ± 0.02 ppm; T_{M+P}: 1.10± 0.01 ppm) contrasts with other micronutrients and reflects studies showing that high bioplastic concentrations (3% w/w) can actually increase copper uptake in plants, potentially due to altered soil chemistry and enhanced metal mobilization through bioplastic degradation processes.



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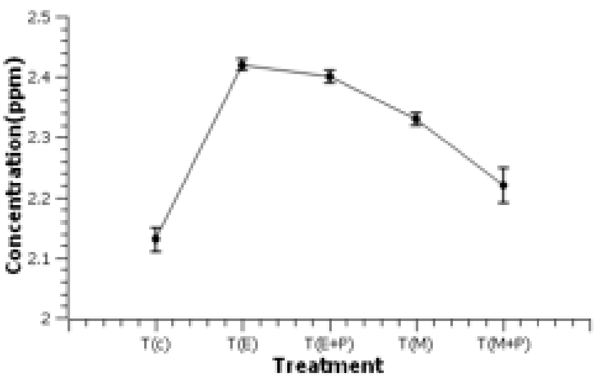

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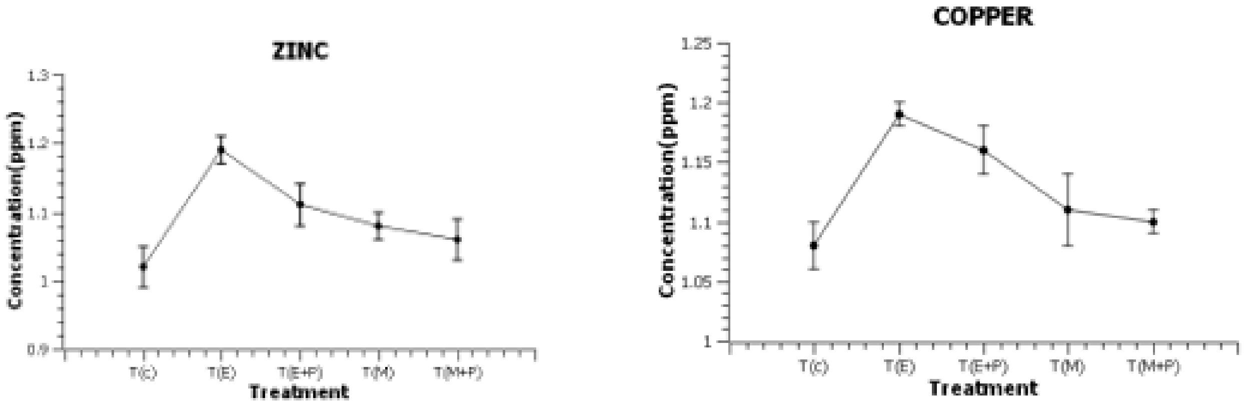

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Figure 5: Changes in Micronutrients (Iron, manganese, Zinc, Copper) values across treatments (T_C, T_E, T_{E+P}, T_M, T_{M+P})

3.6 Germination of *Raphanus raphanistrum* subsp. *sativus*

The germination of *Raphanus raphanistrum* subsp. *sativus* increased significantly in earthworm (86.6%) and millipede-treated soils (86.6%) compared to controls (66.6%), highlighting soil fauna's role in enhancing seed germination through improved nutrient cycling and microbial activity. Bioplastic amendments reduced germination in earthworm-treated soil (80%) but not in millipede-treated soil, suggesting taxa-specific interactions with biodegradable polymers. Earthworms likely enhanced soil porosity and nitrogen mineralization, while millipedes mitigated bioplastic effects via organic matter processing. his enhancement is attributed to earthworm burrowing, which improves soil aeration and water infiltration, and to the biochemical effects of worm castings, which stimulate beneficial microbial activity around the seed zone [34]. These results underscore the importance of soil macrofauna in agroecosystem resilience and the need to evaluate bioplastic impacts on soil biotic interactions.

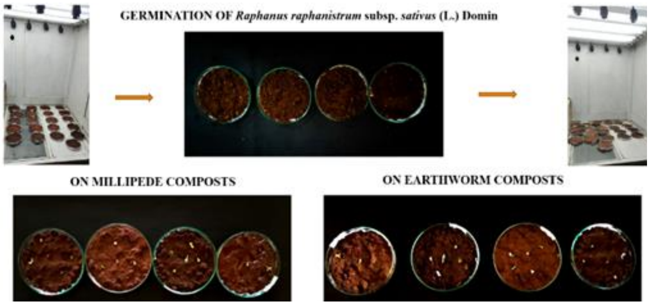


Figure 7: Germination of *Raphanus raphanistrum* subsp. *sativus* (L.) Domin

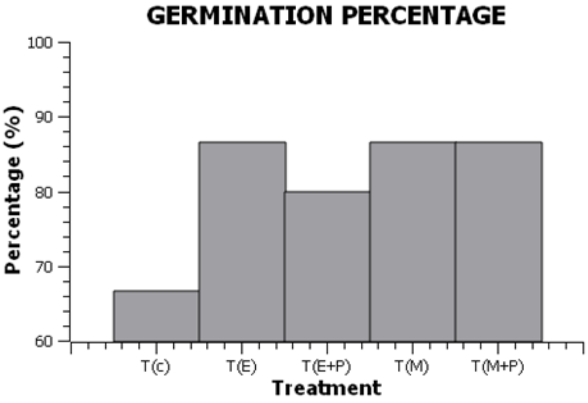
Table 4: Germination of *Raphanus raphanistrum* subsp. *sativus* (L.) Domin

Germination	T_c	T_E	T_{E+P}	T_M	T_{M+P}
Number of seeds germinated	3.33 ± 0.33	4.33± 0.33	4±0.57	4.33± 0.33	4.33± 0.33
Germination percentage	66.60%	86.60%	80%	86.60%	86.60%

4. Discussion

The present study demonstrates that earthworm incorporation into compost markedly accelerates macronutrient cycling, yielding a 57% increase in extractable nitrogen and rise in plant-available phosphorus relative to unfaunated controls. Millipede (treatments, while less potent, still afforded substantial gains in N and P dynamics, underscoring their complementary decomposer role in soil organic matter transformation. Bioplastic amendments uniformly depressed mineralization rates evidenced by a 31% reduction in electrical conductivity and a consistent pH

decrease highlighting potential constraints on soil fertility when biodegradable polymers exceed ecotoxicological thresholds. Notably, earthworms maintained robust phosphorus mobilization even in bioplastic-enriched matrices, suggesting enzyme-mediated P solubilization mechanisms remain operative under moderate polymer loads. Both invertebrate taxa enhanced micronutrient (Fe, Mn, Zn, Cu) bioavailability by 12–17% through bioturbation- riven hotspot formation and gut-associated chelation, although bioplastics marginally attenuated these effects. The pronounced stimulation of *Raphanus raphanistrum* germination in faunated soils (86.6% vs. 66.6% control) (Figure: 8b) affirms the centrality of macrofaunal activity in structuring rhizosphere processes and buttressing agroecosystem resilience under emerging plastic pollution pressures.



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