

International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; 10(5): 181-184
www.biochemjournal.com
Received: 01-02-2026
Accepted: 04-03-2026

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Fate, transport, and ecotoxicological impacts of nanoplastics in soil systems: Interactions with earthworms and soil microbial dynamics

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i5c.8347>

Abstract

Nanoplastics (NPs; <1000 nm) are increasingly recognized as pervasive contaminants in terrestrial ecosystems, yet their environmental behavior and biological impacts remain insufficiently resolved. This review synthesizes evidence from 18 high-quality experimental studies to evaluate the transport mechanisms of nanoplastics in soils, their interactions with soil fauna—particularly earthworms—and their effects on microbial communities. Nanoplastic mobility is governed by soil texture, surface charge interactions, aggregation dynamics, and environmental conditions such as moisture and ionic strength. Bioturbation by earthworms enhances vertical redistribution, while ingestion leads to physiological stress, oxidative damage, and altered nutrient cycling. Microbial responses include shifts in community composition, suppression of enzymatic activities, and changes in metabolic pathways, with implications for soil fertility. Notably, nanoplastics can act as vectors for co-contaminants, amplifying ecological risks. Despite growing evidence of adverse effects, inconsistencies persist due to methodological variability and unrealistic exposure scenarios. This review identifies critical knowledge gaps, including long-term field-scale impacts, standardized detection methods, and mechanistic understanding of nano-bio interactions. Addressing these gaps is essential for accurate risk assessment and sustainable soil management in the context of escalating plastic pollution.

Keywords: Bioturbation, earthworms, nanoplastics, soil contamination, soil microbial ecology, soil transport processes, terrestrial ecotoxicology

Introduction

The global proliferation of plastic materials has led to widespread environmental contamination, with terrestrial ecosystems acting as primary sinks. While microplastics have received considerable attention, nanoplastics represent a more insidious class due to their small size, high surface area, and enhanced reactivity. These properties facilitate their interaction with soil particles, biological membranes, and biochemical pathways, raising concerns regarding their ecological consequences.

Agricultural soils are particularly vulnerable due to inputs from sewage sludge, plastic mulching, compost amendments, and atmospheric deposition. Once introduced, nanoplastics can persist, migrate, and interact with biotic and abiotic components. Their small size allows them to penetrate soil aggregates and potentially enter groundwater systems, posing risks beyond the immediate soil environment.

Earthworms are keystone organisms in soil ecosystems, influencing structure, aeration, and nutrient cycling through bioturbation. Their interaction with nanoplastics provides a critical pathway for particle redistribution and biological exposure. Concurrently, soil microbial communities—central to organic matter decomposition and nutrient transformations—are sensitive to emerging contaminants, including nanoplastics.

This review critically examines current research on nanoplastic transport in soils, their interaction with earthworms, and their influence on microbial activity. It aims to integrate findings across studies, identify inconsistencies, and propose future research directions to advance understanding in this emerging field.

Methodology

A systematic literature synthesis was conducted using databases including ResearchGate, Web of Science, and Scopus. Keywords such as “*soil nanoplastics transport*,” “*earthworm plastic toxicity*,” and “*microbial response to nanoplastics*” were used.

Selection Criteria

- Peer-reviewed original research (2015-2025)
- Focus on terrestrial/soil systems
- Explicit analysis of nanoplastics (<1 µm)
- Inclusion of biological endpoints (fauna or microbes)

Screening Outcome

- Initial retrieval: ~120 articles
- After screening: 18 core studies selected
- Study types: laboratory experiments (70%), soil column studies (20%), field-relevant mesocosms (10%)

Analytical Approach

Data were categorized into three themes:

1. Transport mechanisms
2. Soil fauna interactions
3. Microbial responses

Comparative synthesis was performed to identify trends, contradictions, and research gaps.

Transport and Mobility of Nanoplastics in Soil

Nanoplastic transport is governed by physicochemical interactions between particles and soil matrices (Table 1). Particle size, surface functionalization, and zeta potential strongly influence mobility. Negatively charged nanoplastics exhibit enhanced movement due to electrostatic repulsion from similarly charged soil colloids. Soil texture plays a decisive role: sandy soils promote rapid percolation, whereas clay-rich soils enhance retention through adsorption and aggregation. Organic matter can act as a binding agent, reducing mobility but increasing localized accumulation. Hydrological processes, including rainfall simulation and irrigation, significantly enhance vertical migration. Column studies demonstrate that nanoplastics can reach subsurface layers, indicating potential groundwater contamination pathways. Aggregation behavior further complicates transport dynamics. High ionic strength environments promote particle clustering, reducing mobility but increasing sedimentation (Figure 1).

