Journal of Agricultural Sciences (JAS) 32(3):552-563
DOI: 10.15832/ankutbd.1886411

J Agr Sci-Tarim Bili
e-ISSN: 2148-9297
jas.ankara.edu.tr

Micro- and Nanoplastic Effects on Nematodes: A Systematic Review of Toxicity Mechanisms, Exposure Characteristics, and Soil Ecological Implications

Sedat Gündoğdu[a,b*], Ece B. Kasapoğlu Uludamar[c], Sümeyya Vuslat Dişkaya[c], Salim Avcıoğlu[c], İbrahim Halil Elekcioğlu[c]

[a]*Sabancı University, Istanbul Policy Center, Istanbul, TÜRKIYE*
[b]*Çukurova University, Faculty of Fisheries, Adana, TÜRKIYE*
[c]*Çukurova University, Faculty of Agriculture, Department of Plant Protection, Adana, TÜRKIYE*

ARTICLE INFO
Review Article
Corresponding Author: Sedat Gündoğdu, E-mail: sgundogdu@cu.edu.tr
Received: 10 February 2026 / Revised: 12 March 2026 / Accepted: 19 March 2026 / Online: 28 July 2026

Cite this article
Gündoğdu S, Kasapoğlu Uludamar E B, Dişkaya S V, Avcıoğlu S, Elekcioğlu İ H (2026). Micro- and Nanoplastic Effects on Nematodes: A Systematic Review of Toxicity Mechanisms, Exposure Characteristics, and Soil Ecological Implications. *Journal of Agricultural Sciences (Tarim Bilimleri Dergisi),* 32(3):552-563. DOI: 10.15832/ankutbd.1886411

ABSTRACT
Micro- and nanoplastics (MNPs) are now widely recognized as pervasive contaminants in terrestrial ecosystems. However, their effects on soil nematodes remain largely confined to dispersed experimental studies, resulting in a fragmented evidence base that necessitates integrative synthesis. In this review, we consolidate current knowledge on the biological and ecological consequences of MNP exposure in nematodes, with particular emphasis on agricultural and greenhouse soil environments where plastic inputs are especially intensive. To achieve this, we followed PRISMA guidelines and screened 251 records retrieved from the Web of Science and Scopus databases. After duplicate removal and eligibility assessment, 166 studies were retained for qualitative evaluation, of which 154 provided extractable experimental datasets suitable for comparative analysis. Species representation revealed a pronounced taxonomic skew, with *Caenorhabditis elegans* serving as the dominant experimental model in more than 150 studies. In contrast, other free-living and entomopathogenic nematodes were only sporadically investigated. Exposure characterization further demonstrated a strong reliance on polystyrene (PS)-based materials, with both micro- and nanopolystyrene frequently employed in experimental designs, followed by polyethylene (PE) as the second most studied polymer. Particle size distributions showed a marked bias toward nanoscale fractions—most commonly around ~100 nm—whereas larger microplastics more representative of soil contamination profiles were comparatively underexplored. Reported exposure concentrations spanned a wide gradient, ranging from environmentally relevant μg L^{-1} levels to elevated mechanistic doses designed to elicit toxic responses. Across studies, recurring toxicological outcomes included oxidative stress induction, intestinal injury, neurotoxicity, reproductive impairment, and transgenerational effects mediated through epigenetic pathways. Toxicity was often intensified by environmental aging processes, polymer-specific chemistry, and interactions with co-occurring contaminants. Taken together, the available evidence indicates that although mechanistic understanding of MNP toxicity in nematodes has advanced substantially, significant gaps persist in ecological realism, polymer diversity, and multi-species soil assessments. Addressing these limitations will be critical for refining terrestrial risk frameworks and clarifying the long-term implications of plastic contamination for soil ecosystem functioning.

Keywords: Microplastics, Nanoplastics, Nematodes, Soil ecotoxicology, Transgenerational toxicity

1. Introduction

Plastics have become indispensable in modern agriculture—especially greenhouse cultivation—where mulching films, covers, and related plastic inputs promote chronic and cumulative contamination of soil environments (Sajjad et al. 2022; Akca et al. 2024; Gündoğdu et al. 2025; Akca 2025; Pehlivan et al. 2026; Gündoğdu et al. 2026). Annual global plastic production surpasses 450 million tons, and fragmentation and weathering processes progressively transform macroplastics into MPs and nanoplastics (NPs) (Ali et al. 2021). MPs are plastic particles <5 mm, derived from mulch films, greenhouse covers, irrigation pipes, packaging, or degraded macroplastics. NPs are particles <1 µm, with higher reactivity and easier cellular penetration (Gigault et al. 2021). Common polymers include PE, PP, PS, and PVC. Micro- and nanoplastics (MNPs) adsorb pesticides, fertilizers, and heavy metals, increasing their ecotoxicological impact (Boctor et al. 2025). Major sources of MNP in agricultural soils are constituted by the degradation of mulching films and greenhouse covers, the application of sewage sludge and compost, wastewater irrigation, and atmospheric deposition. It has been demonstrated in the extant literature that there is considerable variability in the concentrations of MNP across soils. Agricultural soils are among the environmental compartments most exposed to MNP pollution due to plasticulture practices (e.g., plastic mulch, greenhouse covers) and the application of fertilizer and wastewater sludge, alongside other anthropogenic activities (de Souza Machado et al. 2018; Gündoğdu et al. 2022; Gündoğdu et al. 2025a). MNPs have garnered increasing attention owing to their widespread occurrence across environmental compartments. Although aquatic systems have historically dominated research efforts, terrestrial ecosystems—particularly agricultural soils—are increasingly recognized as substantial sinks for MNPs (Rillig 2012). In terrestrial settings, the scale of

MNP contamination may be considerable, yet ecological consequences for terrestrial biota remain less comprehensively characterized (Oliveira et al. 2019). These particles originate primarily from plastic mulching, compost and sludge applications, wastewater irrigation, and atmospheric deposition in agricultural soils (Bläsing & Amelung 2018; Gencer et al. 2026).

Once entered into soil, MNPs can interact with mineral particles, organic matter, and microbial communities and may alter soil quality (Gencer et al. 2026). MNPs in soil act as significant biological vectors, facilitating the survival, proliferation, and transport of various pathogenic microorganisms through the terrestrial environment (Yang et al. 2024). These plastic fragments provide a unique, hydrophobic surface that allows for the formation of dense microbial biofilms, a microenvironment often referred to as the "plastisphere" (Rillig et al. 2024). This plastisphere serves as a protective ecological niche, shielding pathogens from environmental stressors such as UV radiation, pH fluctuations, and chemical activity.

The role of MNPs as vectors is largely driven by their selective adsorption properties, which attract microbial communities that are distinct from those in the surrounding bulk soil. This selection is influenced by the physical characteristics of the plastic, such as surface roughness, charge, and polymer type (Trojan et al. 2024). For example, rougher surfaces like polyethylene terephthalate (PET) may preferentially adsorb cocci, while smoother surfaces like polystyrene (PS) tend to enrich bacilli. These microhabitats can accumulate opportunistic human pathogens, including Phoma-like species, cryptococcal yeasts like *Naganishia diffluens*, and common soil-borne pathogens such as *Fusarium oxysporum*. Bacterial pathogens, including members of the genera *Vibrio*, *Aeromona*s, and *Pseudomonas*, have also been identified on plastisphere surfaces (Trojan et al. 2024).

