Spectrum of Engineering Sciences

ISSN (e) 3007-3138 (p) 3007-312X Volume 4, Issue 3, 2026

THE IMPACT OF SYNTHETIC MICROFIBERS FROM LAUNDRY WASTEWATER ON SOIL INVERTEBRATE GUT MICROBIOMES AND NUTRIENT CYCLING

Shahid Mahmood[*1], Razia Iqbal[*2], Hamna Haider[3], Saira Gulzar[4], Fozia Ashfaq[5], Esha Mustansar[6]

[*1, *2, 3,4,5,6] *Department of Zoology, University of Gujrat, Gujrat 50700, Pakistan*

[*1]shahid.mahmood@uog.edu.pk, [*2]razia.iqbal@uog.edu.pk

DOI: https://doi.org/10.5281/zenodo.19016320

Keywords

Synthetic Microfibers, Microplastics, Wastewater, Bio-sludge, Microbiome

Article History

Received: 14 January 2026

Accepted: 26 February 2026

Published: 14 March 2026

Corresponding Author: *

Shahid Mahmood, Razia Iqbal

Abstract

Synthetic microfibers, which are artificially produced during the process of laundry, are a major concern for soils, as a considerable portion of this synthetic material is deposited in agricultural soils via irrigation of these soils using wastewater and sewage sludge or bio-sludge. Though there has been extensive research regarding marine plastic pollution in the past, recent research has been conducted to study the physiological and ecotoxicological effects of synthetic microfibers on soil invertebrates, which are ecosystem engineers and play an essential role in maintaining the structure and fertility of the soil. This study is a systematic review of ten years of research to evaluate the relationship between microfiber exposure, microbiological dysbiosis, and nutrient cycling disorders. High consumption of microplastics results in epithelial damage, obstruction of the intestine, and decreased appetite in some invertebrates, such as earthworms belonging to the family Lumbricidae and springtails belonging to the class Collembola. Microfibers are substrates for recruitment to the solid phase in the gut of these invertebrates, leading to decreased beneficial Proteobacteria and increased Firmicutes, an indicator of inflammatory stress. Decomposition of organic matter is affected if the microbiota of the gut is altered. According to recent statistical data, which goes back to 2025, it has been observed that soils containing microfibers have shown an approximate decrease of 15% in nitrogen mineralization rates and an increase in emissions of nitrous oxide. The microfibers can transfer adsorbed heavy metals and other harmful additives to the stomachs of invertebrates through a "Trojan horse" effect, which increases oxidative stress and harms DNA. According to this study, it is absolutely necessary to conduct long-term field studies to fill the gap between scientific data and actual environmental impacts, despite the presence of dose-response relationships. The mitigation measures should also include textile engineering methods to control microfiber emissions and wastewater filtration systems to maintain significant ecosystems.

1. INTRODUCTION

Microplastic pollution has turned into a significant worldwide issue. Previous studies have mainly centered on the issue of plastic contamination in aquatic and marine environments, yet over the most recent ten years, the impact on terrestrial ecosystems has been the focal point of more examination. The rising levels of plastic production and their high resistance to biodegradation lead to the development of plastic accumulation in the environment (Hohn et al., 2020; Rillig et al., 2019; Möhrke et al., 2022). Synthetic microfibers, which are microplastics with fibrous textures and diameters smaller than 5 mm, are the most widely dispersed type of microplastic and are more dangerous than bigger plastic pieces (Alimi et al., 2018; Rillig et al., 2022). According to recent worldwide estimates, 5.6 million tons of synthetic microfibers have been discharged into laundry wastewater worldwide since 1950 (Gavigan et al., 2021). These synthetic microfibers enter the terrestrial environment as sewage sludge and wastewater-based biowaste are generally used as soil amendments, with synthetic fibers making up 92% to 97% of the microplastic particles present, which is the direct pathway for household laundry waste to enter the soil (Nizzetto et al., 2016; Zhang and Liu, 2018; Corradini et al., 2019; Selonen et al., 2020).

Soil invertebrates, especially earthworms (*Lumbricidae*), isopods, and springtails, are known to perform a vital function in terrestrial ecosystems. Their burrowing activity is a key component in maintaining soil structure and thus influences nutrient cycling and nutrient availability (Prendergast-Miller et al., 2019). When exposed to synthetic microfibers, a particular problem is experienced in invertebrates due to their elongated shape. Physiological problems include damage to the internal epithelium, intestinal obstruction, nutritional problems, molecular genetic biomarkers, and burrowing behavior (Prendergast-Miller et al., 2019). Besides this physical problem, microfibers are a significant threat in ecotoxicology due to their unique composition. When microplastics are consumed by earthworms, they are known to fragment and depolymerize in the intestinal tract, leading to intestinal dysbiosis and changing the symbiotic interaction between the host and microbiota (Sofield et al., 2024; Meng et al., 2023).

Gut microbiota in invertebrates is vital to soil health and ecosystem functioning, playing a vital role in nutrient and carbon cycling processes. Microfiber incorporation into invertebrates is known to impact microbiota and organic matter decomposition processes, which is vital to ecosystem functioning and carbon sequestration and fertility (Lehmann et al., 2021). Recent findings (2025) indicate that microplastics can significantly impact microbial nitrification, microbial nitrogen cycle, and denitrification processes, as well as nitrous oxide emissions (Lagos et al., 2025).

Despite the vast scientific literature regarding microplastics and their ecological impact, yet there has been no comprehensive review of the role of microfibers derived from laundry in the disruption of the microbiota balance in the gut of soil invertebrates. This review aims to assess the literature conducted within the last decade regarding the relationship between exposure to microfibers, microbiota imbalance, and the eventual disruption of nutrient cycling, illustrated in table 01 summarizes the main findings of relevant studies conducted over the past ten years.

3. Characteristics of soil contamination with microfibers

Soil ecosystems represent the most complex and biodiverse terrestrial environments; however, the interactions between receptors and anthropogenic microplastic pollution remain poorly understood. Among the various morphological categories of microplastics, microfibers, defined as partially elongated and filamentary with variable aspect ratios (typically greater than 100:1), constitute the numerically dominant fraction in ambient soils (Boots et al., 2019). Specific ecotoxicological risks are also linked to microfibers. Their entry into rural and peri-urban soils is well known. Synthetic textile fibers are released into wastewater treatment plants during domestic laundry processes. Most of these microfibers are removed in wastewater treatment plants (between 72 and 99.9%, depending on treatment plant technology). Their presence is then concentrated in wastewater, especially in sewage effluents (Ngo et al., 2022). One of the most common practices in fertilizing agricultural soils is the application of sewage sludge. This closes the life cycle of sewage sludge, as it is reintroduced into the soil (Wan et al., 2023). The following subsections provide a critical analysis of the physicochemical characteristics of microfiber contamination in soil and those regulating their bioavailability, exclusively based on publications in the last five years.

3.1 Synthetic fibers vs. natural fibers

Classification of synthetic and natural fibers is not only a matter of taxonomy but also has implications regarding sustainability, toxicity, and soil impact. Synthetic fibers usually comprise polyethylene terephthalate (PET), commonly known as polyester, polyamide known as nylon, and polyacrylonitrile known as acrylic. These fibers originate from petroleum-based products and cannot be broken down by enzymes or microbes. While this property is essential to enable their use as fabric materials, it is also responsible for rendering synthetic fibers immune to degradation when introduced to soil (De Falco et al., 2020).

The most commonly used synthetic fibers in the world are polyester microfibers, which account for 52% of total polyester fiber production globally (Wan et al., 2023). Ecotoxicologically, PET fibers are known to break into particles of sizes ranging from 100 to 5000 μm after washing, with a mode of 10 to 20 μm in diameter (De Falco et al., 2020). The analysis of soil samples from wastewater treatment plants using FTIR and Raman spectroscopy showed that PET is the predominant material in wastewater treatment plants, accounting for 768% of all microplastic material found in fabrics (Corradini et al., 2021). It is worth mentioning that PET fibers are not hydrolyzed under normal environmental pH levels but are subjected to surface oxidation and degradation after prolonged exposure to UV light, resulting in micro cracks on the surface of the fibers that repel water and allow for the uptake of organic substances (Ngo et al., 2022).

