

# Microplastics as Modulators of Soil Nutrient Cycling under Hydrological Connectivity in Earth's Critical Zone

Haider Ali<sup>1</sup>, Hassan Ali<sup>2</sup>, Komal Yaseen<sup>3</sup>, Muhammad Ahmad<sup>4</sup>, Waqas Altaf<sup>5</sup>

<sup>1</sup>School of Hydrology and Water Resources Nanjing University of Information Science and Technology, Nanjing, 210044, China.

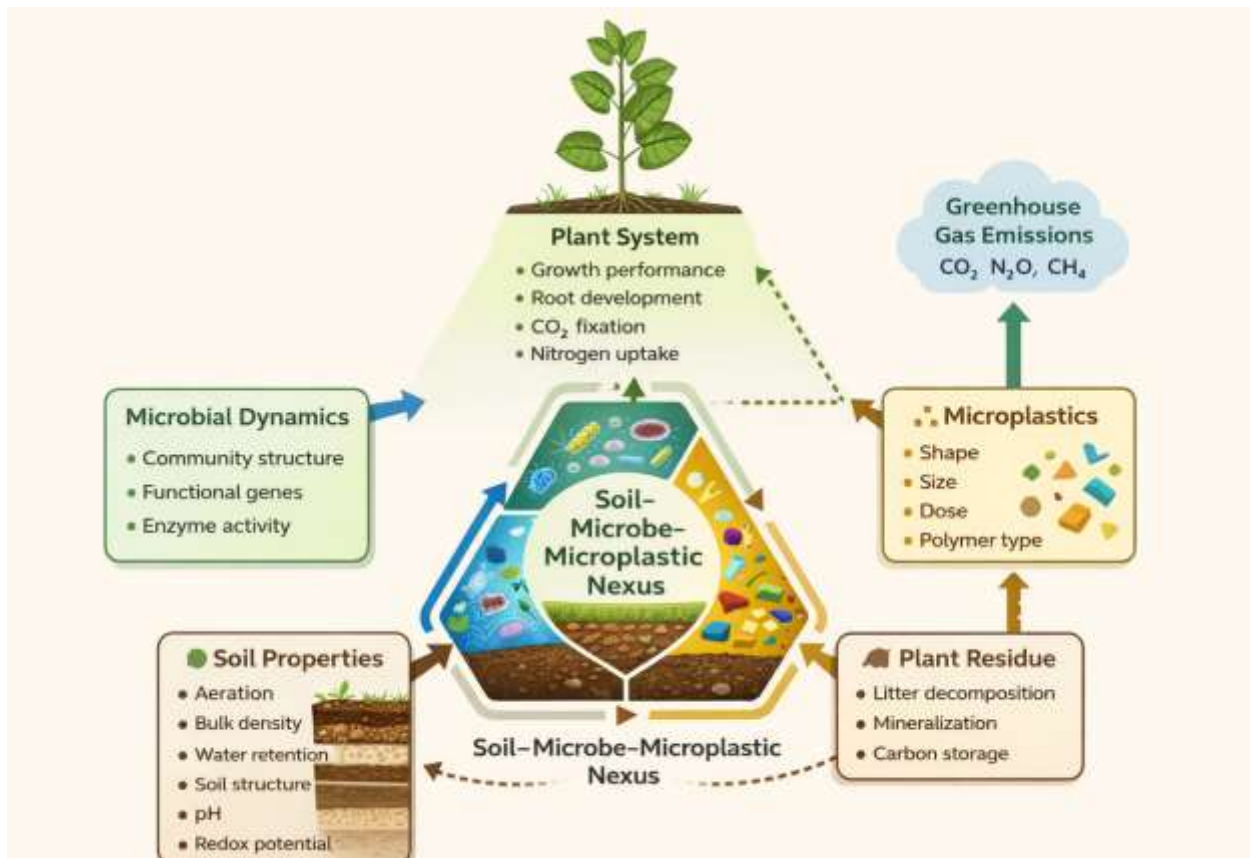
<sup>2</sup>School of Climate Change Management Hochschule Weihenstephan-Triesdorf University of Applied Sciences, D-85350 Freising, Germany

<sup>3</sup>College of Chemistry and chemical Engineering, Zhejiang Sci-Tech University, Hangzhou, 314423, China;

<sup>4</sup>School of Electronics and Information Engineering, Nanjing University of Information Science and Technology, Nanjing, 210044, China

<sup>5</sup>School of Veterinary Sciences. University of Agriculture Faisalabad, Faisalabad, 38000, Pakistan;

## GRAPHICAL ABSTRACT



**Abstract-** Microplastics have emerged as pervasive contaminants in terrestrial ecosystems, with agricultural soils serving as major sinks through sources including plastic mulch, sewage sludge, and atmospheric deposition. This comprehensive review synthesizes current knowledge on how microplastics modulate soil nutrient cycling within the Earth's Critical Zone, with particular emphasis on the mediating role of hydrological connectivity. The physical presence of microplastics fundamentally alters soil structure, porosity, aggregate stability, and hydraulic properties in polymer- and concentration-dependent manners, creating preferential flow pathways that govern both microplastic transport and nutrient dynamics. Biodegradable microplastics generally exert more pronounced effects than conventional polymers, increasing CO<sub>2</sub> emissions while simultaneously altering microbial carbon use efficiency. Nitrogen cycling is consistently disrupted, with reduced nitrate concentrations, enhanced N<sub>2</sub>O emissions (up to 140.6% increase), and shifts in nitrogen-transforming microbial guilds. Tire wear particles and their associated chemicals, particularly the highly toxic transformation product 6PPD-quinone, represent emerging contaminants of high concern with substantial emissions (estimated 79.5 kt annually in the U.S.), accumulation in roadside soils (up to 26,400 mg/kg), and demonstrated toxicity to soil biota. The effects of microplastics on nutrient cycling are profoundly context-dependent, modulated by soil properties, microplastic characteristics, environmental conditions, and biological factors. Significant knowledge gaps remain regarding deep Critical Zone processes, temporal dynamics, and interactive effects with global change factors. As plastic production continues to increase, understanding and mitigating the effects of microplastics on soil nutrient cycling under varying hydrological regimes represents a pressing environmental imperative with implications for soil health, agricultural productivity, and climate regulation.