MNPs facilitate the transport of pathogens through multiple terrestrial pathways (Yang et al. 2024). Abiotic factors such as wind erosion (aeolian transport) and surface water runoff can move colonised plastic fragments over long distances, potentially introducing invasive or pathogenic species into new habitats. Vertically, MNPs can migrate into deeper soil layers through macropores, cracks, and water infiltration, potentially reaching groundwater systems. Biological vectors, particularly earthworms and collembolans, play a crucial role by ingesting MNPs and transporting them through the soil profile via bioturbation. The earthworm gut, in particular, acts as a "microbial gateway" where the specific conditions enhance biofilm formation and selective microbial adaptation before the particles are egested back into the soil (Liu et al. 2026).

Furthermore, MNPs serve as hotspots for the dissemination of antibiotic resistance genes (ARGs) and mobile genetic elements (MGEs). The high bacterial density within plastisphere biofilms facilitates horizontal gene transfer (HGT), increasing the risk that pathogenic bacteria will acquire multi-drug resistance (Jaafarzadeh & Talepour 2024). These contaminated MNPs can also be taken up by plant roots (e.g., lettuce or wheat) and translocated to edible tissues, posing a potential route for pathogens and ARGs to enter the human food chain (Xu et al. 2024). Because nanoplastics are small enough to pass through cell membranes, they present an even greater biohazard potential by carrying pathogens directly into prokaryotic and eukaryotic cells.

Their fate and behavior are shaped by particle size, morphology, polymer identity, and surface chemistry (Gündoğdu et al. 2026). In turn, MNPs may modify soil porosity, water retention, and microbial community structure (de Souza Machado et al. 2019), thereby potentially reshaping habitat conditions for soil organisms, including nematodes.

Nematodes are among the most abundant and functionally important components of soil ecosystems. They regulate key ecosystem processes through trophic interactions and include bacterivores, fungivores, predators, omnivores, and plant parasites, making them central to nutrient cycling, decomposition, and biological control; accordingly, nematode communities are widely used as bioindicators of soil condition (Yeates et al. 2009). In this context, understanding how MNP pollution influences nematode populations is critical for sustaining soil biodiversity and the functional integrity of agricultural ecosystems (Bongers & Ferris 1999; Kim & An 2020; Sucharitakul et al. 2024). This issue is particularly relevant under plastic-intensive production systems.

Despite the expanding literature on MNP pollution, evidence for effects on soil biota remains fragmented, particularly for nematodes. Existing reviews predominantly emphasize aquatic organisms or present broad terrestrial summaries, often underrepresenting nematodes or treating them as secondary endpoints. Moreover, the evidence base is complicated by methodological heterogeneity and contamination challenges, underscoring the need for standardized protocols and robust QA/QC in soil microplastic (MP) research (Gündoğdu et al. 2025b). To move beyond narrative listing and provide a structured synthesis, we therefore conducted a systematic literature review following PRISMA guidelines to evaluate experimental evidence on the effects of MNPs on insects with specific emphasis on nematodes. Specifically, this review aims to (i) identify dominant polymer types, particle sizes, and exposure conditions used in nematode-focused studies, (ii) synthesize reported physiological, behavioral, molecular, and transgenerational effects, and (iii) assess ecological relevance with particular emphasis on soil systems. By systematically screening and synthesizing available research, this review seeks to clarify current knowledge gaps and provide a foundation for improved ecological risk assessment of MNPs in terrestrial ecosystems.

2. Literature review

A systematic literature review was conducted in accordance with the PRISMA guidelines (Figure 1). The review protocol was designed to identify peer-reviewed experimental studies evaluating the effects of MNPs on nematodes within terrestrial and insect-related ecological contexts. Comprehensive literature searches were performed using Web of Science Core Collection and Scopus databases. The following search string was applied consistently across both platforms: microplastics OR microplastic OR nanoplastics OR nanoplastic OR micro and nanoplastics OR micro and nanoplastic (Title) AND nematode (Abstract) AND insects (Abstract). Searches were restricted to original research articles, excluding reviews, meta-analyses, conference proceedings, editorials, and book chapters. No temporal restriction was imposed at the database level.

The initial search yielded 251 records, including 106 (42.2%) from Web of Science and 145 (57.8%) from Scopus. After removal of 35 (13.9%) duplicate records, 216 unique studies remained for screening (Figure 1). Titles and abstracts were independently screened to exclude studies unrelated to nematodes, terrestrial systems, or biological effects of MNPs. Studies focusing solely on aquatic organisms, analytical detection methods, or human toxicology were excluded. Following this step, 50 (23.1% of 216 records) records were removed. A total of 166 full-text articles were assessed for eligibility based on predefined inclusion criteria: (i) experimental or observational exposure to MPs or NPs, (ii) nematodes as focal organisms, and (iii) reporting of biological, ecological, or molecular endpoints. All 166 studies met the eligibility criteria and were included in the qualitative synthesis.

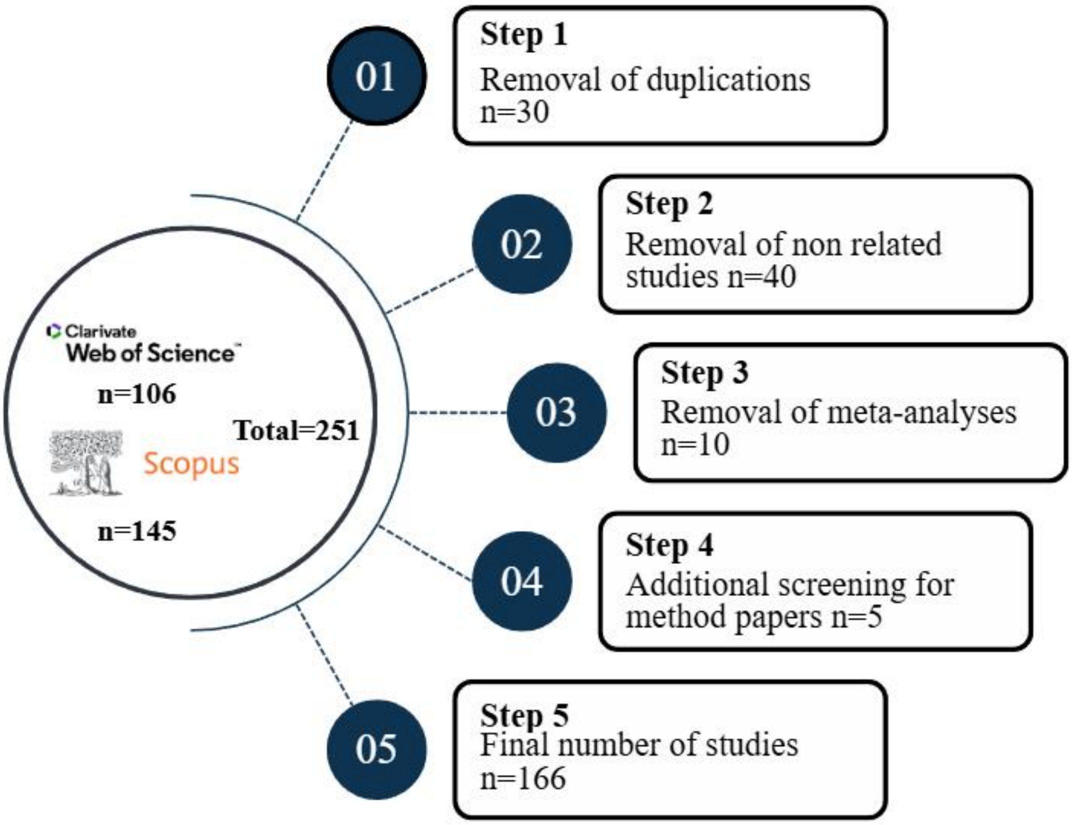

Figure 1- Schematic overview of the literature screening and selection process for studies on MNPs and nematodes, illustrating database sources, sequential exclusion steps, and the final number of studies included in the systematic review

Analysis of source journals revealed that the majority of studies were published in a limited number of environmental science journals. Science of the Total Environment accounted for the highest number of publications (n = 28; 16.8%), followed by Journal of Hazardous Materials and Environmental Pollution (n = 18 each 10.8%) (Figure 2). This concentration indicates that research on MNP effects on nematodes is predominantly framed within environmental pollution and ecotoxicological perspectives, with relatively limited representation in soil ecology or nematology-focused journals.