On the other hand, nylon or polyamide fibers are prone to hydrolytic degradation in alkaline and alkaline earth environments owing to caprolactam monomers and oligomers of adipic acid and hexamethylenediamine, which are highly electro-toxic in soils (Rillig et al., 2021). Acrylic fibers, derived from polyacrylonitrile, represent an environmental threat owing to its major component: nitrile groups (-C≡N), which may lead to the formation of toxic degradation products, thereby degrading soil health. Acrylic fibers may contain residues of acrylonitrile monomers of up to 2000 mg/kg, a compound known to be carcinogenic and neurotoxic (Ranjan & Bhattacharya, 2020).

Unlike cotton, natural cellulose (cotton) and protein-based fibers (wool) are biodegradable. Cotton, consisting of crystalline cellulose (90% α-cellulose), is prone to degradation by cellulolytic microbes in the soil, and its biodegradation is complete within 1-5 months under optimal conditions, depending on temperature. Wool, consisting of keratin proteins held together by disulfide bonds, degrades slower than cotton owing to the unstable disulfide bond but still degrades under mesophilic conditions within 1-2 years. It is important to emphasize that biodegradation does not necessarily have a positive impact on the environment. Several studies have shown that cotton and wool microfibers, particularly those obtained from commercial textiles that have undergone surface treatments (mercerization, bleaching, etc.), can have significant sublethal effects on terrestrial invertebrates (Haegerbaumer et al., 2022; Ranjan and Bhattacharya, 2020).

Table 01: Comparative summary of studies (2020-2026) on usage of different fiber types on different soil invertebrates, their effect on gut microbiome and nutrient cycling, and the mechanism.

Target organism	Type	Gut microbiome	Impact	Innovation/Mechanism	Reference
Chironomus dilutus	Polyester microfibers	Decreased alpha diversity of intestinal microbiota.	Increase in stress biomarkers by 24.3 times.	Physical abrasion of intestinal microvilli.	Erdle et al. (2026)
Lumbricus terrestris	Polyethylene and nylon fibers	Reduction in the number of nitrifying bacteria in the intestine.	Nitrogen mineralization decreased by 15%.	Direct link between intestinal dysbiosis and nitrogen loss in the soil.	Lagos et al. (2025)
Soil biota in general	Synthetic textile waste	Induced formation of reactive oxygen species (ROS).	Disruption of decomposition pathways.	DNA degradation and cellular apoptosis were demonstrated.	Ekanem (2025)
Earthworms (various species)	Members of Parliament from the Laundry Services Sector	Changes in the composition of ammonium-oxidizing archaea (AOA).	Disruption of nitrogen denitrification pathways.	The leaky gut syndrome hypothesis in invertebrates.	Takuria et al (2025)
Collembola	Biodegradable (PBAT) vs. Polyethylene (PE)	The PE effect resulted in more severe instability of the microbial network.	PBAT had a positive effect; PE had a negative effect on nitrogen content.	This calls into question the "safety" of biodegradable plastics.	Zheng et al. (2025)
Earthworms and other invertebrates	NPL and MPL	Modification of microbial communities at the level of the plastisphere.	PVC microparticles (80–250 μm) disrupted the absorption of elemental carbon and nitrogen by springtails, affecting decomposition processes and nutrient cycling.	The study highlighted the role of microplastics as a pathogen vector, as well as the absorption/transportation of Nanoplastics by terrestrial plants.	Muñoz and Berio (2025)
Eisenia fetida	High-density polyethylene (HDPE)	Enrichment of intestinal microbiota with representatives of the *Nocardiaceae family*.	Slower processing of soil organic matter (SOM).	Potential of bioremediation against toxicological stress.	Zhu et al. (2024)
Eisenia fetida	PMMA and PS (0.1, 1, 10 μm)	The diversity and richness of the microbial community (proteobacteria, actinobacteria, firmicutes) has changed.	No detailed description is provided; the focus is on the ecological and toxicological aspects of behaviour.	The smallest microparticles (0.1 μm) effects on bioaccumulation and oxidative stress.	Wang et al. (2024)

A study by Rillig et al. (2021), based on 77 experiments with 19 taxa, found that, regardless of polymer type, fibers had a more pronounced adverse effect than films or residues at equivalent concentrations due to their hexagonal structure, which is in turn influenced by topography. Furthermore, the analysis showed that the effect size was larger for synthetic fabrics than for natural ones (Hedges' g = 0.58 vs. 0.31), mainly due to additive-induced toxicity. This finding has important policy implications: risk assessment systems that consider only natural materials may systematically underestimate the environmental risk posed by commercial textiles made with high-quality dyes and finishes, regardless of their physical characteristics (Rillig et al., 2021).

The relative strength of different types of soil fibers was calculated using the accelerated aging method. Wang et al. (2023) stored polyester, cotton, and wool fibers in soil samples (25 °C, 60% water retention) for 180 days to determine their density and structural stability. The polyester yarns lost very little mass (<2%), while the fabric and wool yarns lost 38% and 22% of their original weight, respectively. Notably, scanning electron microscopy (SEM) revealed that partially degraded cotton fibers had a higher specific surface area, and the microstructure, morphology, and roughness of pyrene, a hydrophobic contaminant, were 3.4 times more pronounced than those of intact fibers (Wang et al., 2023).

The chemical complexity of industrially produced textile fibers further complicates direct comparisons between different fiber types. Commercial polyester fabrics typically contain 2% to 8% by weight of additives, such as UV stabilizers, optical reflectors, and antimicrobial agents such as silver nanoparticles or triclosan (Ngo et al., 2022). Wool and commercial fabrics often contain azo dyes (primarily arylamine-forming azo dyes, which are prohibited by Annex XVII of the EU REACH Regulation), formaldehyde-based binders, and perfluoroalkyl substances (Corradini et al., 2021). Ecotoxicological literature has not yet fully elucidated the effects of chemical additives on the polymer matrix, revealing a gap in our knowledge that modern research is beginning to fill by analyzing liquids containing these additives.

3.2 Bioavailability and oral administration

Bioavailability, which refers to the proportion of a contaminant present in soil that can be absorbed by a target organism, depends on the physicochemical properties of the contaminant and the characteristics of the host organism's environment. In the case of soil microfibers, bioavailability cannot be measured using chemical extraction methods used for dissolved organic contaminants; therefore, it must be interpreted functionally, taking into account the potential for collisions and predation of each taxonomic group during its feeding behavior (Lehmann et al., 2021).

Fiber length is a quantitative parameter that determines the dispersal ability of invertebrates. Earthworms (*Lumbricus terrestris*, *Eisenia fetida*) feed on small particles, primarily due to their mouth size and the ability to select particles by size. Fiber aging has been studied at various depths (100–4000 μm), and some studies have shown that fibers shorter than 500 μm age faster than normal-sized fibers (Boots et al., 2019). However, fiber length selectivity is not absolute. Fiber geometry, independent of active particle selection, allows for passive particle capture within the cavity through a porous layer at the base of the fiber, with fibers being larger than individual particles (Boots et al., 2019). Springtails (summer flycatchers) with body lengths between 1 and 5 mm feed on smaller particles, and experimental evidence suggests that 20-500 μm fibers are the main components of digestion (exposure to 20 μm food often occurs through substrate particles adhered to the hyphae of fungi on which springtails feed) (Shen et al., 2022).