**Keywords:** Critical zone, Microplastics, Plastisphere, Soil nutrient cycling, 6PPD-quinone.

## I. INTRODUCTION

*The Ubiquity and Significance of Soil Microplastics*  
*The Pervasive Nature of Microplastic Pollution*

Microplastics are tiny fragments of plastic that are smaller than five millimeters. The bigger plastic polymers eventually disintegrate into smaller particles known as microplastics (less than 5 mm). Microplastics from sources like sewage sludge, landfills, plastic mulch from farming, fertilizers, and municipal wastewater discharge are naturally absorbed by the soil (Omidoyin and Jho, 2023).

Microplastics have garnered increased attention worldwide due to their extensive distribution in many environmental compartments, food, and drinking water. (Wang, Zhao and Xing, 2021). It is suggested that whereas soil fauna responses to conventional MPs and BMPs varied slightly over time, the short-term effects of all MP types on soil faunal communities were negligible. (Huang *et al.*, 2023). Plastic garbage has contaminated the environment worldwide due to the extensive and widespread use of plastics and the items made from them. (W. Wang *et al.*, 2020). The most common types and sizes are fibers and tiny

particles (0–0.49 mm). Particles of polystyrene (PS), polyethylene (PE), polypropylene (PP), high-density polyethylene (HDPE), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) are found in agricultural soil. (Ding *et al.*, 2020).

The big plastic fragments will eventually disintegrate into microplastics (less than 5 mm), which are extremely persistent organic pollutants that draw attention from all around the world because of their tiny particle size and possible ecological risks. Terrestrial systems, such soils, are more vulnerable to plastic contamination than marine systems because they act as sinks for microplastics. (Ya *et al.*, 2021). The microplastics also carried the adsorbed nutrient (nitrogen; N), pollutant (cadmium; Cd), and green fluorescent *Escherichia coli* (GFP-*E. coli*) (Luo *et al.*, 2023).

Antibiotic resistance genes and silencing RNAs attached to microplastics may increase resistance and modify gene expression in environmental bacteria, respectively. (Maguire and Gardner, 2023).

### **Physicochemical Properties and Environmental Fate of Soil Microplastics**

The types, sizes, and concentrations of microplastics had a substantial impact on soil compression. While fibrous microplastics increased the void ratio significantly more at low stress than at high stress, granular microplastics increased the void ratio uniformly within the applied stress. (Dong *et al.*, 2025). It is stated that microplastic exposure significantly reduced soil bulk density (lnRR = 0.04) and aggregate stability (lnRR = 0.085), suggesting that microplastics may harm the soil's surface or structural integrity. Soil is an interconnected complex, and exposure to microplastics can either directly or indirectly interact with environmental chemical processes in the soil environment, potentially harming the soil ecosystem. (Qiu *et al.*, 2022). The most prevalent form of microplastic particle was micro fragments, which made up 34% of all microplastics, followed by microfibers (30%). (Zhou *et al.*, 2021). Microplastics can age through hetero-aggregation, bioturbation, and oxidative breakdown triggered by light and heat after they are discharged into the terrestrial environment. Aging alters the physiochemical characteristics of microplastics by increasing their surface roughness and oxygen-containing groups, which may improve their mobility and sorption in the soil and groundwater environment. (Ren *et al.*, 2021).

Aging processes are inevitable for microplastics (MPs) in the soil environment. The microbial community that developed on the surface of MPs was different and less varied than that of the surrounding soils, and the kind of MP determined the microbial population in the biofilm. Aged MPs, particularly those aged in soil containing manure, had a significant impact on the reproduction of soil worms with a more noticeable disruption to their gut microbiota. The primary causes of these changes were biofilm characteristics and changes in the leaching properties of MPs during aging. (Ding *et al.*, 2024). The biotic and abiotic elements of the ecosystem are seriously threatened by their

ongoing use, buildup, and contamination of soil and water.

It adds to global warming in addition to raising carbon footprints. (Singh *et al.*, 2022). By altering their properties, microplastics can modify a number of important soil biogeochemical processes, which can have a variety of implications on the functions and activities of soil microorganisms. (Yu *et al.*, 2022). Microplastics may undergo trophic transmission across food chains after translocating into terrestrial systems and gradually bioaccumulating inside plant tissues, potentially endangering human populations' health. (Meng and Zhang, 2025). Microplastics tended to considerably reduce the amounts of soil water-stable macro-aggregate (> 0.25 mm), with a statistically negative standard mean difference (- 0.90) in the meta-analysis. Furthermore, by having negligible effects on crop biomasses both above and below ground, soil microplastics appeared to have little influence on crop development. (Li *et al.*, 2022).

Plastics, including macroplastics, mesoplastics, microplastics, and nanoplastics, have been shown to have a major impact on soil properties. They have the potential to change the physical characteristics of soil, such as bulk density, texture, structure, water aggregate stability, water-holding capacity, and rainwater infiltration. By affecting pH levels, electrical conductivity, nutrient cycling, enzyme activity, and even the buildup of heavy metals in plants, microplastics can alter the chemical characteristics of soil.

Additionally, soil species, especially earthworms, collembolans, and microbial communities made up of bacteria and fungi, are significantly impacted by microplastics. These organisms are essential to the health of the soil and the cycling of nutrients. Microplastics can have a profound impact on the terrestrial food web by upsetting their habitats, altering their behavior, and possibly changing the composition of the soil biota. Plant growth and development are impacted by microplastics, which can even be

absorbed and moved within plant tissues. (Aijaz, Akhtar and Babur, 2024).

Human activity, environmental variables, and the physical and chemical characteristics of the plastics themselves all have an impact on the distribution of microplastics in soil. (Chunhui Wang *et al.*, 2022). Both biotic and abiotic factors affect the migration of microplastics in soil, and common soil organisms use bioturbation to speed up this process. (Feng *et al.*, 2025). It has been demonstrated that microplastics interact with a variety of contaminants, including as heavy metals, pesticides, persistent organic pollutants, and antibiotics and build up over several trophic levels, which could have a negative impact on human and other organisms' health. (Dulanja *et al.*, 2022). Microplastics affect the DOM contents, properties, and constituents in terrestrial and aquatic ecosystems once they have entered the environment. (Sun *et al.*, 2023). Sewage sludge application is expected to be the main cause of plastic particle accumulation in these systems.