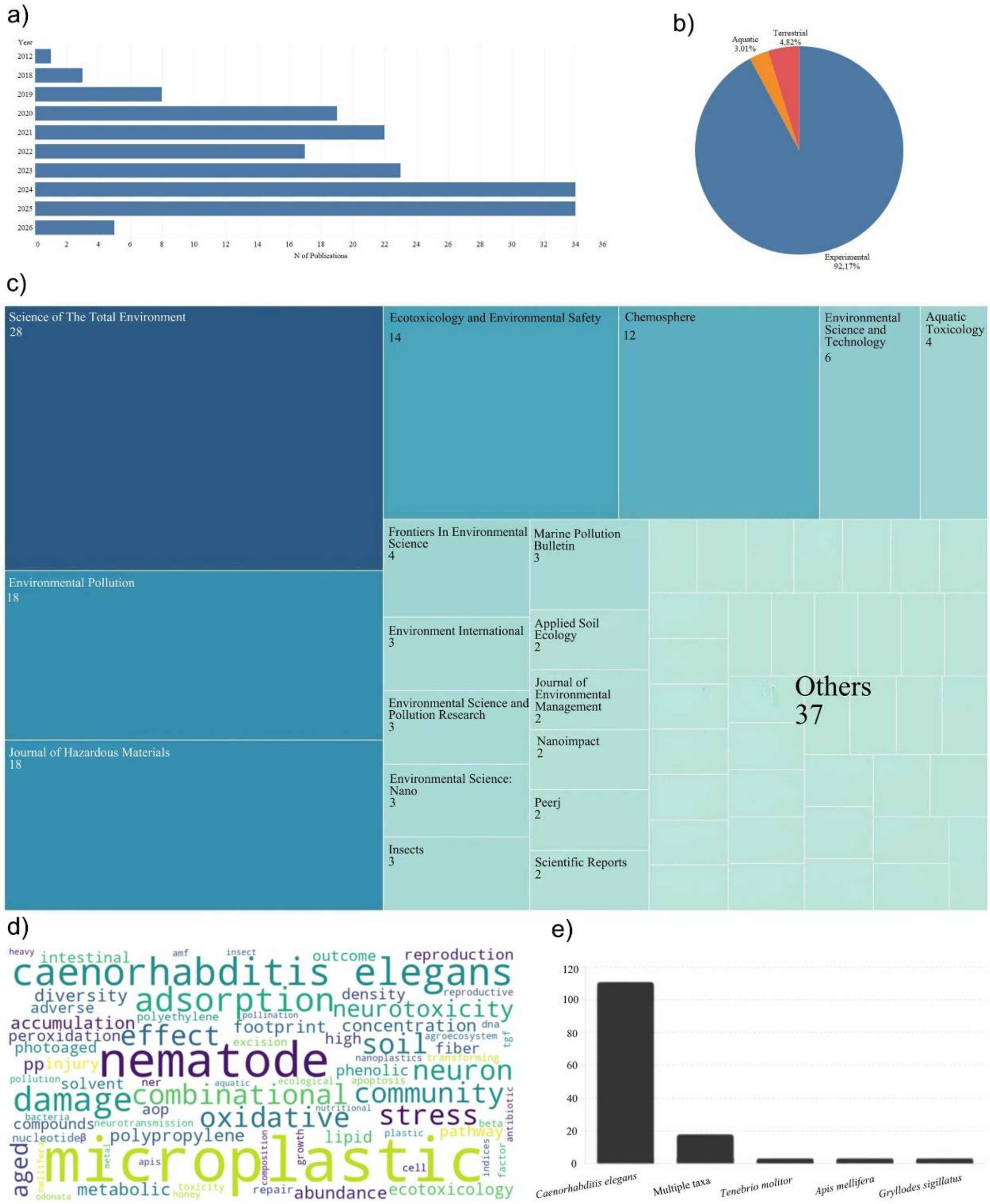

Figure 2- Bibliometric and thematic overview of studies included in the systematic review on micro- and NP effects on nematodes. (a) Temporal distribution of publications by year; (b) Proportional distribution of study types; (c) Distribution of publications across source journals; (d) Word cloud of author-provided keywords; (e) Frequency distribution of the five most commonly studied species or taxa.

The author keyword analysis revealed a strong emphasis on MP- and NP-related toxicity endpoints, with terms such as “microplastics,” “nanoplastics,” “oxidative stress,” and “*Caenorhabditis elegans*” occurring most frequently (Figure 2). Keywords associated with molecular and physiological responses were more prominent than those related to ecological interactions or community-level processes, indicating a prevailing focus on mechanistic laboratory studies rather than ecosystem-scale assessments.

Analysis of species representation revealed a strong reliance on the model nematode *C. elegans*, which accounted for the majority of experimental studies (n = 108) (Figure 2). In contrast, other free-living and entomopathogenic nematodes, including *Acrobeloides nanus*, *Plectus acuminatus*, and *Steinernema* spp., were investigated far less frequently, typically appearing in one or two studies. A subset of studies (n = 18) examined multiple taxa simultaneously, often within community-level or soil mesocosm designs. This taxonomic imbalance underscores the need for broader species coverage to better capture ecological complexity and improve the environmental relevance of MNP risk assessments.

3. Characteristics of MNPs and Effects on Nematodes

The presence of MNPs has been widely demonstrated to exert detrimental effects on nematode habitats and their associated food resources (Kumar et al. 2020; Luo et al. 2023; Cusworth et al. 2023). By altering soil structure, organic matter dynamics, and microbial assemblages, MNP contamination disrupts the environmental conditions upon which soil nematodes depend. Such habitat-level perturbations represent the first layer of ecological stress, preceding organism-level toxic responses. Physiologically, nematode populations exposed to MNPs frequently exhibit reduced growth rates and impaired reproductive output, ultimately leading to population-level declines (Mueller et al. 2020). Behavioral impairments have also been consistently reported, including intestinal accumulation of particles, reduced feeding efficiency, and impaired locomotion (Qu et al. 2018). Given the central role of nematodes within soil food webs, such reductions in abundance and functionality can compromise key ecosystem processes, including nutrient mineralization and organic matter turnover, thereby disrupting soil biogeochemical cycles (Schöpfer et al. 2020).