Table 02: Physicochemical properties, environmental persistence, and ecotoxicological significance of microfibers reported in terrestrial soil studies (2019–2023)

Fiber type	Polymer composition	Environmental sustainability	Degradation mechanism	Major ecotoxicological problems	Reference
Polyester (PET)	polyethylene terephthalate	Very stable (<2% weight loss in 180 days)	Surface oxidation under UV radiation; limited hydrolysis	Adsorption of hydrophobic contaminants; leaching of additives; intestinal obstruction	Wan et al., 2023); Boots et al., 2019
Nylon (polyamide)	Polyamide	Moderate persistence	Hydrolytic degradation (under acidic/alkaline conditions)	Caprolactam release; acute toxicity; bloating.	Rillig et al., 2021
Acrylic	Polyacrylonitrile	Persistent	Reductive degradation of nitriles	Acrylonitrile residues; carcinogenic potential	Ranjan and Bhattacharya, 2020
Cotton	Cellulose (~90% α-cellulose)	Mild to moderate (38% weight loss in 180 days)	Microbial cellulolytic degradation	Toxicity of dyes/additives; increased sorption after decomposition.	Hagerbaumer et al., 2022
Wool	Keratin (protein based)	Moderate result (22% weight loss in 180 days)	Slow biodegradation by keratinolytic microbes.	Additive toxicity; long-term residence time in the body.	Wang et al., 2023

Fiber diameter independently influences bioavailability because it determines both the length-to-diameter ratio and mechanical flexibility. Fibers with a high length-to-diameter ratio (>200) are more likely to align with the soil pore network and bind to mucilage secreted by plant roots and soil microorganisms (rhizosphere biofilms), thereby increasing the likelihood of their contact with soil invertebrates (Lehmann et al., 2021). Fiber diameter also determines its potential for physical penetration through tegmental pores or gill surfaces in semi-aquatic terrestrial invertebrates such as isopods (Porcellio scaber), a pathway experimentally demonstrated for fibers less than 5 µm in diameter (Rillig et al., 2021).

The gradual distribution of microfibers within the soil structure is an important, yet often overlooked, factor determining bioavailability. Microfibers embedded in the surface of biolaminates from sewage sludge initially accumulate in the top 5 cm of the soil profile. Their subsequent migration to greater depths is primarily driven by bioturbation (primarily controlled by spongy and endogenous sedimentary species), macropore expansion during rainfall, and freeze-thaw cycles in wet soils (Corradini et al., 2021). The depth of fiber distribution is directly related to their bioavailability, as functional groups of soil invertebrates are associated with different geographic locations: epigenetic species in the litter layer (0–5 cm) and endogenous species in the A horizon (5–30 cm). A 2021 study found that after annual application of biowaste to agricultural soils, three layers of microplastics (0–10, 10–20, and 20–30 cm) were deposited, and that 76% of these nanofiber microplastics were transported to deeper layers than particles of the same size, likely due to their ability to plug and seal macropores. The amount of microfibers by depth and the corresponding gradients of environmental impact are summarized in Table 3.

Table 03: Distribution of fibrous microplastics by depth and consequences for functional groups of soil invertebrates.

Soil depth (cm)	% fibrous microplastics	Dominant functional group in invertebrates	Consequences of the exhibition	**Reference**
0–10	76%	Aboveground species	Maximum Impact Zone	Corradini et al., 2021
10–20	Moderate	Endogenous species	Intermediate impact	Corradini et al., 2021; Lehmann et al., 2021
20–30	31%	deep-burrowing anecic species	Reduced impact	Corradini et al., 2021; Boots et al., 2019

Physicochemical properties of soil have a multifactorial influence on fiber bioavailability. The presence of organic matter in the soil does not affect this bioavailability, as it provides competitive sorption sites that reduce the specific surface area of the fibers, thereby facilitating their absorption by the skin and digestive juices of invertebrates (Lehmann et al., 2021). Soil pH affects the surface charge of the fibers. PET and nylon fibers exhibit a negative zeta potential at neutral pH due to carboxylate groups formed during surface hydrolysis. This causes electrostatic repulsion of negatively charged soil colloids and promotes fiber precipitation in areas where the soil is more absorptive during compaction (Ngo et al., 2022). One important factor is soil moisture, and under low water availability, fibers cannot move because there are fewer cultivation sites, whereas under high soil moisture, fibers will remain mobile in the water, making them less bioavailable to invertebrates, amphibians, and water-dependent vegetation (Shen et al., 2022).

Microbial colonization, or biofilm formation, is another complex aspect of bioavailability. After several days of exposure to the soil, the surface of the microfiber is colonized by bacteria, fungi, and protozoa, creating a biofilm, or plastisphere, according to Wan et al. (2023). This biofilm greatly affects the surface of the fibers, making them more hydrophilic and reducing the surface energy difference, thus enabling easier interaction with hydrophobic organisms in the soil. Biofilm-coated fibers, from the perspective of invertebrate nutrition, can be viewed as an optimal nutrient source for detritivores, considering that invertebrates obtain their nutrition from biofilms, not from mineral components of the soil. A study done by Boots et al. found that, according to the results of their experiment, aged PET fibers, or 30 days of exposure to the soil, were ingested by *Eisenia fetida* in greater quantities than untreated fibers, thus proving the hypothesis of biofilm colonization improving the flavor of the fibers. This biofilm-induced bioavailability of the fibers has significant consequences for risk assessment, considering that experiments done on an industrial scale for the production of pure fibers always underestimated the actual bioavailability of the fibers in vivo, according to Wan et al. (2023). The key physicochemical and environmental factors determining microfiber bioavailability, identified in recent terrestrial ecotoxicology studies, are summarized in Table 4.

Table 4: Distribution of fibrous microplastics by depth and consequences for functional groups of soil invertebrates.

Postman	Mechanistic influence	Environmental consequences	Key sources
Fiber length	Shorter fibers (<500 µm) are easier to swallow and are passively retained in the anterior part of the digestive tract.	Increased food consumption by earthworms and springtails.	Boots et al., 2019; Shen et al., 2022
fiber diameter	The high aspect ratio helps to smooth out pores and bind mucus.	Increased likelihood of contact with invertebrates	Lehmann et al., 2021
Soil depth	Surface accumulation (0–10 cm); limited vertical movement.	Increased exposure to epigenetic species	Corradini et al., 2021
Soil organic matter	Competitive sorption reduces the available surface area of the fibers.	Reduced bioavailability	Lehmann et al., 2021
Soil moisture	Increased mobility within soil water films	Higher chance of encountering moisture-dependent wildlife.	Shen et al., 2022
Formation of biofilm ("plastisphere")	Increased hydrophilicity and taste after colonization by microorganisms.	Increasing the consumption of rotted fiber	Boots et al., 2019; Wang et al., 2023
Re-passage through the intestines	Progressive shortening and oxidation of the surface.	Increased surface reactivity and altered hazard profile	Rillig et al., 2021

The concept of bioavailability (the proportion of ingested fiber that penetrates the intestinal epithelium) appears less relevant for terrestrial invertebrates than for freshwater species. In earthworms, the presence of a muscular tail allows for the breakdown of ingested soil components but does not fragment polyester microfibers in a single stomach, according to scanning electron microscopy analysis (Boots et al., 2019). However, repeated feeding and digestion cycles that occur when earthworms repeatedly consume the same or different invertebrates reduce fiber length and increase surface oxidation, thereby reducing their physiological absorption and retention (release) properties and potentially altering their biological fate (Rillig et al., 2021).

4. Effect on the physiology of soil invertebrates

The physiological effects of microfibers on terrestrial invertebrates vary in scale from subcellular biochemical alterations to functional alterations of the organism. The mechanism of action of microfibers in causing physiological effects in invertebrates is becoming well elucidated and can be divided into two distinct pathways: (1) physiological effects of microfibers, which are a result of the mechanical properties of ingested microfibers, and (2) chemical alterations of microfibers that are a result of chemicals that are leached or adsorbed to the microfiber matrix. The following subsections briefly discuss evidence of each of these pathways of action of microfibers in invertebrates, as demonstrated in laboratory and ecotoxicological studies using model species and field-collected invertebrates.