The germination rate of seeds exposed to 4800 nm microplastics decreased from 78% in the control group to 17% in the maximum exposure. The impact on germination is probably caused by microplastics physically blocking the pores in the seed capsule. (Bosker *et al.*, 2019). Terrestrial microplastics penetrate freshwater environments in addition to being retained in soil and penetrating underground with rains. Microplastics in the environment interact with both biotic and abiotic elements, causing entrainment, settlement, biofouling, degradation, fragmentation, and entry into the food chain, followed by transfer across the food chain. (Kee *et al.*, 2020). Microplastics (MP) are already regarded as a major issue in aquatic habitats and pose a quiet, ongoing harm to the environment. (Sarker *et al.*, 2020).

The main features of microplastics observed in terrestrial environments were small particle sizes (<500  $\mu\text{m}$ ), fragment, fiber, and film forms, transparent and white color, and polymers made of polyethylene (PE), polypropylene (PP), and

polyethylene terephthalate (PET). Biodegradation, which uses bacterial strains to break down microplastics by enzymatic hydrolysis, is one of the current abatement strategies that shows promise for the terrestrial environment. (Islam and Cheng, 2024). Due to the widespread use and careless disposal of plastics, microplastic contamination has grown to be a global environmental concern. (Yu *et al.*, 2021). Environmentally persistent contaminants such as microplastics (size <5 mm) negatively impact terrestrial ecosystems by encouraging the loss of soil fertility and microbiota.

Microplastics' detrimental effects on the terrestrial environment resulted in modifications to the physic-chemical and biological properties of soil, which altered the cycle of nutrients and increased the risk of future climate change. (Kumar *et al.*, 2023). There is mounting evidence that microplastics interact with terrestrial organisms—such as soil-dwelling invertebrates, terrestrial fungus, and plant pollinators—that mediate crucial ecosystem services and activities. (Abel *et al.*, 2017). Microplastics (a) are extremely persistent global pollutants that will last for centuries; (b) can interact complexly with the abiotic environment; (c) can directly or indirectly affect terrestrial organisms; and (d) can interact with other contaminants and facilitate their transport. (Baho, Bundschuh and Futter, 2021). The sustainability of ecosystems has been demonstrated to be threatened by microplastics, a new pollutant. It has a tendency to bioaccumulate and biomagnify through the food chain. (He *et al.*, 2020).

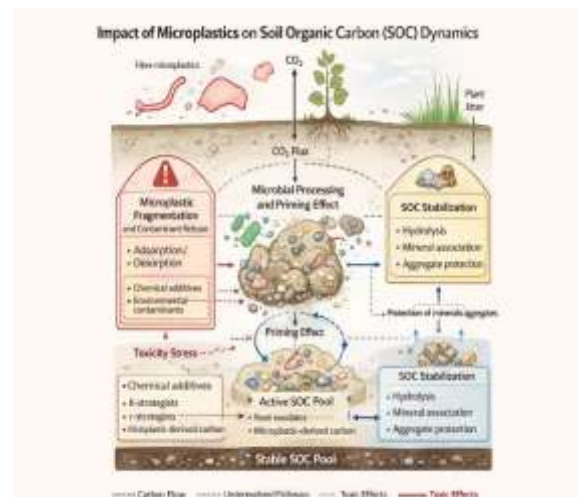
## II. MICROPLASTICS AS AGENTS OF CHANGE IN SOIL PHYSICAL AND HYDROLOGICAL PROPERTIES

### ***Impacts on Soil Structure, Porosity, and Hydraulic Conductivity***

Global discussion centers on the hazards that microplastics (MPs) pose to crop growth and agricultural soil structure. MPs can reach the soil in a number of ways, including by atmospheric deposition and the application of agricultural

mulch. (Deng *et al.*, 2024). Due to source and movement, microplastics are present in soil ecosystems all over the world. Microplastics are thought to be present in terrestrial ecosystems than in marine habitats. The three primary sources of soil microplastics are sewage sludge, transportation, and film mulching. (Yang *et al.*, 2022). Within the farmland environment, plastic mulch debris undergoes weathering and degradation processes, leading to the formation of secondary microplastics, which are then subject to further interactions with the soil microbiome (He *et al.*, 2018).

Specific microorganisms capable of degrading polyethylene can colonize these particles, enzymatically depolymerize the molecular chains and mineralize them to carbon dioxide, a process that can alter the composition of the indigenous soil microbial community and lead to cascading effects on soil biogeochemistry, including changes in nutrient concentrations and enzyme activity. (Qiang *et al.*, 2023). The biological uptake of these particles by soil-dwelling fauna disrupts their energy investment, influencing growth and behavior, while the physical presence of these hydrophobic particles within the soil matrix simultaneously alters soil water dynamics, contributing to water repellency and reducing availability. (Guo *et al.*, 2020). By altering the physical and chemical environment of soil and compromising vital ecological processes, microplastics (MPs) pose an increasing threat to soil fertility and health. The hydraulic conductivity of sand samples containing 5% PVC and 5% PE was reduced by 39% and 74%, respectively, due to changes in pore structure and clogging of pore throats by MPs. Overall, hydrodynamic dispersion was increased by the creation of low-permeability zones and preferential flow routes, which enhanced pore-scale flow heterogeneity (Aminzadeh *et al.*, 2025).



**Fig. 1.** The figure illustrates that microplastic fibres disrupt macroaggregate structure and reduce SOC storage, while films and fragments hinder aggregate formation, limiting carbon stabilization. Microplastics embedded within soil aggregates can also enhance SOC storage by adsorbing organic matter and protecting it within aggregate structures.

### **The Role of Microplastics in Preferential Flow and Vadose Zone Transport**

PET is more mobile than PP and that MPs hinder water entry into favored routes, with a greater effect for the more hydrophobic PP. PP's reduced density, which restricts downhill movement, its larger impedance on the water flow that conveys the MPs (the driving force), and its surface charge, which improves its adsorption onto soil particles. (Li *et al.*, 2025). The presence of plastics in soil created pathways for water transport, which greatly accelerated the rate of soil water evaporation. The effect increased with increasing plastic content and was more noticeable in soils treated with 2 mm plastics than in soils treated with 5 and 10 mm plastics. Plastic pollution can change the water cycle in soils, which could worsen soil water scarcity and have an impact on the vertical movement of pollutants.