The analyzed data belongs to experimental studies (n=154) selected in the reviewed data reveals a significant research focus on the toxicological impacts of plastics, predominantly utilizing *C. elegans* as the primary model organism (Figure 2e). Other species such as *Steinernema feltiae, Pristionchus pacificus*, and various marine nematodes are also employed to assess broader ecological impacts. The experimental designs show a clear predominance of Polystyrene (PS) and its nano-formulations (nanoPS) as the most frequently studied polymer type (Figure 3 a). Following PS, Polyethylene (PE)—including high-density (HDPE) and low-density (LDPE) variants—is extensively researched. Additionally, studies incorporate a range of other polymers such as Polypropylene (PP), Polyvinyl Chloride (PVC), Polylactic Acid (PLA), and Poly (butylene adipate-co-terephthalate) (PBAT) to reflect the complexity of environmental plastic pollution.

Concentration levels vary significantly depending on the polymer size and the exposure medium (Fig 3). In NP research, concentrations typically range between 1 µg/L and 100 µg/L, which are often cited as environmentally relevant or low-dose thresholds. For larger MPs or tire-wear particles in soil and sediment studies, concentrations are frequently reported in mg/kg or as a weight-based percentage, commonly ranging from 0.1% to 10% w/w. High-dose studies exceeding 1,000 mg/L are also present to identify acute toxicity thresholds.

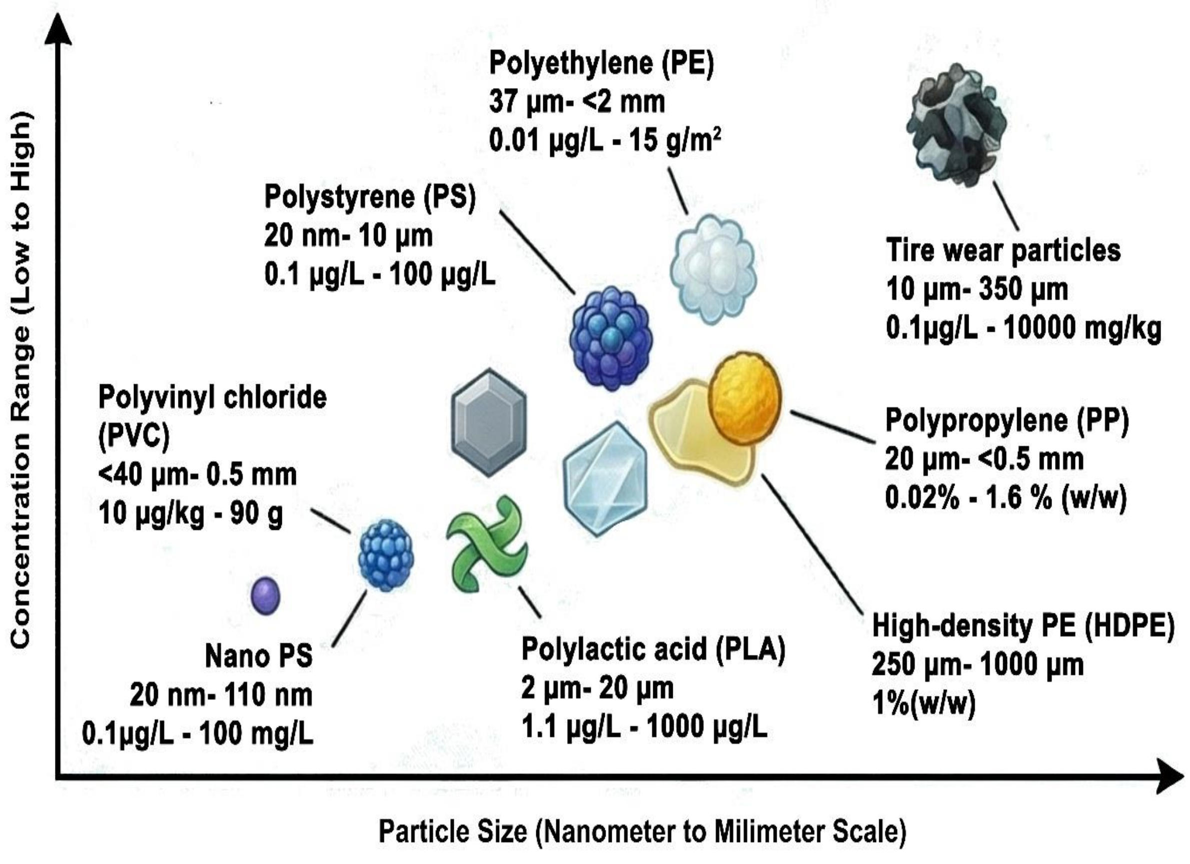

Figure 3- Overview of polymer types used in nematode studies, showing reported particle size ranges (nanometer to millimeter scale) and corresponding exposure concentrations from low to high

Polymer Size Distribution; The size of the exposed polymers is a critical variable, with a heavy emphasis on the nanoscale (approx. 20–100 nm) and small microscale (1.0–5.0 µm). Studies focusing on larger fragments or fibers report sizes ranging from 100 µm to 5 mm, often representing secondary MPs derived from consumer products like tires or face masks.

3.1. Intestinal injury and oxidative stress as primary toxicity initiators

Across the reviewed studies, intestinal injury and oxidative stress consistently emerge as the earliest and most fundamental responses to micro- and NP exposure in nematodes. This mechanistic framework was first clearly established by Lei et al. (2018), who demonstrated that short-term exposure to a mixture of polymers (PA, PE, PP, PVC, and PS; 0.1–5.0 µm) resulted in significant reductions in survival, body length, and reproduction in *C. elegans.* These organism-level effects were accompanied by decreased intestinal Ca^{2+} levels and elevated gst-4 expression, indicating disruption of intestinal homeostasis coupled with oxidative stress. Importantly, Lei et al. (2018) showed that toxicity was strongly size-dependent, with 1.0 µm PS inducing the greatest lethality and intestinal accumulation, highlighting that even within a single polymer type, particle size critically shapes biological outcomes.

Further evidence from Lei et al. (2018) reinforced oxidative stress as a central toxicity axis. Exposure to PS particles across nano- and microscale sizes (100–500 nm and 1–5 µm) induced excitatory locomotor toxicity, downregulation of neurotransmission-related genes (unc-17, unc-47), and damage to cholinergic and GABAergic neurons. The repeated induction of gst-4 across exposure scenarios, together with the successful mitigation of toxicity by antioxidant compounds, strongly supports oxidative stress as a primary and modifiable driver of MP-induced injury.

3.2. Intestinal barrier integrity and systemic exposure

Building upon these findings, subsequent studies revealed that intestinal damage is not merely a downstream consequence of exposure but also a determinant of susceptibility. As showed in Qu et al. (2018), impairment of intestinal barrier function dramatically increased vulnerability to nanoPS toxicity. Using acs-22 mutants, Qu et al. demonstrated that compromised barrier integrity allowed NPs to translocate beyond the gut lumen and accumulate in secondary tissues, effectively shifting exposure from a localized intestinal event to a systemic one. This transition was accompanied by altered oxidative stress–related gene expression and activation of Nrf signalling, establishing a tight mechanistic link between barrier dysfunction and redox imbalance.

These findings provide a critical conceptual bridge between physical particle accumulation and downstream molecular toxicity, suggesting that individuals or species with reduced intestinal barrier robustness may experience disproportionately severe effects even at relatively low exposure concentrations.