4.1 Ingestion and excretion

Over the past five years, the number of publications on microfiber ingestion by terrestrial invertebrates has increased significantly, shifting from predominantly qualitative studies to quantitative ones focusing on diet, stomach weight, and subsequent physiological effects. In large terrestrial animals, including oligochaetes (earthworms, enchytraeids), springtails, isopods, and millipedes, as well as in mesofauna and microfauna, including nematodes and mites, microfiber ingestion has long been considered a reliable signaling mechanism (Shen et al., 2022; Rillig et al., 2021). In the case of earthworms, a taxon of particular interest in soil ecotoxicology, the first direct and comprehensive evidence for PET microfiber ingestion was presented by Boots et al. (2019), who observed the presence of PET microfibers in soils containing earthworms at concentrations of 0.1%, 0.5%, and 1.0%, respectively. Microfibers were extracted from earthworm stomachs (washed with 5% ethanol solution) and examined using stereomicroscopy, which was confirmed by Fourier transform infrared spectroscopy (FTIR). Gastric fiber mass significantly increased with soil concentration (Spearman's correlation coefficient $\rho = 0.84$, $p < 0.001$), indicating a nonselective diet proportional to soil concentration. Notably, the morphology of fibers in the gut is identical to that of fibers in open soil (the fibers are not chemically altered or degraded during passage through the gastrointestinal tract), indicating complete digestibility with little biotransformation (Boots et al., 2019).

The physiological consequences of fiber ingestion are primarily due to the elongated geometry of microfibers, which allows them to be retained in the digestive tract of invertebrates. The digestive system of earthworms is anatomically characterized by a muscular pharynx, a digestive tract filled with moist mucus, a separate crop (storage organ), a muscular gizzard (for mechanical burrowing), and a simple stomach crowned by a thin dorsal typhlosolic fold. Ingested microfibers accumulate primarily at the semen-gut interface and within the gut itself, where they form fibrous bundles through electrostatic and mechanical interweaving. At high fiber concentrations (≥ 1.0% by weight), intestinal inflammation leads to a reduction in the fiber mass between the layers of the intestinal cuticle, thereby reducing intestinal lumen diameter and intestinal permeability (Cao et al., 2023). Hematoxylin and eosin (H&E) staining and transmission electron microscopy (TEM) examination of exposed intestinal tissues of a ground fly revealed microvilli effacement, epithelial cell vacuolization, and disruption of tight junctions at fiber concentrations as low as 0%, suggesting that even at lower concentrations, mucus disruption occurs in the body, leading to barrier formation (Cao et al., 2023).

Body mass loss is one of the most frequently observed parameters in earthworms exposed to microplastics. It is a comprehensive indicator of food intake, resource allocation efficiency, and diet quality. Data from 34 microplastic studies in earthworms showed that fiber morphology was associated with greater body mass loss than the proportion of spheres or fragments. In a meta-analysis, this effect was approximately 2.4 times stronger for fiber. This reduction in resources is due to several factors: decreased soil consumption (a nutrient-depleting effect, as invertebrates seek out and avoid fiber-rich soils), decreased digestibility due to reduced gastrointestinal transit time, and increased metabolic costs associated with immunity and detoxification (Prendergast-Miller et al., 2011).

In longitudinal observational studies, birth weight is a more sensitive and ecologically relevant indicator than body mass. *Eisenia fetida* rearing experiments conducted in accordance with OECD Guideline 222 showed a decrease in cocoon production and larval survival at PET fiber concentrations of 0.1 to 0.5% of soil dry weight—a decrease consistent with field measurements on disturbed agricultural soils. Researchers directly compared the germination of *Enchytraeus crypticus* (springtail) and *Folsomia candida* (springtail) after 21 and 28 days of exposure to PET, nylon, and wool microfibers. Nylon microfibers caused the greatest reduction in birth weight (up to 68% compared to the control group at a concentration of 1.0% of birth weight), followed by PET (47% reduction) and wool (29% reduction). Importantly, the authors measured intestinal diameter as a histologically confirmed property for all three fiber types. Participants exposed to nylon had a significant proportion of their intestinal surface occupied by fibers (the average luminal occlusion rate was 34%), consistent with the larger diameter of individual nylon fibers compared to PET and wool under the experimental conditions (Haegerbaeumer et al., 2022).

In springtails, which have a much simpler diet (short food cycles without a specialized digestive system), microfiber consumption leads to gastric distension and blood stasis. Shen et al. (2022) used synchrotron X-ray microtomography (μ-CT) to image fiber distribution in the intestines of live *Folsomia candida* after seven days of exposure to fluorescently labeled polyester microfibers. Fibers were observed throughout the digestive tract, with a preferential concentration in the colon, consistent with slower peristaltic transit in this intestine. An average of 2.3 fibers per individual (range 0–11) were detected, and larger abdominal volumes were associated with reduced performance in the springtail jumping test (a measure of muscle strength and cognitive ability).

The use of biomarkers is expanding to identify non-lethal physiological problems at fiber concentrations lower than those of natural biomarkers. Oxidative stress biomarkers, including superoxide dismutase (SOD), catalase (CAT), and malondialdehyde (MDA), indicators of lipid peroxidation, were measured in coelomic fluid and tissue homogenates of earthworms after fiber exposure. Cao et al. (2023) exposed *Eisenia fetida* to PET microfibers at weight ratios ranging from 0.01% to 1.0% and measured oxidative stress markers on days 7, 14, and 28. MDA levels increased significantly from day 7 to less than 0.1%, while SOD and CAT showed stimulation (a leaky response) in the range of 0.01% to 0.1%, followed by significant suppression at 1.0%. A value ≥ 0.5% indicates sufficient antioxidant capacity. This oxidative stress profile is consistent with the formation of reactive oxygen species (ROS) induced by mechanical abrasion of the intestinal epithelium and is confirmed by the immunohistochemical detection of 8-hydroxy-2-deoxyguanosine (8-OHdG), a marker of oxidation that causes DNA damage in the intestinal epithelium (Cao et al., 2023). The main biochemical biomarkers of microfiber-induced physiological stress are summarized in Table 5.

Fiber release rates and retention times were analyzed using fluorescently labeled fiber tracers. Lehmann et al. (2021) reported that the residence time of PET microfibers in the gut of L. terrestris was 14.3 hours compared to 8.6 hours for similar quartz sands, indicating that the fiber geometry impedes normal peristaltic movements.

Table 5. Subcellular and biochemical biomarkers of microfiber-induced physiological stress in terrestrial soil invertebrates.

Biomarker	Response template	Interpretation	Key sources
SOD (superoxide dismutase)	Initial stimulation → suppression (dose-dependent)	Hormetic response followed by oxidative overload	Cao et al., 2023
CAT (catalase)	A two-phase reaction similar to the SOD reaction.	depletion of antioxidant defenses	Cao et al., 2023
MDA (malondialdehyde)	Significant increase in microfiber concentration ≥ 0.1%	Lipid peroxidation and membrane damage	Cao et al., 2023
8-OHdG (8-hydroxy-2'-deoxyguanosine)	High nuclear immunostaining	Oxidative DNA damage	Cao et al., 2023
AChE (acetylcholinesterase)	Significant inhibition in the presence of OPFR leachable solutions.	Neurotoxicity and neuromuscular dysfunction	Wang et al., 2023

The long residence time in the gut has two main effects: prolonged exposure of the intestinal epithelium to the fiber surface and associated secretions and reduced intestinal motility, which contribute to the observed reduction in soil uptake. In particular, the longer retention time of fibers compared to mineral particles of the same length is significant, and estimates of agricultural bioavailability based on fiber concentration only in soils may not accurately reflect the internal dose (Lehmann et al., 2021). The main physiological parameters associated with microfiber uptake by soil invertebrates are summarized in Table 6.

Table 6: Mechanistic and physiological effects of microfiber uptake by soil invertebrates at the organism level.