(Wan *et al.*, 2019). MP has accumulated more frequently in upper floodplain soils (0–50 cm) deposited by flood dynamics since the 1960s than in subsoils. In-situ vertical transport of mobile MP particles through natural processes (e.g.,

preferred flow, bioturbation) is indicated by the first MP detection to a depth of 2 m and below recent (> 1960) sediment formation. (Weber *et al.*, 2022). The addition of microplastics did not significantly alter the wind erosion threshold for any of the concentrations or geometric forms (fibers or beads) examined when compared to either of the untreated substrate beds (0 mg kg<sup>-1</sup> dw) (Bullard *et al.*, 2021). The PSMP migration rate followed a non-linear trend, first declining and then rising. The concentration of PSMPs in the effluent decreased from 60.16% to 50.49% as a result of FT cycles damaging soil aggregate stability and the ensuing fragmented soil particles obstructing PSMPs' mobility. Both soil and PSMPs particle sizes dramatically shrank as FT cycles increased, while PSMPs' absolute zeta potential rose from 33.61 mV to 65.89 mV (Jiang *et al.*, 2025).

#### **Leaching Dynamics and Chemical Release from Microplastics in Soil**

Concern over microplastics in aquatic habitats is growing, especially as a result of chemical additives like plasticizers leaking. DEHP leaching was regulated by surface rinsing, BPA leaching was temperature-dependent (diffusion-limited). (Gulizia, Philippa, *et al.*, 2023). Due to their hydrophobic surfaces, significant sorption capacity, and huge specific surface area, migration rates declined as hydrophobicity increased (as DOW and KOC), but the microplastics had no effect on the pesticides' leaching order. (Ulrich *et al.*, 2025). BPA and BPS plasticizers showed temperature- and size-dependent leaching and were constrained by molecular diffusion throughout the bulk polymer (i.e., the microplastic), DEHT and DEHP plasticizers' leaching behaviors were significantly influenced by the microplastic-surface water boundary layer properties.

As a result, wave action, or water agitation, increased the leaching rate of these plasticizers up to 66% over 21 days. (Gulizia, Patel, *et al.*, 2023). The three primary categories of additives found in microplastics that have the potential to interfere with endocrine, reproductive, brain, and

kidney functions are flame retardants, plasticizers, and antioxidants. In both biotic and abiotic settings, the two primary mechanisms of leaching are diffusion and partitioning. In the latter, photo degradation is more common, producing reactive oxygen species that lead to microplastic aging and leaching with little chemical damage. (Y. Li *et al.*, 2024).

The leaching of dangerous chemicals is one of the most significant problems with microplastics. Because of their varied physicochemical characteristics and mass fractions in plastics, organic additives have become popular in plastic goods. Microplastic surface modifications and biofilms that colonize microplastic surfaces can change the kinetics and equilibrium of leaching as well as modify additives. (Do, Ha and Kwon, 2022). A polyvinyl chloride (PVC) pencil case exhibited the highest total PAE migration ( $\approx 6660$  ng/g), followed by a rubber glove ( $\sim 1390$  ng/g) and a polyamide (PA) brush ( $\sim 1830$  ng/g). In contrast, polypropylene (PP) and polyethylene terephthalate (PET) items (e.g., a straw, brush, and shampoo bottle) released minimal amounts (<105 ng/g). Furthermore, the conogenic composition of the leachate was polymer-specific: di-n-butyl phthalate (DBP) dominated releases from PA, PP, and PET (47–84%); diethyl phthalate was the major congener from PVC and rubber (45–92%); and diisobutyl phthalate and DBP co-dominated from polyethylene (PE). It is estimated that microplastics could be a substantial vector, discharging between 16,100 kg of PAEs into the global oceans annually. (Cao *et al.*, 2022). Polyvinyl chloride (PVC) pipes as a source of microplastics (MPs) in the water supply system, peaks linked to PVC-typical C–Cl and C–H bonds, indicating that the particles held in the filter are probably PVC microplastics. (Temam and Mortula, 2023).

Bio-based polylactic acid exhibits the highest and fastest dissolved organic carbon leaching, whereas petroleum-based polymers like polyethylene and polystyrene show incremental increases primarily under prolonged UV exposure. MP-DOM represents a dynamic

mixture whose reactivity and ecological impacts evolve with weathering history, necessitating time-resolved assessments in future fate and risk evaluations (Wang et al., 2026). PVC microplastics are a long-term source of phthalates in the environment. As phthalates are highly hydrophobic, it is demonstrated that ABLD is the dominant diffusion process for the continuous leaching of phthalates, slowing down the diffusion through the ABL. Additionally, the polymer DPVC has a reasonably high diffusion coefficient (about  $8 \times 10^{-14} \text{m}^2 \text{s}^{-1}$ ), which improves IPD. (Henkel and Hofmann, 2022).

### **Microplastic Transport via Runoff and Surface Processes**

The environment is full of microplastics (MPs). Globally, MP pollution has been discovered in the environment, posing a direct risk to human health. There are three types of variables that influence MP migration: chemical, physical, and biological. (Liu et al., 2022). The majority of marine microplastic contamination comes from land-based sources. One of the primary sources of microplastics in aquatic systems is urban runoff. The ranges of microplastic abundance in stormwater and sediment were 0.02–15499 items/L and 106–109089 items/kg, respectively. Fibers and lines were the most prevalent microplastic morphologies seen in stormwater and sediment. Microplastics made of polyethylene are most commonly detected in stormwater systems around the world. The most prevalent color among stormwater microplastics is black.