3.3. Activation of stress-response pathways and post-transcriptional regulation

As exposure persists, nematodes engage structured molecular defence pathways that modulate susceptibility to NP stress. Qu et al. (2019) demonstrated that prolonged nanoPS exposure activates the pmk-1 (p38 MAPK) pathway, with pmk-1 mutants exhibiting heightened sensitivity. This pathway was shown to function upstream of ATF-7 and SKN-1, coordinating an intestine-centered response that integrates detoxification, immune-like signalling, and the XBP-1–mediated ER unfolded protein response (ER UPR). These findings reposition NP toxicity as an outcome of dynamic interactions between exposure intensity and cellular stress-adaptation capacity, rather than a single linear toxic endpoint.

Extending this molecular framework, Qu et al. (2019) further identified extensive dysregulation of regulatory RNAs under long-term, low-dose exposure. Both lncRNAs and microRNAs (mir-35, mir-38, mir-76, mir-354) were shown to modulate resistance or susceptibility by influencing intestinal ROS levels and locomotor behavior. This layer of post-transcriptional regulation provides a mechanistic explanation for why similar exposure conditions can yield variable outcomes across genetic backgrounds or experimental designs.

3.4. Neurotoxicity and mitochondrial ROS as central effectors

As oxidative stress and stress-response signalling intensify, neurotoxicity emerges as a prominent downstream consequence. Studies by Chen et al. (2021) and Chen et al. (2024a) demonstrated that nanoPS-induced neurotoxicity is a multi-neuronal process, affecting dopaminergic neurons first and subsequently cholinergic and GABAergic systems. These neuronal disruptions were associated with reduced neurotransmitter levels and altered expression of neurotransmission-related genes, translating into measurable behavioral impairments such as reduced head thrashing and body bending.

Crucially, Chen et al. (2024b) provided direct evidence that mitochondrial ROS generation represents a causal driver of this neurotoxicity. NanoPS exposure increased ROS production, activated gst-4, and reduced SOD-2 protein levels, while mitochondrial ROS scavenging with MitoQ effectively alleviated both neuronal damage and behavioral deficits. These findings firmly place mitochondrial dysfunction at the core of NP-induced neurobehavioral toxicity.

3.5. Environmental aging and chemical reactivity amplify toxicity

Environmental aging further amplifies these toxic mechanisms. As showed in Chen et al. (2021), aged PS MPs induced more severe neurotoxicity than virgin particles even at low concentrations (1 μg/L), with enhanced degeneration of multiple neuronal classes and broader disruption of neurotransmitter homeostasis. Importantly, these effects were not confined to directly exposed individuals but persisted into subsequent generations, indicating that aging-enhanced toxicity has long-lasting biological consequences.

Complementary evidence from Chen et al. (2024b) demonstrated that photoaging increases plastic reactivity and adsorption capacity, thereby intensifying toxicity during co-exposure scenarios. UV-aged PS significantly enhanced the toxicity of tetrabromobisphenol A (TBBPA), leading to reduced growth, reproduction, and locomotion, as well as increased intestinal permeability and oxidative stress. Together, these studies illustrate how aging transforms plastics from relatively inert particles into chemically active stressors and vectors that exacerbate the effects of co-occurring pollutants.

3.6. Transgenerational and epigenetic persistence of effects

One of the most consequential insights from the reviewed literature is the persistence of plastic-induced effects across generations. As showed in Chen et al. (2024), surface-modified NPs (PS-NH_2) induced the strongest reproductive and transgenerational toxicity, reducing brood size and reproductive output across generations. These effects were mechanistically linked to elevated histone marks (H3K4me2, H3K9me3) and upregulation of epigenetic regulators (set-30, met-2), with loss-of-function mutants abolishing inheritance of toxicity.

Similarly, Yang et al. (2020) demonstrated that germline microRNAs play a central role in mediating inherited susceptibility. Overexpression of mir-38 and manipulation of its downstream targets altered resistance to nanoPS toxicity, while additional work linked NP exposure to lipid accumulation and ER UPR activation via metabolic regulators (mdt-15, sbp-1). These findings collectively indicate that NP exposure can reprogram germline regulatory networks, allowing toxic effects to persist well beyond the initial exposure window.

3.7. Size-Dependent persistence and aging chemistry

Particle size further modulates the persistence of these effects. Liu et al. (2021) showed that smaller nanoPS particles (20 nm) induced more severe and longer-lasting transgenerational toxicity than larger particles (100 nm), with effects persisting up to the F6 generation. This size dependence was associated with differential activation of oxidative stress pathways, antioxidant defences, and mitochondrial and ER stress responses, emphasizing that "NPs" represent a heterogeneous hazard category.
Finally, Li et al. (2024) provided mechanistic resolution to the long-standing observation that aged plastics are more toxic than pristine ones by identifying environmentally persistent free radicals (EPFRs) as key mediators. Photoaged nanoPS impaired locomotion and neurotransmission, while radical quenching reduced EPFR levels and alleviated toxicity. Parallel findings for photoaged MPs demonstrated accelerated aging, increased intestinal ROS, and shortened lifespan, confirming that chemical aging fundamentally alters plastic hazard profiles.

3.8. Extending findings beyond model nematodes

Importantly, these mechanisms are not restricted to *C. elegans*. As showed in Li et al. (2024), exposure of the entomopathogenic nematode *Steinernema feltiae* to PS MPs reduced survival, reproduction, and pathogenicity in a size- and concentration-dependent manner. Toxicity was linked to oxidative stress, mitochondrial dysfunction, and suppression of oxidative phosphorylation, indicating that plastic contamination may compromise biological control functions in agricultural ecosystems. Taken together, these mechanistic pathways converge on a common toxicity cascade the physiological characteristics of EPNs were influenced, resulting in a decrease in their effectiveness. The reproductive system is capable of facilitating the transfer of MPs between generations. Dopamine levels in EPNs may decrease due to PS-MP exposure, leading to a decrease in motivation for reproduction and dopaminergic neurotoxicity. The terrestrial organisms can be adversely affected by PS-MPs

4. Effects on Soil - Nematode system

In addition to direct organismal toxicity, MNPs can indirectly affect soil systems by modifying soil physicochemical properties. MPs have been shown to release dissolved organic matter (DOM), thereby altering nutrient availability and microbial activity (Lee et al. 2022). The structure and diversity of soil nematode communities are widely recognized as sensitive bioindicators of soil disturbance arising from chemical stressors, physical alterations, and agricultural practices (Sánchez-Moreno 2006). Bacterivorous nematodes belonging to the families Rhabditidae, Panagrolaimidae, and Diplogastridae are particularly abundant in nutrient-rich soils (Yeates et al. 2006; Hu & Qi 2010), and shifts in their abundance can signal changes in soil health. Alterations in soil porosity and moisture caused by plastic inputs further exacerbate habitat degradation, compounding stress on nematode communities (Wang et al. 2024).