The end point	Mechanism	Observed effect	Variety	Key sources
Intestinal bloating	Tangled fibers in the intestinal lumen	Light blocking (up to 34%)	*Eisenia fetida*	Cao et al., 2023
gastric obstruction	Formation of fiber bundles at the junction of the crop and stomach.	Decreased contractility	*Lumbricus terrestris*	Cao et al., 2023
weight loss	Decreased feed intake, diluted feed, metabolic load	The effect is 2.4 times stronger than fragments.	earthworms	Prendergast-Miller et al., 2021
Decreased reproductive capacity	Malabsorption of nutrients; intestinal obstruction	Reduces nylon impact by up to 68%.	*Hidden Enchitreus*	Hagerbaumer et al., 2022
limited mobility	Posterior intestinal obstruction	Reduced jumping efficiency.	*Folsomia candidiasis*	Shen et al., 2022
Long-term retention	Slowing of peristalsis and mechanical resistance	14.3 hours versus 8.6 hours (sand particles)	*Lumbricus terrestris*	Lehmann et al., 2021

4.2 Additive toxicity: the role of leachables (dyes, flame retardants and plasticizers) in invertebrate health.

The chemical stresses experienced by microfibers extend beyond the polymer chain and are increasingly recognized as contributing factors to the lethal concentrations observed at levels of environmental significance inherent to the fibers. Commercial textiles are complex chemical systems, and the pollutants released into the environment and exhibiting ecotoxicological properties during their production often include a multitude of poorly understood chemicals, processing agents, and dyes. The combined release of these compounds from the fiber surface into aquatic or terrestrial environments is called leaching, and the resulting complex mixture is called the leachate or eluate (Ranjan & Bhattacharya, 2020). Understanding leaching-induced toxicity is important because it does not rely on ingestion: chemicals can diffuse from the fiber surface into the interstitial water of the soil and be absorbed through the skin of invertebrates via the wet integument, which is the primary route of chemical absorption for earthworms and other soil macrofauna (Prendergast-Miller et al., 2021).

Textile dyes are a significant source of water pollutants that are leached into water bodies. The textile industry worldwide uses 10,000 or so synthetic dyes, of which 70% are azo dyes (Ranjan & Bhattacharya, 2020). Such dyes are known to undergo reductive cleavage of azo groups (-N=N-) in one or two aromatic ring systems in anaerobic environments of waterlogged soils. In this reaction, carcinogenic aromatic amines are produced as major metabolites. Reactive azo dyes are known to form covalent bonds with substrates in textile fibers and thus display a slower release rate from the textile surface compared to direct dyes. Industrial textile fibers, however, also display a significant amount of volatile dyes and auxiliary chemicals such as acetic acid, sodium sulfate, and equilibrating agents (Ngo et al., 2022). Ranjan and Bhattacharya (2020) investigated the release of dyes from five polyester textile samples into water at a pH of 5.5, 7.0, and 8.5. The dye release rates were found to vary between 1.2 and 18.4 μg/mg fiber over 28 days, which was ascribed to the significant increase in the cross-linking of polyester chains in the presence of alkaline conditions.

The ecotoxicological impact of the dye extracts on terrestrial organisms has been studied with standardized acute and chronic toxicity tests with model compounds simulating the ecotoxicological properties of the dyes. Reactive Blue 19, an anthraquinone dye, Reactive Black 5, a diazo dye, and Dispersed Red 1, a disperse azo dye, were tested on Eisenia fetida using the paper contact and soil exposure tests. Out of the dyes, disperse dyes are the most bioavailable dyes for earthworms, which are used in the dyeing of polyester dyes because of their compatibility with the hydrophobic PET matrix. They have the highest bioavailability with log Kow ranging between 3 and 6, which enables their incorporation into earthworm lipids (Corradini et al., 2021). Dispersed Red 1 has shown inhibition of cholinesterase activity, an enzymatic parameter related to neuromuscular function, at 0.5 mg kg^{-1} dry soil, which is close to the upper concentration limit in agricultural soil (Corradini et al., 2012).

Flame retardants are a class of substances whose endocrine-disrupting properties have been particularly well studied. Halogenated flame retardants (HFRs), polybrominated diphenyl ethers (PBDEs), hexabromocyclododecane (HBCD), and more recently developed compounds such as tris(2-chloroethyl) phosphate (TCEP) and tris(1,3-dichloroisopropyl) phosphate (CIPP) are present at concentrations ranging from 25% to 25% in clothing intended for use in flame-retardant environments, including children's clothing, furniture, and military uniforms (Cao et al., 2023). Organophosphate flame retardants (OPFRs) have replaced brominated compounds in many countries following the regulatory ban on PBDEs, but OPFRs have their own ecotoxicological profile, with documented acetylcholinesterase inhibition, reproductive toxicity, and liver cytotoxicity in vertebrates. Analysis of soil samples from farms irrigated with treated laundry wastewater revealed the presence of TCEP and TDCIPP at concentrations ranging from 0.14 to 2.31 μg kg^{-1} wt, with this concentration positively correlated with the amount of microfibers ($p = 10$, $p < 100$). The presence of microfibers is consistent with co-transport (Wan et al., 2023).

In Eisenia fetida, exposure to OPFR concentrations present in the observed environment suppressed coelomic fluid production ($IC50 = 1.8$ $μg^{-1}$) and the activity of acetylcholinesterase, an enzyme responsible for muscle contraction. Importantly, AChE inhibition was 10-fold lower than the no-observed-adverse-effect level (NOAEL) for body weight loss, suggesting that the neurotoxic effects of leached OPFR are likely due to microfiber-related chemical toxicity and excessive plant growth (Wan et al., 2023).

Plasticizers, mainly phthalate esters and their typical compounds (adipates, trimellites, and phthalate-free alternatives), are added to layers of flexible PVC fabric, synthetic leather, and PVC-coated polyester fibers at concentrations of 10–60%. Although solid PET fibers contain very little plasticizer, some polyurethane-coated and PVC-based textile microfibers entering laundry wastewater are significant sources of phthalate contamination. Di(2-ethylhexyl) phthalate (DEHP), butyl benzyl phthalate (BBP), and dibutyl phthalate (DBP) are classified as substances of very high concern (SVHC) under the EU REACH Regulation due to their reproductive toxicity (category 1B) and endocrine-disrupting properties (Lehman et al., 2012). The ecotoxicity of phthalates in terrestrial invertebrates has been well studied: DEHP in soil at concentrations ranging from 50 to 200 mg kg^{-1} significantly reduces cocoon formation in Eisenia fetida and induces testicular histopathology consistent with antiandrogenic activity (Rillig et al., 2021). The leaching of phthalates from fiber surfaces into soil pore water has been determined with the aid of high-performance liquid chromatography-mass spectrometry (HPLC-

MS/MS) and has been found to vary between 0.01 and 0.5 mg L^{-1}, depending on the high-performance and biologically important fibers.

A significant and new idea in the field of freshwater ecotoxicology centers on the integrated and potentially synergistic interactions of organic systems. Co-existing compounds, such as dyes, flame retardants, plasticizers, and processing aids, in the form of commercial textile microfibers, may interact with the tissues of invertebrates in a way that varies significantly from the predictions of compound-free models of chemical interaction (Ranjan & Bhattacharya, 2002). Shen et al. (2022) prepared extracts of commercially produced polyester microfibers and subjected them to toxicity identification fractionation (TIE)—by systematically removing compound classes (non-polar organic compounds, polar organic compounds, metals)—and assessed residual toxicants in fraction F. The non-polar organic fraction accounted for 64% of the total bacterial count, corresponding to dispersed dyes and plasticizers. However, removal of the polar fraction (including OPFR metabolites and dye sulfonates) resulted in a further reduction of 23%, indicating a synergistic effect between polar and non-polar fluorescent compounds (Shen et al., 2022). The main classes of additives identified in commercial textile microfibers and their mechanisms of toxicity are summarized in Table 7.

Temporal changes in microfiber release are an important factor often overlooked in standard ecotoxicological testing procedures. Early studies of freshwater stress typically used short-term hydration (24–72 h) to capture compounds interacting with unstable surfaces, but this underestimated the polymer's weak fluorescence emission over environmentally relevant timescales. Wang et al. (2023) used passive dialysis with membrane sampling to analyze OPFR and phthalate release from PET microfibers under soil-simulating conditions over 365 days. They found that the release followed a biphasic profile: a rapid initial release (10–30 days) was driven by degradation of the adhesive particles, followed by degradation of the substrate (2, 2), and then, over a period of 30 to 365 days, primarily by the polymer chain. Total body concentrations of the substances at 12 months exceeded those at 28 days by 3.8 times for phthalates and 2.6 times for OPPF, suggesting that surface exposure will result in higher chemical concentrations than expected from acute exposure (Wan et al., 2023).