The majority of microplastics were between 100 and 500  $\mu\text{m}$  in size. (Sewwandi et al., 2024). Wastewater effluent positively correlated with fiber and polyvinyl chloride (PVC), while storm water-associated discharges (including CSOs) correlated with polypropylene (PP) (Liu, Lorenz and Zhao, 2025). Lake samples had anthropogenic particle concentrations of 0.8 particles L<sup>-1</sup>. Stormwater and wastewater in source waterways had average concentrations of 15.4 particles L<sup>-1</sup> and 13.3 particles L<sup>-1</sup>, respectively, whereas agricultural runoff had an

average value of 0.9 particles L<sup>-1</sup> (Helm, Athey and Rochman, 2020). Stormwater retention ponds are commonly used to manage the diverse range of pollutants found in stormwater runoff from metropolitan areas. On average, 88% of small microplastics (less than 500  $\mu\text{m}$ ) were retained in the ponds, but the removal effectiveness for large microplastics (more than 500  $\mu\text{m}$ ) was 95%. The retention ponds removed, on average, 95% of the tire worn material. (Rasmussen et al., 2024). In a key experimental study, Han et al. (2022) employed a runoff plot setup to systematically investigate the horizontal transport of macro- and microplastics (ranging from 50 mm to 0.25 mm) via rain-induced surface runoff—a pathway increasingly recognized as critical for the flux of terrestrial plastic waste into aquatic systems.

The findings highlighted that vegetation cover significantly enhanced the retention of plastics by approximately 20%. Plastic mobility was further influenced by particle size and polymer density, with smaller (<1 mm) and lower-density particles exhibiting higher transport potential. Runoff is a significant route for the movement of land-based microplastics (MPs) from soil to surface water, and MPs are thought to be the main source of MPs in aquatic habitats. MPs from soils and fertilizers traveled alongside the agricultural runoff. Higher mobility was demonstrated by small and low-density MPs, such as polyethylene (PE), chlorinated polyethylene (CPE), and polyurethane (PU) in film/fragment form with 20–50  $\mu\text{m}$ . The distribution of runoff MPs with the application of various fertilizers did not change statistically (Liu et al., 2024).

Microplastic concentrations were highest in stormwater runoff (0.009 to 3862 particles/L), despite the fact that the majority of research was concentrated on wastewater treatment facility effluent (85%). It is revealed that water filtered through a lower volume (e.g., 6 L) and a finer (<200  $\mu\text{m}$ ) mesh collected more particles with a marginally higher morphological diversity. (J Wang et al., 2022). For every liter of groundwater, contamination levels can reach 6,832

microplastics. Microfiltration, ultrafiltration, nanofiltration, and reverse osmosis are membrane technologies that remove 93–99% of Microplastics (Hoang *et al.*, 2025). Microplastics (MPs) are thought to be transported from soils to aquatic ecosystems by erosion. Approximately 65–75% of MP sands and particles were extracted from the soil surface by raindrop-driven assimilation into the soil matrix prior to surface discharge. About 47% of PMMA and 57% of PS were transported by surface runoff and splash erosion, but only 30% of sand particles were mobilized by similar mechanisms. (Severe *et al.*, 2025). Runoff from metropolitan areas introduces significant volumes of microplastics (MPs) into our environment. The MPs in the pond's water and fauna were much smaller than those in the sediments, and their sizes were very comparable. MPs were retained in the pond at efficiency comparable to those of other particulate matter found in storm water discharge, according to a conservative estimate (Olesen *et al.*, 2019).

### III. MICROPLASTIC DYNAMICS IN THE VADOSE ZONE

The vadose zone, which extends from the surface of the soil to the groundwater table, is a vital conduit for the cycling of nutrients and permits a variety of biogeochemical processes. Because of their increased mobility in the vadose zone, nanoplastics are more common in groundwater. They have a larger sorption capacity, which makes it easier for hazardous materials like trace metals and hydrophobic organic contaminants to enter and accumulate in groundwater. (Carpanez, Castro and Santos, 2025). Macropores and other preferred routes can carry microplastic particles, a growing contaminant. Regardless of macropore size, microplastics were preferentially leached during artificial rainfall (30.6 mm h<sup>-1</sup> for 30 min), with over 50% of the 75–90 µm and 125–150 µm particles transported. There was a high correlation between vertical soil particle transport and macropore parameters such as pore diameter, number, and surface area. (A. Maqbool *et al.*, 2025).

Paddy settings showed higher pH, lower moisture, more oxidizing conditions, higher quantities of dissolved organic nitrogen, and lower amounts of dissolved organic carbon than aquaculture environments. Nutrients (C, N, P, and Fe), moisture, cation exchange capacity, and the majority of cations all generally decreased logarithmically with depth at both sites. Deeper layers of the aquaculture site showed more noticeable variations, perhaps as a result of past agricultural activity and groundwater fluctuation. Up until a depth of two to three meters, microbial diversity, nitrogen cycling potential, and resilience to environmental perturbations decreased. After that, they grew, most likely due to nutrient availability and a lithological shift from clay to sand. (Qiao *et al.*, 2025).

In agricultural vadose zones, preferential flow (Pf) accelerates the movement of contaminants to groundwater while also acting as biogeochemical hotspots, posing environmental problems. Compared to matrix zones, Pf zones showed an average 5.7-fold increase in nitrification gene abundance (*amoABC* and *hao*) and 26.4% more organic/total nitrogen but 24.4–38.0% lower inorganic nitrogen species. (Rao *et al.*, 2025). Within the Earth's Critical Zone (CZ), soil is a complex natural resource that is regarded as non-renewable in policy frameworks and is essential to the maintenance of many ecosystem services (ES) and life-sustaining material cycles. (Menon *et al.*, 2014). Porosity increases, directs fluid movement, and releases nutrients from minerals when bedrock weathers into regolith, which is weathered rock, saprolite, and soil. As rock is extracted and changed close to the Earth's surface, chemical weathering increases steadily upward in the weathered bedrock with spikes of more intense weathering along fractures, illustrating the combined effects of time, reactive fluid movement, and fracture opening (Holbrook *et al.*, 2019).