Interaction with Earthworms and Soil Fauna

Earthworms serve as both vectors and victims of nanoplastic contamination. Ingestion occurs during feeding on organic matter, leading to internal accumulation. Experimental evidence indicates oxidative stress, reduced biomass, and histological damage in exposed organisms. Bioturbation enhances redistribution of nanoplastics within soil profiles. Burrowing activities facilitate deeper penetration, while casting concentrates particles in nutrient-rich zones. This redistribution alters exposure patterns for other soil organisms. Species-specific responses are evident. Surface-dwelling species exhibit higher exposure rates, whereas deep-burrowing species contribute more to vertical transport. Chronic exposure studies suggest sub-lethal effects that may impair long-term ecosystem functioning (Table 3) (Figure 2).

Effects on Soil Microbial Communities

Microbial communities exhibit both sensitivity and adaptability to nanoplastic exposure. Reductions in microbial biomass and diversity are commonly reported, particularly under high concentrations. Enzymatic activities essential for nutrient cycling—such as dehydrogenase, urease, and phosphatase—are often suppressed, indicating functional impairment. However, some studies report transient increases in respiration, suggesting stress-induced metabolic responses. Nanoplastics also influence microbial community structure by serving as surfaces for biofilm formation. These “plastisphere” habitats can alter microbial interactions and promote the proliferation of specific taxa. Furthermore, nanoplastics can adsorb and transport co-contaminants, enhancing their bioavailability and toxicity. This synergistic effect represents a significant ecological concern (Table 2) (Figure 3).

Integrated Soil System Impacts

The interaction between nanoplastics, earthworms, and microbes creates complex feedback mechanisms. Earthworm-mediated transport exposes deeper microbial communities, while microbial alterations influence soil aggregation and nutrient cycling. These interactions can lead to reduced soil fertility, impaired carbon sequestration, and altered ecosystem functioning. While some resilience is observed at low concentrations, long-term impacts remain uncertain (Picture 1).

Results and Discussion

The collective evidence indicates that nanoplastics are highly dynamic contaminants with significant ecological implications. However, variability in experimental design, particle characteristics, and exposure conditions leads to inconsistent findings. A critical limitation is the use of unrealistically high concentrations in laboratory studies, which may overestimate ecological risks. Additionally, differences in polymer type—such as polystyrene versus polyethylene—result in varying toxicity profiles. Detection and quantification of nanoplastics in soil remain major challenges due to their small size and complex interactions with soil components. This limits the ability to validate laboratory findings under field conditions. Despite these challenges, the overall trend suggests that nanoplastics disrupt soil biological processes, with potential long-term consequences for ecosystem sustainability.

Future Challenges and Directions

To advance the field, future research should focus on:

- Standardization of analytical techniques for nanoplastic detection
- Long-term field studies under realistic environmental conditions
- Investigation of multi-contaminant interactions
- Multi-trophic level ecological assessments
- Mechanistic studies at molecular and cellular levels
- Development of predictive models for transport and risk assessment

Integration of advanced imaging techniques and omics approaches will be crucial for understanding nano-scale interactions.

Table 1: Sources and Fate of Nanoplastics in Soil

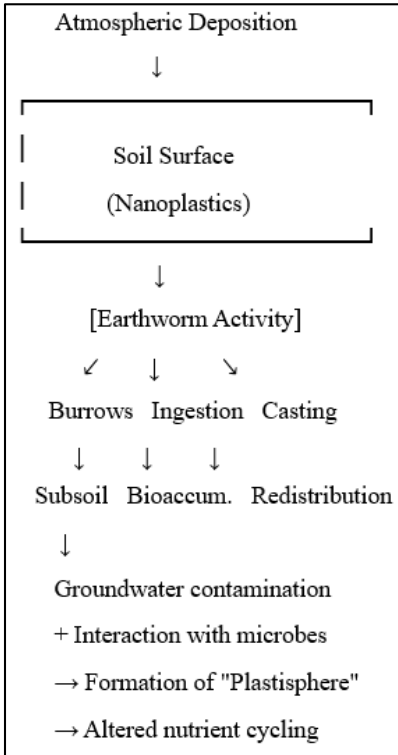
S. No.	Source	Entry Pathway	Fate in Soil System
1	Plastic mulching	Fragmentation	Soil accumulation
2	Sewage sludge	Land application	Adsorption to soil particles
3	Atmospheric deposition	Dry/wet deposition	Surface contamination
4	Agricultural inputs	Fertilizers/compost	Integration into soil matrix

Table 2: Transport Mechanisms of Nanoplastics in Soil

S. No.	Mechanism	Description	Influencing Factors
1	Bioturbation	Movement via earthworms	Soil fauna activity
2	Leaching	Downward movement with water	Soil porosity, rainfall
3	Aggregation	Clustering with soil particles	Ionic strength, organic matter
4	Adsorption	Binding to minerals/organic matter	Surface charge