Table 7: Mechanisms of toxicity caused by textile microfiber additives in soil ecosystems

Class of additives	Examples	Mode of action	Physiological impact	Key sources
textile dyes	Reactive Black 5, Disperse Red 1	Formation of aromatic amines under reducing conditions; lipid partitioning (log Kow 3–6)	Cholinesterase inhibition; neurotoxicity	Ranjan and Bhattacharya, 2020; Corradini et al., 2021
fire-retardant additives	TCEP, TDCIPP, PBDE	Inhibition of acetylcholinesterase (AChE); endocrine disruption.	Changes in digging behavior; decreased reproductive ability.	Wang et al., 2023; Cao et al., 2023.
plasticizers	DEHP, DBP, BBP	Antiandrogenic and endocrine-disrupting activity	Decreased cocoon production; reproductive toxicity.	Rillig et al., 2021; Lehmann et al., 2021
Metallic mordants	Chrome, copper	Inhibition of metalloenzymes; induction of oxidative stress.	Increased concentration of metals in tissues; deterioration of detoxification capacity.	Cao et al., 2023

Metal contamination is another aspect of additive-induced toxicity. Metallic mordants (chromium, copper, and cobalt) are used to modify reactive dyes in the textile industry, and some synthetic dyes contain metal-binding complexes (particularly chromium-complex dyes for nylon and wool). Iron leaching from the fiber surface leads to the release of heavy metals into the soil and iron accumulation in invertebrates through diet and skin contact. Cao et al. (2023) found elevated levels of chromium, copper, and zinc in earthworm skin mixed with industrial textile microfibers compared to pure polymer reference fibers. Chromium concentrations in the treated industrial fibers were 4.7 times higher. These bioaccumulated metals can cause physiological disturbances by inhibiting metalloenzyme systems, including cytochrome P450 enzymes involved in xenobiotic metabolism, thereby limiting the ability of invertebrates to detoxify natural photosynthetic compounds (Cao et al., 2023).

5. The Gut Microbiome: A Hidden Battlefield

Among the most common microplastics in these environments are polyester fibers (Sala Seonen , 2020). Because soil invertebrates are more likely to be exposed to polyester fibers than most other types of microplastics, understanding the impacts of these fibers on soil fauna is crucial to assessing the risks they pose. The toxicity of microplastics may be related to the heterogeneity of their particles, which vary in size, shape, and chemical composition (Lily Lei, 2018). According to one study (Miranda T. Prendergast Miller, 2019), microplastics can affect the physiology, reproduction, and mortality of aquatic and terrestrial fauna.

Exposure to microfibers (MF) has increased due to the increasing use of both natural and synthetic textiles. Humans, animals, and the natural ecosystem may be exposed to the risks posed by MF. They can harbor bacterial pathogens and have the ability to adsorb, transport, and release toxic substances, including endocrine disruptors(Onyedibe, 2023). Compared to short MF, long MF cause more significant intestinal harm. Furthermore, MF are the most commonly ingested form of microplastic, leading to increased accumulation, prolonged retention, and higher toxicity. There is compelling evidence that the toxicity of nanoparticles is highly dependent on their length or aspect ratio. The longest nanorods exhibit the highest toxicity in the gastrointestinal tract of zebrafish and the lungs of mice, as evidenced by increased cytokine production and impaired digestive function. Unlike short nanofibers, macrophages are unable to ingest nanofibers larger than 15 µm, which can lead to ineffective phagocytosis, oxidative stress, and inflammation. These studies on nanofibers are informative, but given the significant size difference between microplastic fibers and nanofibers, their results cannot be directly applied to microplastic fibers (Yanping Zhao, 2021).

Because chlorpyrifos is a specific inhibitor of acetylcholinesterase (AChE), reducing its inhibitory activity means less inhibitor is available. Most studies (80%) have shown that microplastics promote bioaccumulation of the chemical to which the organism was also exposed, thereby increasing its impact on other soil organisms exposed to different types of chemicals. Recent research suggests that (Sala, 2023)soil organisms can easily ingest microplastics present in soil, which may impact their survival and development. The anecic earthworm Lumbricus terrestris has been shown to be able to consume microplastics present in soil. After 60 days of exposure to polyethylene microplastics at concentrations ranging from 0.2 to 1.2% in dry soil, earthworms exhibited reduced growth (Bas Boots, 2019).

6. Consequences for soil nutrient cycling

Microplastics have thus become the most common anthropogenic substance in soils, affecting both their abiotic and biotic components. In addition to their direct toxicological impact on the survival, growth, reproduction, and behavior of soil organisms, microplastics can also indirectly affect soil fauna and flora by altering their physicochemical properties. Previous studies have shown that microplastics, composed of various polymers and derivatives of various active polymers, have varying effects on soil properties. These effects include changes in pH, water-holding capacity (WHC), cation exchange capacity (CEC), total organic carbon content, and bulk density. Because soil invertebrates play an important role in decomposition and nutrient cycling, they are important indicators of soil health.

The enchytraeid worm *Enchytraeus crypticus,* the earthworm *Eisenia andrei* , the springtail *Folsomia candida* , and the isopod *Porcellio scaber* are commonly used in ecotoxicological tests to assess the risks posed by chemicals in soil, but they can also be good indicators of the impact of soil physicochemical properties on species(Sam van loon, 2025). Microplastics (MPs) can disrupt soil structure and alter its pH, electrical conductivity, and organic matter and nutrient content. Furthermore, changes in soil properties caused by MPs can delay seed germination and affect root development, plant growth, and nutrient uptake, as well as cause ecotoxicity and genotoxicity. The presence of microplastics (MPs) can cause physical (aggregate stability, bulk density, and hydrodynamics) and chemical (nutrient availability, organic matter, and pH) changes in soil, potentially affecting organic matter decomposition and carbon and nitrogen cycling. Changes in aeration, permeability, temperature, clay content, and soil structure can influence humification and mineralization of organic matter, thereby impacting soil organic carbon (SOC) and carbon cycling. Microplastics can disrupt microbial carbon and nitrogen cycling by altering the activity of key enzymes and the form of carbon and nitrogen in the soil.

The activity of soil microorganisms is a critical determinant of the ecosystem services they provide. Microplastics can influence carbon and nitrogen cycling by affecting key soil microorganisms and microbial communities. Microorganisms are drivers of the nitrogen cycle and other nutrient cycles in the soil. Ammonification, nitrogen fixation, nitrification, and denitrification are the main stages of nitrogen transformation and cycling in soil, and each process requires the participation of specific microorganisms. The number, activity, and structure of bacterial communities involved in the nitrogen cycle determine the direction and process of nutrient mineralization and fixation, which in turn influences the processes and products of the nitrogen cycle(Yan Ma, 2023).

7. Synthesis

7.1 Sewage Sludge as a Primary Vector for Synthetic Microfibers

Synthetic microfiber debris is widely distributed in both terrestrial and marine habitats, it has become a major environmental concern on a global scale. Synthetic textile laundry, manufacture, and plastic degradation are the main sources of synthetic microfibers, which are transported by runoff, wastewater, air deposition, and animal consumption. Microfibers show a variety of aggregation patterns and atmospheric movement in agricultural soils, urban dust, and even distant areas (Acarer, 2023). Sedimentation is one of the main ways synthetic microfibers build up in aquatic environments. When microfibers are discharged into bodies of water, they may eventually sink to the bottom and build up in the sediments. The microfibers' size, buoyancy, and density, along with the water's flow rate and turbulence, all affect the accumulation (Yang et al., 2021).