#### **IV. THE CRITICAL ZONE FRAMEWORK AND SOIL BIOGEOCHEMICAL PROCESSES**

##### ***Earth's Critical Zone and Soil Function***

The "Critical Zone," the living skin of Earth that most directly supports life, is made up of soil and its biota. The physical layer that lies between the top of the vegetation canopy and the depth of groundwater circulation under the surface of the land is known as the Earth's crucial zone (Nie *et al.*, no date). The creation of surface mounds, soil burial, downslope transport, and soil generation from saprolite are the main consequences of bioturbation. Bioturbation modifies the basic characteristics of soil, such as the distribution of particle sizes, porosity, carbon and other nutrient content, and creep flux rate, in conjunction with surface geomorphic processes (Banwart *et al.*, no date). Soil structure, which is characterized by the size, shape, and arrangement of soil particles and pores, plays a crucial role in how soil operates. At least 25% of Earth's biodiversity is stored in the network of pores, and the quantity, size, and connectedness of the pore space control the heat, water, nutrient, and gas fluxes that characterize the physical and chemical environment. Soil structure can change with wetting and drying events, frequently oscillating seasonally. The United Nations recently recognized that 33% of the Earth's soils are already degraded and over 90% could become degraded by 2050.

(Qiao *et al.*, 2018). The production of more atmospheric aerosols and the intensification of surface erosion as a result of greater runoff are byproducts of soil erosion. (Casazza *et al.*, 2018). There was no cross-correlation between SHP and the soil organic carbon level and that SHP was not significantly correlated with the silt content. The majority of the variation in SHP are by the physical characteristics of the soil, such as bulk density, sand content, and clay content. (Sullivan *et al.*, 2022). The creation of soil aggregates as essential ecological units is the source of soil functions, which appear during bedrock weathering and, in fully developed soil profiles, correspond with the porosity architecture of soil

structure. (Wilkinson, Richards and Humphreys, 2009).

##### ***Critical Zone Hydrology and Nutrient Cycling***

All of the basic physical, chemical, and biological processes necessary for maintaining life take place and interact in the Earth's outer shell, known as the Critical Zone (CZ). The source, storage, flux, pathway, residence time, availability, and spatiotemporal distribution of water in the root and deep vadose zones of the landscape are all included in this definition of landscape water flux. (Lin *et al.*, 2006). Microbes in deep regions of the CZ rely on deposited organic matter or a chemolithoautotrophic metabolism that permits a full food chain independent of the surface because they have limited access to carbon derived from recent photosynthesis. All of the CZ's regions contain microbes, which can mediate significant biogeochemical activities. (Akob and Küssel, 2011). The biogeochemical changes occurring in the subsurface, a temporally dynamic and spatially varied section of the Earth's critical zone, are essential for the cycling of nutrients. Microbial activity, distribution, and abundance are sensitive to the applied flow regime and that the mobile (i.e., detectable by groundwater sampling) part of microbial biomass is a fluctuating (Khurana *et al.*, 2022). In the subsurface, microbial populations are essential to central biogeochemical cycles. Microcoleaceae predominated in topsoil seepage, whereas Candidatus Brocadiaceae predominated in deeper and farther-off groundwater wells. From summer by Nitrosomandaceae to fall by Candidatus Brocadiaceae, nitrifying bacteria demonstrated a change in dominance from drought to rewetting occurrences. The reductive pentose phosphate route was a significant CO<sub>2</sub>-fixation method. (Lohmann *et al.*, no date).

#### **V. MICROPLASTICS AS MODULATORS OF SOIL NUTRIENT CYCLING**

##### ***Overview of Microplastic Effects on Nutrient Dynamics***

Microplastics primarily affect the soil environment and, to a lesser degree, other

habitats when it comes to the element cycle. Microplastics have an impact on carbon sources, carbon dioxide (CO<sub>2</sub>) emissions, and carbon conversion processes. The soil microbiota and nutrient cycling are significantly impacted by microplastics (MPs), which are pervasive in agroecosystems. By altering gene abundance, enzyme activity, and the makeup of microbial communities, microplastics can impact nitrogen sources, nitrogen fixation, ammonification, nitrification, and denitrification processes. (Xin Wang *et al.*, 2022). Biodegradable microplastics significantly changed the microbial N functional profiles and increased the abundance of many important genes related to denitrification, organic N mineralization, N fixation, and N reduction. Additionally, compared to conventional microplastic treatments, biodegradable microplastics dramatically reduced net N mineralization (Nm), indicating that microbial N immobilization exceeded N mineralization. Microbes in the nutrient-rich acid black soil were less vulnerable to biodegradable microplastics than those in the less fertile alkaline loess soil. (Shi, Zhang, *et al.*, 2025). Through modulating soil nutrient availability, soil enzyme activity, functional microbial populations, and their possible ecological roles, MNPs can modify soil nutrient cycle. Additionally, the features of MNPs (such as polymeric type, size, dosage, and form), chemical additives, soil physicochemical conditions, and soil biota all affect the impacts of MNPs. (Salam *et al.*, 2023).

Exposure to MPs increased soil water content (11.2–84.5%) and decreased bulk density (11.4–42.8%); with PP and PE exposure, soil saturated hydraulic conductivity increased by 7.3–69.4%. Exposure to MPs increased soil organic matter, accessible phosphorus, NO<sub>3</sub><sup>-</sup>-N, and NH<sub>4</sub><sup>+</sup>-N; the bacterial populations involved in N and C cycling underwent considerable changes. The main factors influencing soil N and C storage under MPs exposure were soil hydraulic properties (such as soil water content, saturated water capacity, and soil saturated hydraulic conductivity) (Ma *et al.*, 2023). Photochemical and microbiological degradation continued to take

center stage; fungi are thought to degrade microplastics more quickly than bacteria. Microplastics with a high carbon content can change the C/N ratio and microbial interaction even if they mineralize slowly.

Additionally, the uptake of secondary microplastics through roots or stomata can have a direct impact on plant health, and microplastic-induced changes in soil characteristics, microbial activity, and/or nutrient dynamics can have an indirect impact (Rehman *et al.*, 2025). In agroecosystems, Soil autotrophic ammonium oxidation processes, such as nitrification, complete ammonium oxidation (comammox) and anaerobic ammonium oxidation coupled to iron reduction (Feammox); these mechanisms are the phases that control the pace of nitrogen cycling.