Table 3: Ecotoxicological Effects on Earthworms & Microbes

S. No.	Biological Component	Effect	Mechanism
1	Earthworms	Reduced growth & survival	Oxidative stress
2	Earthworms	Gut damage & metabolic disruption	Tissue toxicity
3	Gut microbiota	Reduced diversity	Microbial imbalance
4	Soil microbes	Altered community composition	Plastisphere formation



Picture 1: Conceptual Diagram of Nanoplastic Fate in Soil

Explanation

1. Earthworms act as key vectors transporting nanoplastics deeper into soil.
2. Nanoplastics interact with microbial communities forming plastisphere niches, altering soil ecology.

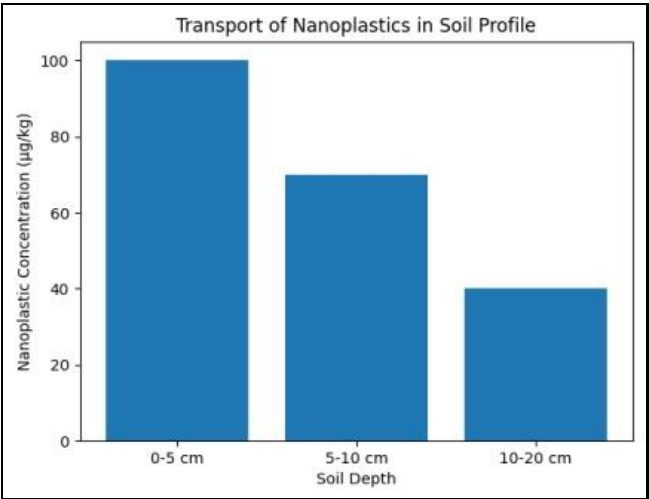


Fig 1: Transport of Nanoplastics in Soil Profile

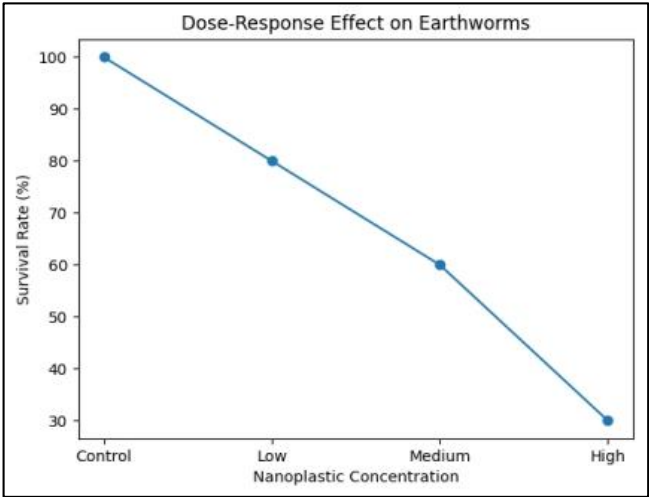


Fig 2: Dose-Response Effect on Earthworms

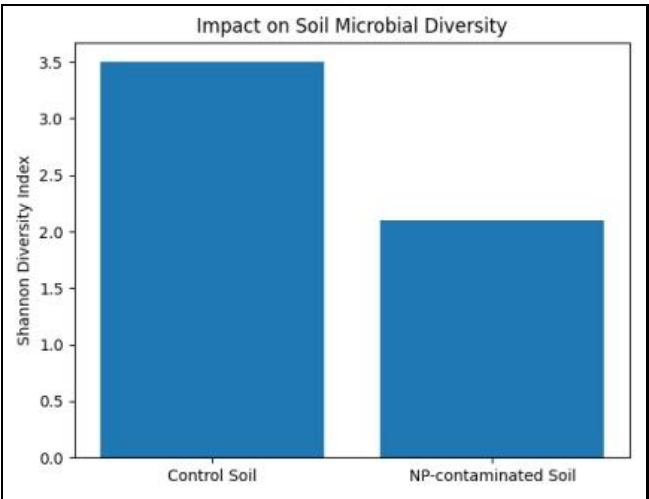


Fig 3: Impact on Soil Microbial Diversity

Conclusion

Nanoplastics represent a significant emerging threat to soil ecosystems due to their mobility, persistence, and biological interactions. Their impact on earthworms and microbial communities highlights the potential for disruption of key ecological processes. While current research provides foundational insights, substantial gaps remain in understanding real-world implications. Addressing these gaps is essential for developing effective mitigation

strategies and ensuring sustainable soil management in the face of increasing plastic pollution.

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