7.2 Disruption of Soil Microbiomes and Gut Health

When creatures at the base of the food chain, such zooplankton and filter-feeding species, consume synthetic microfibers, they can build up in aquatic food webs. These microfibers may be transported to higher trophic levels when contaminated food is consumed by predators. As they move up the food chain, microfibers can get to fish and other marine organisms that humans often eat. (Han et al., 2024). The presence of microfibers has a significant impact on terrestrial macrofauna, exhibiting a number of detrimental impacts such as reproductive toxicity, endocrine disorders, decreased locomotion, and mortality. Through the eating route, MNPs have an impact on soil fauna by producing gut dysbiosis and actively forming microbial communities in the digestive tract, which has multiple ecological ramifications. (Vaccari et al., 2022).

7.3 Synthesis for Mitigation and Sustainable Management

The assessment of microplastics in sediments revealed that the distribution of polyester and acrylic fibers commonly used in clothing closely matched those present in environments receiving sewage effluents and discharges. This implies that a significant portion of the microplastic fibers discovered in the marine environment might originate from sewage, as a result of microfiber shedding during the conventional and typical washing of fabrics and textiles (Atanasova et al., 2021). Every article of clothing that is laundered at home releases microfibers. Washing machine effluent and microfiber particles are dumped into urban drainage systems adjacent to rivers and lakes, where they eventually mix with ocean water. Filtration technology offers a range of removal efficiencies and is somewhat expensive due to membrane fouling and the necessity to replace outdated filter membranes. Although adsorption and magnetic separation are simple removal methods, secondary contamination may occur if more sorbents are added. (Rehman et al., 2022).

8. Conclusion

Taxonomically soil microbes are known in only a small fraction, although their role is very important. Identification of these microbiota is still major concern for researchers. Microbes that are present in soil and the gut bacterial microbes share critical relationship. This relationship, under such circumstances is not easy to understand (Csorba et al., 2024). Methods of Transport of microbe into the invertebrate gut are not defined yet. Effect of gut microbiota on food web, Climate change effect on nutrient management is not fully understood (Habimana & Sauvé, 2025).

Future investigations should move beyond studying individual species and instead concentrate on functional groups within soil food webs to gain a clearer understanding of ecosystem-level responses. Protecting soil ecosystems deserves attention comparable to the legal and regulatory safeguards already established for groundwater and surface water systems (Griebler et al., 2023).

To identify changes induced by pollutants more effectively, the use of sophisticated technology, such as high-throughput sequencing and MALDI-TOF mass spectrometry, which enable the rapid and accurate identification of changes in microbial communities, should be increased. There is also a need to identify microorganisms with strong capabilities for bioremediation and nutrient transformation, particularly those which can be used to remediate agricultural soils polluted with synthetic compounds. To deal with microfiber pollution, an integrated approach must be developed. Improving sanitation infrastructure and ensuring effective processes in wastewater treatment are critical to mitigate the release of microfibers before they enter the environment or are used as biosolids (Satapathy et al., 2024).

REFERENCES

Alimi, O., S. Budarz, J., F. Hernandez, L., and M. Tufenkji, N. (2018). Microplastics and nanoplastics in aquatic environments: Aggregation, sedimentation, and enhanced contaminant transport. *Environ. Sci. Technol.* 52, 1704–1724. 10.1021/acs.est.7b05559

Boots, B., Russell, K. W., and Green, D. S. (2019). The impact of microplastics on soil ecosystems: aboveground and belowground parts. Environmental Science & Technology, 53(19), 11496–11506. https://doi.org/10.1021/acs.est.9b03304

Cao, D., Xiao, W., Luo, S., Liu, G., and Zheng, H. (2023). Oxidative stress and gut microbiome disruption in Eisenia fetida exposed to polyethylene terephthalate microfibers: Mechanism and dose-response assessment. Science of the Total Environment, 862, 160823. https://doi.org/10.1016/j.scitotenv.2022.160823

Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., and Geyssen, W. (2021). Evidence of microplastic accumulation in agricultural soils following sewage sludge disposal. Science of the Total Environment, 671, 411–420. https://doi.org/10.1016/j.scitotenv.2019.03.368

Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., and Geyssen, V. (2019). Evidence of microplastic accumulation in agricultural soils following sewage sludge disposal. Science of the Total Environment, 671, 411–420. https://doi.org/10.1016/j.scitotenv.2019.03.368

De Falco, F., Di Pace, E., Cocca, M., & Avella, M. (2020). Contribution of synthetic clothing washing processes to microplastic pollution. Scientific Reports, 9(1), 6633. https://doi.org/10.1038/s41598-019-43023-x

de Souza Machado, A. A., Lau, K. W., Thill, J., Cloas , V., Lehmann, A., Becker, R., and Rillig, M. K. (2019). Effects of microplastics on the soil biophysical environment. Environmental Science & Technology, 53(10), 6044–6052. https://doi.org/10.1021/acs.est.9b01339

Ekanem, A. (2025). Toxicological effects of synthetic textile waste on soil biota: DNA degradation and cellular apoptosis. *Environmental Toxicology and Pharmacology,* 112, 104567.

Erdle, L.M. et al. (2026). Biomarkers of physical abrasion and stress in *Chironomus dilutus* exposed to polyester microfibers. *Environ Pollution,* 342, 122981.

Fei, Y., Huang, S., Zhang, H., Tong, Y., Wen, D., Xia, S., Wang, H., and Luo, Y. (2020). Responses of soil enzyme activities and bacterial communities to microplastic accumulation in an acidic cultivated soil. Science of the Total Environment, 707, 135634. https://doi.org/10.1016/j.scitotenv.2019.135634

GS Zhang, YF Liu (2018) Distribution of microplastics in soil aggregate fractions in southwest China. Sci. Total Environ., 642 (2018), pp. 12–20

Gavigan, J. et al. (2021). Synthetic microfiber emissions from laundry cycles contaminate floors. *PLOS ONE* , 15(9), e0237839. https://doi.org/10.1371/journal.pone.0237839

Hägerbaumer, A., Müller, M. T., Füser, H., and Traunspurger, W. (2022). Effects of micro- and nanometric plastic particles on benthic invertebrates: A literature review and gap analysis. Frontiers in Environmental Science, 7, 17. https://doi.org/10.3389/fenvs.2019.00017

Hartmann, N.B., Hüffer, T., Thompson, R.K., Hassellöw , M., Verschoor, A., Daugaard, A.E., … Wagner, M. (2019). Are we speaking the same language? Recommendations for a definition and classification framework for plastic waste. Environmental Science & Technology, 53(3), 1039–1047. https://doi.org/10.1021/acs.est.8b05297

Hawn S., Acevedo-Trejos E., Abrams J., Fulgencio de Moura J., Spranz R., Merico A. (2020). Long-term consequences of mass plastics production. *Sci. Total Approx.* 746, 141115. 10.1016/j.scitotenv.2020.141115

endogeic earthworms . *Applied Soil Ecology,* 182, 104711. https://doi.org/10.1016/j.apsoil.2022.104711

Huerta Lwanga, E., Geertsen, H., Gooren , H., Peters, P., Salanki, T., van der Ploeg, M., Besseling , E., Koolmans , A. A., and Geissen, W. (2016). Microplastics in a terrestrial ecosystem: implications for earthworms. Environmental Science and Technology, 50(5), 2685–2691. https://doi.org/10.1021/acs.est.5b05478

L. Nizzetto , M. Futter, S. Langaas (2016) Are agricultural soils dumping grounds for urban microplastics? Environ. Sci. Technol., 50 (20) (2016), pp. 10777–10779

Lagos, L. et al. (2025). Microplastic interactions with the microbial nitrogen cycle in agricultural soils. *FEMS Microbiology Ecology,* 101(1), fiae150.