The primary method of removing ammonium from soil was still nitrification (56.4–70.7%), which was followed by comammox (11.7–25.6%), anammox (5.0–20.2%), and Feammox (3.3–11.6%). Biodegradable MPs (like PLA and PBAT) had more noticeable effects on soil nutrient conditions and functional microorganisms when compared to traditional non-biodegradable MPs (like PE and PP), which together caused changes in soil ammonium oxidation. Interestingly, low-dose PLA and PBAT significantly improved the functions of Feammox and Anammox in soil ammonium removal, helping to reduce soil acidity in agroecosystems (She, Qi and Li, 2024). Biodegradable plastic mulch (BM) produced the highest accumulation of MPs, with small size (< 0.25 mm) MPs being particularly enriched. In rhizosphere soils, BM increased MP abundance and improved soil C (9%), N (23%), and P (9%) contents compared to M.

(Zhang, 2025). Particularly in salt-affected soils, polymers (MPs) in soil pose new problems to SAG stability and nitrogen dynamics. High MP abundances severely disturb SAG structure, increasing microaggregates (<0.25 mm) and decreasing the proportion of big aggregates ( $p = 0.032$ ), with microaggregates acting as hotspots for MP accumulation ( $p < 0.05$ ). These stabilizing

effects were further enhanced by the natural properties of salt-affected soils, such as high salinity, alkalinity, and poor organic matter. (Ju *et al.*, 2025). MP inputs enhanced the content of DOC and some dissolved organic matter (DOM) components while continuously lowering the concentration of NO<sub>3</sub>-N. The connectedness and cross-trophic linkages of microbial multitrophic networks were consistently enhanced by MP inputs, notwithstanding the diverse reactions of microbial hierarchical groupings to MPs. (Gao *et al.*, 2025).

### Impacts On Soil Carbon Cycling

Degradable plastics made from plant resources have the potential to augment soil organic carbon (SOC) in place of conventional plastics since soil microorganisms treat them equally with plant residues. However, because of their significant nitrogen deficit and high microbial availability, the degradable microplastics may concurrently increase SOC loss through priming actions. (Yang, Sha and Kumar, 2025). Emissions of nitrous oxide (N<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>) from soil are two major greenhouse gases that contribute significantly to global warming. Soil CO<sub>2</sub> emissions were greatly reduced by biochar, either by itself or in combination with microplastics, however soil N<sub>2</sub>O emissions were unaffected. In the soil with earthworms, microplastics and biochar reduced CO<sub>2</sub> emissions while increasing N<sub>2</sub>O emissions. Earthworms and microplastics selectively affected microbial abundances, resulting in a soil microbial community that was dominated by fungi, whereas biochar produced a microbial community that was dominated by bacteria. Microorganisms and C and N cycling functional genes in earthworm guts were significantly suppressed by microplastics, whereas biochar clearly promoted them.

Adding biochar to soil containing microplastics or earthworms can both reduce CO<sub>2</sub> emissions and control the makeup and activity of the soil microbial community. (Gao *et al.*, 2022). It is demonstrated that both PP and PLA increased CO<sub>2</sub> emissions, with the impact varying according

to the size of soil aggregates and the kind and concentration of microplastics. Changes in organic carbon linked to macroaggregates were the primary cause of changes in soil carbon stores. PP microplastics reduced both dissolved organic carbon (DOC) and soil organic carbon (SOC) for macroaggregates. In microaggregates, silt, and clay, these alterations were reversed. It's interesting to note that PLA raised SOC, DOC, and CO<sub>2</sub> emissions in all three aggregates and bulk soil with a dose-effect response.

These alterations were linked to functional genes, soil microorganisms, and enzymes involved in the breakdown of refractory and labile carbon components. Additionally, in the three aggregates as well as in bulk soil, PP and PLA changed the architecture of the bacterial communities and decreased their diversity. Microplastics' effects on carbon transformation in soil aggregates were mostly caused by changes in functional genes. (Jiixin Wang *et al.*, 2024). In soil CO<sub>2</sub> uptake, autotrophic bacteria are essential. In bulk soil, PS microplastics had a greater inhibitory effect on CFRs than PHBV microplastics. The suppression of CFRs by both kinds of microplastics in rhizosphere soils, however, did not differ significantly. PS and PHBV microplastics changed the organization of autotrophic microbial communities, leading to looser, more delicate coexistence networks and more stochastically dominated assembly. (Fang *et al.*, 2024).

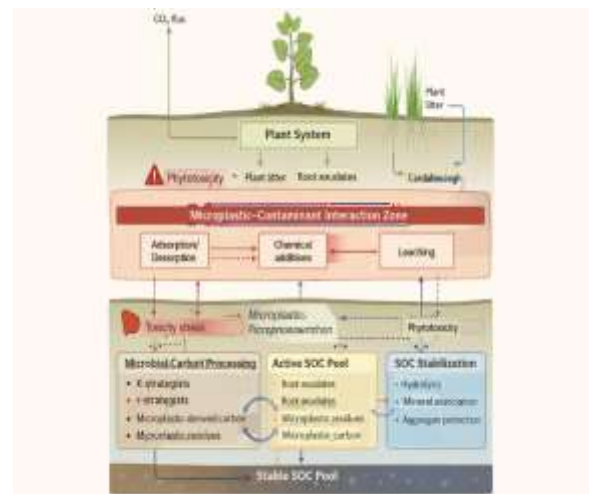
Microplastics are important causes of disruptions in biogeochemical cycles, especially when it comes to controlling the release and storage of soil organic carbon (SOC). Microplastics changed MNC and GRSP dynamics by changing the structure of bacterial and AMF populations. Microplastics mainly impacted SOC sequestration through GRSP rather than MNC. (Ning *et al.*, 2025). The cycling of soil nutrients is greatly impacted by microplastics (MPs). The addition of PE MPs resulted in a maximum increase of 93.94% in SOC and 75.58% in TN storage. PE MPs considerably improved sucrase and urease activity, raised soil water content (WC) and

saturated water capacity (SWC), and decreased soil bulk density (BD). The crucial role of virus-bacteria interactions in determining MPs-driven soil carbon and nitrogen cycling dynamics by indicating that the increase in SOC and TN storage was significantly influenced by lytic virus-bacterial interactions rather than soil physical/chemical properties and enzyme activities under MPs addition (Q. Wang *et al.*, 2025).