The impacts of MNPs extend beyond nematodes to broader ecological contexts, including insects and higher trophic levels. In honey bees, MP exposure disrupts gut microbiota composition and alters immune and detoxification gene expression (Wang et al. 2024). MPs can also be transferred along food chains, for example from insect larvae to mammals, with potential consequences for embryonic development (Wang et al. 2024). Encouragingly, mitigation strategies such as selenium supplementation and the application of arbuscular mycorrhizal fungi (AMF) have shown promise in reducing plastic-induced toxicity within soil ecosystems (Zaman et al. 2026; Yue et al. 2026), suggesting that management interventions may partially offset the ecological risks posed by MNPs. MP exhibited concentration-dependent impacts: low doses (0.06%) elevated total nematode abundance by 74.4% and bacterivore (Ba) metabolic activity, likely through microplastic-surface bacterial colonization. The physical toxicity from sub-50 µm fragments caused a reduction in total nematode abundance from 27.3–27.9%, as indicated by higher concentrations (0.30–0.60%) (Yue et al. 2026). MP concentration negatively affected the abundance, diversity (including genus richness, Margalef's richness, Shannon–Wiener index, and Simpson's dominance index), sigma maturity index (∑MI), structural index, and metabolic footprints. The abundances of plant parasites, bacterivores, fungivores, and omnivores in 2% soils were reduced by 90.16%, 76.06%, 82.35%, and 100% (Yang et al. 2022).

The presence of MP in the soil led to a decrease in nematode movement, with the effect being influenced by the amount of MP and nematode species. Microplastics in soil for nematodes can limit food foraging and choice (Zhang & Ruess, 2025).

5. Gap Analysis

Based on the synthesis of the reviewed studies, several critical knowledge gaps and methodological limitations were identified. Addressing these gaps is essential for improving ecological relevance and advancing risk assessment of MNPs in terrestrial ecosystems.

5. 1. Broadening species coverage beyond model nematodes

Gap: The literature is heavily dominated by *C. elegans*, with limited representation of other free-living, plant-parasitic, and entomopathogenic nematodes.

How to fill: Future studies should incorporate a wider range of nematode taxa representing different trophic guilds and life-history strategies. Comparative studies across bacterivores, fungivores, predators, and plant parasites would improve understanding of functional vulnerability within soil food webs.

Priority area: Linking species-specific sensitivity to ecosystem functions such as nutrient cycling and biological control.

5.2. Increasing ecological realism of polymer types

Gap: Experimental exposures overwhelmingly rely on PS, despite PE and PP dominating agricultural plastic inputs.

How to fill: Research should prioritize environmentally dominant polymers (e.g., PE, PP, PET) derived from mulching films, greenhouse covers, and irrigation infrastructure, including realistic shapes (films, fibers, fragments) rather than spherical beads.

Priority area: Polymer-specific toxicity under soil conditions relevant to agricultural systems.

5.3. Aligning particle size distributions with field conditions

Gap: Nanoscale particles are overrepresented relative to larger MPs that prevail in soils.

How to fill: Studies should incorporate broader and mixed size distributions, including MPs >10 µm, and assess both direct toxicity and indirect habitat-mediated effects (e.g., changes in porosity and moisture).

Priority area: Integrating size-dependent biological effects with soil physical structure.

5.4. Standardization of exposure concentrations and reporting

Gap: Exposure concentrations vary widely in magnitude and units, limiting cross-study comparability.

How to fill: Development of standardized concentration categories (low, environmentally relevant, high/mechanistic) and harmonized reporting units would improve synthesis and meta-analytical potential.

Priority area: Establishing environmentally realistic concentration benchmarks for soil exposure.

5.5. Incorporating environmental aging and weathering processes

Gap: Many studies rely on pristine plastics, underestimating the role of aging, photooxidation, and surface modification.

How to fill: Future research should systematically include aged and weathered plastics and quantify changes in surface chemistry, leachate profiles, and reactive radical formation.

Priority area: Aging-driven toxicity amplification and interactions with co-contaminants.

5.6. Expanding transgenerational and epigenetic investigations

Gap: Transgenerational effects are documented but remain limited to a small number of polymers and exposure scenarios.

How to fill: Multi-generational studies across different polymers, sizes, and exposure durations are needed, with integration of epigenetic, transcriptomic, and metabolic endpoints.

Priority area: Long-term population and evolutionary consequences of chronic MNP exposure.

5.7. Shifting from single-stressor to multiple-stressor frameworks

Gap: Most studies assess MNPs in isolation, whereas soils contain complex pollutant mixtures.

How to fill: Experimental designs should incorporate co-exposure scenarios involving metals, pesticides, antibiotics, and organic pollutants to reflect real soil contamination profiles.

Priority area: Interactive and synergistic toxicity mechanisms.

5.8. Linking laboratory findings to community and ecosystem-level responses

Gap: There is a disconnect between mechanistic laboratory studies and soil community-level outcomes.

How to fill: Integrating microcosm, mesocosm, and field-based approaches with laboratory assays would bridge this gap and improve ecological relevance.

Priority area: Translating organism-level toxicity into ecosystem-scale risk.

Addressing these research priorities will require interdisciplinary approaches combining ecotoxicology, soil ecology, polymer chemistry, and molecular biology. By shifting toward environmentally realistic materials, exposure scenarios, and multi-species frameworks, future studies can substantially enhance the predictive power of micro- and NP risk assessments in terrestrial ecosystems and inform evidence-based management strategies.

6. Conclusive Remark

In conclusion, this systematic review consolidates current experimental evidence demonstrating that MNPs exert multifaceted toxic effects on nematodes, spanning organismal, cellular, and transgenerational levels. Across the screened literature, toxicity is consistently mediated through intestinal injury, oxidative stress induction, neurotoxicity, and disruption of reproductive fitness, with emerging evidence highlighting epigenetic inheritance and mitochondrial dysfunction as critical drivers of long-term biological impact. The dominance of *C. elegans* as a model organism has enabled detailed mechanistic resolution; however, it has simultaneously constrained ecological extrapolation to diverse nematode functional guilds that regulate soil ecosystem functioning.

Experimental designs show a strong methodological bias toward PS—particularly nanoscale particles—despite the environmental prevalence of PE and polypropylene in agricultural soils. Similarly, the frequent use of narrowly defined NP size classes and laboratory exposure systems limits ecological realism relative to heterogeneous, aged plastic debris encountered in field conditions. Aging processes, surface modifications, and co-contaminant interactions further amplify toxicity, underscoring that environmental plastics represent dynamic rather than static stressors.

At the ecosystem scale, MNP contamination alters soil physicochemical properties, microbial assemblages, and trophic interactions, thereby indirectly reshaping nematode community structure and functional diversity. Given the central role of nematodes in nutrient cycling, decomposition, and biological regulation, these impacts may propagate through soil food webs and compromise agroecosystem resilience.

Overall, the synthesized evidence indicates that while mechanistic understanding of MNP toxicity has advanced substantially, significant gaps remain regarding environmentally realistic exposure scenarios, polymer diversity, and multi-species soil interactions. Addressing these gaps through integrative, soil-based, and community-level research will be essential for refining ecological risk assessments and informing sustainable plastic management strategies in terrestrial ecosystems.

Author Declarations

Authors' contributions: Study conception and design: SG, HE, EBKU; data collection: SG, SVD, SA; analysis and interpretation of results: SG, HE, EBKU; draft manuscript preparation: SG, HE, EBKU, SVD, SA. All authors reviewed and approved the final version of the manuscript.

Conflict of interest/Competing interests: The author(s) declare no conflict of interest.

Ethics approval/declarations: No need/ Not applicable.

Funding: This research received no external funding.

Consent to participate: No need/ Not applicable.

Consent for publication: No need/ Not applicable.

Data availability: Data are available on request due to privacy or other restrictions.