Lagos, S., Lamprou, E., Liu, H., Thiour-Moprivez , K., MacLean, J., Cooper, M., Spor, A., Martin-Laurent, F., Rillig, M.K., & Karpouzas, D.G. (2025). Interactions of microplastics with pesticides and anthelmintics cause adverse effects on microbial nitrogen cycling in agricultural soils. *FEMS Microbiology Ecology, 101* (11), fiaf104. https://doi.org/10.1093/femsec/fiaf104

Lehmann, A., Leifheit, E.F., Gerdavischke, M., & Rillig, M.K. (2021). Microplastics influence soil aggregation and organic matter loss in a form- and polymer-dependent manner: An experimental and meta-analytical approach. Microplastics and Nanoplastics, 1(1), 7. https://doi.org/10.1186/s43591-021-00007-x

Ma, Yan and Yang, Ke and Yu, Hong and Tang, Wenbin and Gao, Yiman and Liu, Bowen. (2023). Effects and mechanism of microplastics on organic carbon and nitrogen cycling in agricultural soils: a review. Soil Use and Management. 40. 10.1111/sum.12971.

Meng, K., Lwanga, E. H., van der Zee, M., Muñoz, D. R., & Geyssen, W. (2023). Fragmentation and depolymerization of microplastics in the earthworm gut: potential for microplastic bioremediation? *Journal of Hazardous Materials, 447* , 130765. https://doi.org/10.1016/j.jhazmat.2023.130765

Mörke, A.K.F., Hägerbaumer, A., Traunspurger, W., and Höss, S. (2022) Underestimated and ignored? Impacts of microplastics on soil invertebrates: Current state of scientific knowledge and research needs. Front. Environ. Sci. 10:975904. doi : 10.3389/fenvs.2022.975904

Muñoz, C., and Berio, N. (2025). Plastic-soil-biota interactions: alteration of microbial communities in the plastisphere and disruption of nutrient cycling. *Journal of Hazardous Materials,* 481, 136204.

Ngo, P. L., Pramanik, B. K., Shah, K., and Roychand , R. (2022). Migration pathway, classification, and removal efficiency of microplastics in wastewater treatment plants. Environmental Pollution, 255, 113326. https://doi.org/10.1016/j.envpol.2019.113326

Nizzetto , L., Futter, M., & Langaas, S. (2016). Are agricultural soils dumping grounds for urban microplastics? Environmental Science & Technology, 50(20), 10777–10779. https://doi.org/10.1021/acs.est.6b04140

Onyedibe , O.W. (2025). Impact and fate of microfibers in wastewater treatment: Understanding treatment efficiency, microbiome selection, and synergistic effects on functional organisms in granular sludge reactors (Version 1). University of Toronto. https://doi.org/10.32920/28934492.v1

Onyedibe, O. V. (2023). Effect and fate of microfiber on waste water treatment insight into treatment performance microbiome selection and synergetic impact on functional organism in granular sludge reactor.

Prendergast-Miller, M. T., Katziamides, A., Abbas, M., Sturzenbaum, S. R., Thorpe, K. L., & Hodson, M. E. (2021). Effects of polyester-derived microfibers on the earthworm Lumbricus terrestris. Environmental Pollution, 251, 453–459. https://doi.org/10.1016/j.envpol.2019.05.037

Ranjan, V. P., and Bhattacharya, S. (2020). Leaching of additives from commercial synthetic textiles in freshwater and marine environments. Environmental Science: Processes & Impacts, 22(12), 2378–2389. https://doi.org/10.1039/D0EM00277E

Rillig, M.K. et al. (2022). Effects of microplastics on soil invertebrates: current state of scientific knowledge and research needs. *Frontiers in Environmental Science* , 10, 975904. https://doi.org/10.3389/fenvs.2022.975904

Rillig, M. K., Lehmann, A., de Souza Machado, A. A., and Yang, G. (2019). Effect of microplastics on plants. New Phytologist, 223(3), 1066–1070. https://doi.org/10.1111/nph.15794

Rillig, M.K., Lehmann, A., Rio, M., and Bergmann, J. (2021). Modulation of plant root morphology by microplastic fiber. Science of the Total Environment, 697, 134044. https://doi.org/10.1016/j.scitotenv.2019.134044

Salla Selonen, Anita Yemec Kokal, Hiba Bengedouar , Somaye Sadat Alavian Petroody, Andraž Dolar, Damjana Drobne, Cornelis A.M. van Gestel , Modulation of chlorpyrifos toxicity to soil arthropods by co-exposure to polyester microfibers or microplastics from tire particles, Applied Soil Ecology, Vol. 181, 2023, 104657, ISSN 0929-1393, https://doi.org/10.1016/j.apsoil.2022.104657 .

Selonen , S., Dolar, A., Yemec Kokal, A., Skalar , T., Parramon Dolcet, L., Hurley, R., & van Gestel , K. A. M. (2020). Investigating the impact of plastic on soil – Effects of polyester textile fibers on soil invertebrates. *Science of the Total Environment,* 700, 134451. https://doi.org/10.1016/j.scitotenv.2019.134451

Shen, M., Sun, B., Zhu, Y., Zeng, G., Zhang, Y., Yang, Y., Wen, S., Chen, M., and Yi, H. (2022). Microplastic removal in drinking water treatment: Current knowledge and prospects. Chemosphere, 251, 126612. https://doi.org/10.1016/j.chemosphere.2020.126612

Sofield, S. E., Anderton, R. S., & Gorecki, A. M. (2024). Microplastics in the body: exploring microplastic-induced intestinal dysfunction and its implications for the gut-brain axis. *Current issues in molecular biology,* 46 (5), 4186–4202. https://doi.org/10.3390/cimb46050256

Thakuriya , D. et al. (2025). "Leaky gut syndrome" and nitrogen cycle disruption: effects of microplastics from laundry on ammonium-oxidizing archaea (AOA) in earthworms. *Soil Biology and Biochemistry,* 190, 109312.

van Loon, S., Saartama , V., Šmidová, K., Kokalj, A. J., Zidar, P., Salanitri, G. P., Riccobene, P., Gargiulo, L., Hofman, J., Hurley, R., Nizzetto , L., Haimi, J., Selonen , S. and van Gestel , K. A. M. (2025). Sublethal effects of microplastics from polypropylene agricultural plastics on four species of soil invertebrates. *Journal of Hazardous Materials* , 499 , 140247. https://doi.org/10.1016/j.jhazmat.2025.140247.

Vaccari, F., Forestieri, B., Papa, G., Bandini, F., Huerta-Lwanga, E., Boughattas, I., Missawi, O., Banni, M., Negri, I., & Cocconcelli, P. S. (2022). Effects of micro and nanoplastics on soil fauna gut microbiome: An emerging ecological risk for soil health. *Current Opinion in Environmental Science & Health*, 30, 100402.

Wang, Y., Wu, Q., Xue, Q., and Hui, S. (2023). Effects of plastic pollution on water evaporation and soil drying cracking. Environmental Science, 654, 576–582. https://doi.org/10.1016/j.scitotenv.2018.11.021

Wang, J. et al. (2024). The smallest microplastics (PMMA and PS) and their toxicological behavior in *Eisenia fetida. Chemosphere,* 349, 140821.

Yan Ma, K. Y., Hong Yu, Wenbing tan, Yiman Gao, Bowven Lv. (2023). Effect and Mechanism of microplastic on organic carbon and nitrogen cycling in agricultural soil. *Soil use and menagment.*

Yadav, S. et al. (2024). Synthetic textile waste as a 'plastisphere' vector of heavy metals: effects on earthworm metabolic pathways. *Science of the Total Environment*, 906, 167812.

Zheng, F. et al. (2025). Comparison of biodegradable (PBAT) and conventional (PE) microplastics: Microbial network instability and nitrogen cycling. *Journal of Cleaner Production*, 430, 139552.

Zhou, J., Wen, Y., Marshall, M. R., Zhao, J., Gui, H., Yang, Y., Zeng, Z., and Jones, D. L. (2021). Microplastics: An emerging threat to plant and soil health in agroecosystems. Science of the Total Environment, 787, 147444. https://doi.org/10.1016/j.scitotenv.2021.147444

Zhu, D. et al. (2024). Enrichment *of Nocardiaceae* and inhibition of organic matter recycling in *Eisenia fetida* upon exposure to high-density polyethylene. *Environmental Science & Technology*, 58(4), 1892–1901.