References

Ali S S, Elsamahy T, Al-Tohamy R, Zhu D, Mahmoud Y A G, Koutra E, Metwally M A, Kornaros M & Sun J (2021). Plastic wastes biodegradation: mechanisms, challenges and future prospects. Science of The Total Environment 780: 146590. https://doi.org/10.1016/j.scitotenv.2021.146590

Akca M O (2025). Microplastic accumulation in soils around open dumping and scrapyard sites in Türkiye. Soil Use and Management 41(1): e70021.

Akca M O, Gündoğdu S, Akca H, Delialioğlu R A, Aksit C, Turgay O C & Harada N (2024). An evaluation on microplastic accumulations in Turkish soils under different land uses. Science of The Total Environment 911, 168609.

Bläsing M & Amelung W (2018). Plastics in soil: Analytical methods and possible sources. Science of the Total Environment 612: 422-435.

Boctor J, Hoyle F C, Farag M A, Ebaid M, Walsh T, Whiteley A S & Murphy D V (2025). Microplastics and NPs: fate, transport, and governance from agricultural soil to food webs and humans. Environmental Sciences Europe 37: 68. https://doi.org/10.1186/s12302-025-01104-x

Bongers T & Ferris H (1999). Nematode community structure as a bioindicator in environmental monitoring. Trends in Ecology & Evolution 14(6): 224–228

Chen H, Chen X, Ding P, Gu Y, Jiang Y, Li X, Hu G, Li L. Wang C, Yu J & Li H (2024a). Photoaging enhances combined toxicity of microplastics and tetrabromobisphenol A by inducing intestinal damage and oxidative stress in *Caenorhabditis elegans*. Science of the Total Environment 912: 169259. https://doi.org/10.1016/j.scitotenv.2023.169259

Chen H, Hua X, Yang Y, Wang C, Jin L, Dong C, Chang Z, Ding P, Xiang M, Hui Li & Yu Y (2021). Chronic exposure to UV-aged microplastics induces neurotoxicity by affecting dopamine, glutamate, and serotonin neurotransmission in *Caenorhabditis elegans*. Journal of Hazardous Materials 419: 126482. DOI: 10.1016/j.jhazmat.2021.126482

Chen J, Chen C, Luo Z, Jin X, Chen Y, Wu Q, Gong Z, Yang J, Jiang S, Lin S, Li J, Li F, Wu J, Guo J, Chen X, Lin L, Guo Z, Yu G, Shao W, Wu H & Zheng F (2024b). The role of Sod-2 in different types of neuronal damage and behavioral changes induced by polystyrene nanoplastics in *Caenorhabditis elegans*. Ecotoxicology and Environmental Safety 288: 117416. https://doi.org/10.1016/j.ecoenv.2024.117416

Cusworth S J, Davies W J, Mcainsh M R & Stevens C J (2023). A nationwide assessment of microplastic abundance in agricultural soils: The influence of plastic crop covers within the United Kingdom. Plants people planet

de Souza Machado A A Kloas W, Zarfl C, Hempel S & Rillig M C (2018). Microplastics as an emerging threat to terrestrial ecosystems. Global Change Biology 24(4): 1405-1416. https://doi.org/10.1111/gcb.14020

de Souza Machado A A, Lau C W, Kloas W, Bergmann J, Bachelier J B, Faltin E, Becker R, Görlich A S & Rillig M C (2019). Microplastics can change soil properties and affect plant performance. Environmental Science & Technology 53(10): 6044-6052

Gencer M, Akca M O, Acar M, Abdelrazik Z S, Wahab T S, Gündogdu S & Turgay O C (2026). Microplastic Accumulation and Soil Quality Changes Under Varying Plastic Mulching Durations in the Mediterranean Region. *Journal of Soil Science and Plant Nutrition* 1:16. https://doi.org/10.1007/s42729-026-03010-4

Gigault J, ter Halle A, Baudrimont M, Pascal P, Gauffre F, Phi T, El Hadri H, Grassl B & Reynaud S (2021). Current opinion: What is a nanoplastic? Environmental Pollution 279: 116953. https://doi.org/10.1016/j.envpol.2018.01.024

Gündoğdu S, Köşker A R, Akça H, Akça M O, Harada N & Turgay O C (2025a). Microplastics in food production and agricultural environments. In Microplastics in Agriculture and Food Science (pp. 285-307). Academic Press.

Gündoğu S, Akca M O, Gursoy M, Yılmaz M, Zhang X, Rodrıguez-Seijo A, Bibi A, Di Gioia M L & Velimirovic M (2025b). Microplastics in soil: a comprehensive review of analytical techniques. Frontiers in Soil Science 5: 1614075. doi: 10.3389/fsoil.2025.1614075

Gündoğdu S, Akça M O, Özkan İ, Sarıdaş M A, Küçükel E, Rodríguez-Seijo A, Er E & Turgay O C (2026). A review of non-petroleum alternatives of plastic mulches in agriculture: Knowledge gaps and future recommendations. *European Journal of Agronomy* 172: 127831. https://doi.org/10.1016/j.eja.2025.127831

Gündoğdu R, Önder D, Gündoğdu S & Gwinnett C (2022). Plastics derived from disposable greenhouse plastic films and irrigation pipes in agricultural soils: a case study from Turkey. Environmental Science and Pollution Research 29(58): 87706-87716. https://doi.org/10.1007/s11356-022-21911-6Hu C & Qi Y C (2010). Abundance and diversity of soil nematodes as influenced by different types of organic manure. Helminthologia 47(1): 58-66. https://doi.org/10.2478/s11687-010-0009-8

Jaafarzadeh N & Talepour N (2024). Microplastics as carriers of antibiotic resistance genes and pathogens in municipal solid waste (MSW) landfill leachate and soil: A review. *Journal of Environmental Health Science and Engineering* 22(1): 1–12. https://doi.org/10.1007/s40201-023-00879-6

Kim S W & An Y J (2020). Effects of different microplastics on nematodes. Environmental Science & Technology 54: 13868–13878

Kumar M, Xiong X, He M, Tsang D C W, Gupta J, Khan E, Harrad S, Hou D, Sik Ok Y & Bolan N S (2020). Microplastics as pollutants in agricultural soils. Environmental Pollution 265: 114980. https://doi.org/10.1016/j.envpol.2020.114980

Lee Y K, Yoo H Y, Ko K S, He W, Karanfil T & Hur J (2022). Tracing microplastic (MP)-derived dissolved organic matter in the infiltration of MP-contaminated sand system and its disinfection by products formation. Water resistance 221: 118806. https://doi.org/10.1016/j.watres.2022.118806

Lei L, Wu S, Lu S, Liu M, Song Y, Fu Z, Shi H, Raley-Susman K M & He D (2018a). Microplastic particles cause intestinal damage in zebrafish and nematodes. Science of the Total Environment 619: 1–8. https://doi.org/10.1016/j.scitotenv.2017.11.103

Li H, Gu Y, Jiang Y, Ding P, Chen X, Chen C, Pan R, Shi C, Wang S & Chen H (2024). Environmentally persistent free radicals on photoaged nanopolystyrene induce neurotoxicity by affecting dopamine, glutamate, serotonin and GABA in *Caenorhabditis elegans*. Science of The Total Environment 906: 167684. https://doi.org/10.1016/j.scitotenv.2023.167684

Li M, Ha B, Li Y, Vrieling K, Fu Z, Yu Q, Rasman S, Wei X & Ruan W (2024). Toxicological impacts of microplastics on virulence, reproduction and physiological process of entomopathogenic nematodes. 273: 116153. https://doi.org/10.1016/j.ecoenv.2024.116153

Liu H, Zhao Y, Bi K, Rui Q & Wang D (2021). Dysregulated mir-76 mediated a protective response to nanopolystyrene by modulating heme homeostasis related molecular signaling in nematode *Caenorhabditis elegans*. Ecotoxicology and Environmental Safety 212: 112018. https://doi.org/10.1016/j.ecoenv.2021.112018

Liu Y, Luo Z, Xiao Y, Li Y, Liu M, Shi Y, Li Z, Lei W, Li C, Jin L N & Yan W (2026). Microplastics in motion: How earthworm guts become microbial gateways through plastic surface dynamics. Environmental Science & Technology 60(1): 338–349. https://doi.org/10.1021/acs.est.5c15257

Luo Y, Wang L, Cao T, Chen J, Lv M, Wei S, Lu S & Tian X (2023). Microplastics are transferred by soil fauna and regulate soil function as material carriers. Science of The Total Environment 857(3):159690. Doi: 10.1016/j.scitotenv.2022.159690

Mueller M T, Fueser H, Höss S & Traunspurger W (2020). Species-specific effects of long-term microplastic exposure on the population growth of nematodes, with a focus on microplastic ingestion. Ecological indicators, 118, 106698. https://doi.org/10.1016/j.ecolind.2020.106698

Oliveira M, Ameixa O M, & Soares A M (2019). Are ecosystem services provided by insects “bugged” by micro (nano) plastics? TrAC Trends in Analytical Chemistry 113: 317-320. https://doi.org/10.1016/j.trac.2019.02.018

Qu M, Liu Y, Xu K & Wang D (2019). Activation of p38 MAPK signaling-mediated endoplasmic reticulum unfolded protein response by nanopolystyrene particles. Advanced Biosystems 3(4): 1800325. DOI: 10.1002/adbi.201800325

Qu M, Xu K, Li Y, Wong G & Wang D (2018). Using acs-22 mutant *Caenorhabditis elegans* to detect the toxicity of nanopolystyrene particles. Science of the Total Environment 643: 119-126. https://doi.org/10.1016/j.scitotenv.2018.06.173

Pehlivan N, Terzi Y, Gündoğdu S, Öztürk R Ç & Gedik K (2026). Navigating microplastic-induced stress in plants: adaptations from physiology to gene regulation. Plant Molecular Biology 116(1): 5. https://doi.org/10.1007/s11103-025-01669-4

Rillig M C (2012). Microplastic in terrestrial ecosystems and the soil? Environmental Science & Technology 46(12): 6453-6454

Rillig M C, Kim S W & Zhu Y G (2024). The soil plastisphere. Nature Reviews Microbiologyn 22(2): 64-74

Sajjad M, Huang Q, Khan S, Khan M A, Liu Y, Wang J, Lian F, Wang Q & Guo G (2022). Microplastics in the soil environment: A critical review. Environmental Technology & Innovation 27: 102408. https://doi.org/10.1016/j.eti.2022.102408

Sánchez-Moreno S, Inoshıma M H, Ferrıs H & Jackson L E (2006): Linking soil properties and nematode community composition: effects of soil managementon soil food webs. Nematology 8: 703 – 715. https://doi.org/ 10.1163/156854106778877857

Schöpfer L, Menzel R, Schnepf U, Ruess L, Marhan S, Brümmer F, Pagel H & Kandeler E (2020). Microplastics effects on reproduction and body length of the soil-dwelling nematode *Caenorhabditis elegans*. Frontiers in Environmental Science 8: 41. https://doi.org/10.3389/fenvs.2020.00041

Sucharitakul P, Wu W M, Zhang Y, Peng B Y, Gao J, Wang L & Hou D (2024). Exposure pathways and toxicity of microplastics in terrestrial insects. Environmental Science & Technology 58(27): 11887-11900. https://doi.org/10.1021/acs.est.4c02842

Trojan M, Koutný M, Brtnický M, Holátko J, Zlámalová Gargošová H, Fojt J & Kučerík J (2024). The interaction of microplastics and microbioplastics with soil and a comparison of their potential to spread pathogens. Applied Sciences 14(11): 4643

Wang Y, Nan X, Sun H, Shi Y, Miao J, Li Y, Han X, Zhang N, Wang H, Ren N, Zhao X & Liu B (2024). From insects to mammals! Tissue accumulation and transgenerational transfer of micro/nano-plastics through the food chain. Journal of Hazardous Materials 480: 136424. https://doi.org/10.1016/j.jhazmat.2024.136424

Wang Z, Li J, Qu Z, Ayurzana B, Zhao G & Li W (2024). Effects of microplastics on the pore structure and connectivity with different soil textures: Based on CT scanning. Environmental Technology & Innovation 36: 103791. https://doi.org/10.1016/j.eti.2024.103791

Xu G, Li Y, Lin X & Yu Y (2024). Effects and mechanisms of polystyrene micro- and nano-plastics on the spread of antibiotic resistance genes from soil to lettuce. Science of the Total Environment 912: 169293. https://doi.org/10.1016/j.scitotenv.2023.169293

Yang Y, Wu Q & Wang D (2020). Epigenetic response to nanopolystyrene in germline of nematode *Caenorhabditis elegans*. Ecotoxicology and Environmental Safety 206: 111404. Doi: 10.1016/j.ecoenv.2020.111404

Yang B, Li P, Entemake W, Guo Z & Xue S (2022). Concentration-dependent impacts of microplastics on soil nematode community in bulk soils of maize: evidence from a pot experiment. Frontiers in environmental science. 10, 22. 10:872898. Doi: 10.3389/fenvs.2022.872898

Yang B, Wu L, Feng W & Lin Q (2024) Global perspective of ecological risk of plastic pollution on soil microbial communities. Front. Microbiol. 15:1468592. Doi: 10.3389/fmicb.2024.1468592

Yeates G W, Ferris H, Moens T & van der Putten W H (2009). Nematodes as environmental indicators (Eds.: Wilson, M. J. and Kakouli Duarte, T.) “The role of nematodes in ecosystems”. 1-44 pp

Yeates G W, Speir T W, Taylor M D, Clucas L & Van Schaik A P (2006). Nematode responses to biosolids incorporation in five soil types. Biology and Fertility of Soils 42(6): 550-555. https://doi.org/10.1007/s00374-005-0050-9

Yue J, He Y, Ma W, Zhao C, Liu Y, Zhang L, Li G & Zhang Y (2026). Arbuscular mycorrhizal fungi mitigate microplastic-induced shifts in soil nematode communities. Applied Soil Ecology 219: 106765. https://doi.org/10.1016/j.apsoil.2025.106765

Zaman F, Tasneem F, Shoaib N, Zaib S, Pan Y, Sun X, Tadesse Z, Pan K, Wu X & Zhang L (2026). Selenium-driven trophic restructuring of soil nematode communities and biochemical regulation alleviate the toxicity caused by microplastic pollution in highland barley. Ecotoxicology and Environmental Safety 309: 119673. https://doi.org/10.1016/j.ecoenv.2026.119673

Zhang X & Ruess L (2025). Microplastics lead to behavioral disorders in soil nematode movement, foraging and food choice. Pedobiologia, 111: 151054. https://doi.org/10.1016/j.pedobi.2025.151054