MP-DOM causes 21–576% more CO<sub>2</sub> emissions and 34–83% less mineral-associated organic carbon in soils than NOM. Compared to ordinary microplastics, DOM from biodegradable microplastics causes greater CO<sub>2</sub> emissions. MP-DOM is shown to be 7.96 times more labile than NOM, which increases its accessibility for microbial use. Additionally, MP-DOM had 3.96 times less sorption with mineral particles due to its lower degree of humification, fewer polar functional groups, and greater H/C ratios. (Shi, Tanentzap, *et al.*, 2025). The amounts of dissolved organic carbon were altered by conventional and biodegradable microplastics. DOM with more polar groups was found in the microplastic treatments, indicating a higher degree of electron transfer. Additionally, there was a positive link between CO<sub>2</sub> emission, electron-donating capacity, and carbon content.

By altering O<sub>2</sub> microenvironments, DOM concentration, and DOM electron transport capacity, microplastics may promote the mineralization of SOM (Shi *et al.*, 2023). Biodegradable microplastics dramatically raised soil CO<sub>2</sub> emissions, most likely as a result of increased microbial activity and resource availability. Biodegradable microplastics, on the other hand, improved microbial carbon use efficiency and encouraged microbial community turnover, which further accelerated the buildup of microbial necromass in bulk soil carbon and mineral-associated organic matter. Furthermore, the increase in soil CO<sub>2</sub> emissions and necromass carbon accumulation caused by microplastics was particularly noticeable in barren soil. ("Global Change Biology - 2025 - Shi - A Double-Edged

Sword of Biodegradable Microplastics on the Soil Microbial Carbon Pump.pdf," no date). MPs can have a variety of effects on the carbon cycle, such as being carbon itself and having an impact on plant development, soil microbial activity, and litter breakdown. (Yan *et al.*, 2024). Microplastics affecting microorganisms may be one of the primary agents influencing soil carbon dynamics as a significant player in soil carbon processes. Although nanomicroplastics (0.1µm) strained soil microorganisms more than micron-microplastics, soil microplastics of all sizes invariably and consistently altered microbial metabolism. The impact on microorganisms changed from extracellular to intracellular, with intracellular microplastics showing greater toxicity than extracellular microplastics. As microplastic particle size decreased, the suppressive effect on microbial respiration was gradually lost, the inhibitory effect on microbial CUE increased steadily. (G. Li *et al.*, 2024).



**Fig. 2.** uses blue arrows to represent carbon movement and transformations between plant inputs, microbial processing, and SOC pools, while dashed blue lines indicate indirect or less-understood pathways. Red arrows highlight toxicity and stress effects of Microplastics and associated contaminants on plants and microbes, and green arrows show plant-related inputs and CO<sub>2</sub> flux to the atmosphere.

### Impacts on Soil Nitrogen Cycling

Microbial-driven nitrogen transformation is essential to nitrogen cycling, which is crucial to biogeochemistry. Microorganisms in the environment are the primary drivers of nitrogen transformation and nitrogen cycle, and the presence of microplastics can alter the microbial population, quantity, and type, which in turn affects nitrogen transformation. (Shen *et al.*, 2022). MPs in soil causes biological (microbial activity and soil fauna), chemical (nutrient availability, organic matter, and pH), and physical (aggregate stability, soil bulk density, and water dynamics) changes. All of these modifications affect biogeochemical cycles like the nitrogen (N) cycle, which is a crucial indicator of ecological stability and management in the terrestrial ecosystem, as well as the degradation of organic matter. (Riveros *et al.*, 2022). Polyethylene microplastics, polyethylene resin, and plastic additives raised total nitrogen but reduced dissolved total nitrogen.

While polyethylene resin decreased dissolved organic nitrogen and showed greater microbial biomass, polyethylene microplastics and additives enhanced it. Polyethylene resin and additives had lower rates of gross ammonification, nitrification, and immobilization than polyethylene microplastics. Plastic additives significantly alter the structure of microbial communities, impede transformation rates, and eventually affect nitrogen cycling. They are also less favorable to nitrogen breakdown and microbial immobilization than polyethylene microplastics and resin (Zhou *et al.*, 2024). Cash-crop farming soils frequently contain microplastics from agricultural mulch, which, along with biochar, have an impact on soil N<sub>2</sub>O emissions. PE and PLA were shown to significantly increase N<sub>2</sub>O emissions, with increases of 15.96% and 21.52%, respectively. biochar reduces N<sub>2</sub>O emissions is by making the nosZ gene more abundant. (F. Wang *et al.*, 2024). The presence of microplastics had a minor impact on soil N transformation and bioavailability at 15 °C, but at 25 °C, both microplastics significantly reduced NO, mineral N (MN), total dissolved N (TDN), the

net cumulative N nitrification (Nn), and the net cumulative N mineralization (Nm), suggesting that microplastics reduced soil N bioavailability at elevated temperatures.

Due to the various textures and biochemical characteristics of the two soils, the sandy loam soil was more vulnerable to microplastic pollution in N transformation than the clay soil. This demonstrated that microplastics had a considerable soil heterogeneity-dependent effect on soil N processes. (Shi *et al.*, 2022). Plasticizer-containing polyvinyl chloride (PVC) microplastics at 0.5% (w/w) significantly increased soil NH<sub>4</sub><sup>+</sup>-N content and decreased NO<sub>3</sub><sup>-</sup>-N content by up to 91%. Microplastics of pure PVC polymer (either granule or film) suggesting that phthalate plasticizer released from microplastics was the primary cause of the effects seen (Zhu *et al.*, 2022). The nitrogen cycle can be significantly changed by microplastics. Nitrate reductase activity rose by 4.8% and soil N<sub>2</sub>O emissions increased by 140.6% when exposed to microplastics. The number of denitrifier genes and the denitrification rate both increased by 10.6% and 17.8%, respectively. The increased N<sub>2</sub>O emissions from the soil may be mostly caused by enhanced denitrification. Consequently, nitrate dropped by 22.4% and nitrite rose by 38.8%. It's interesting to note that throughout time, the copy number of denitrifier genes decreased while N<sub>2</sub>O emission increased. N<sub>2</sub>O emissions with a higher rate of denitrification when exposed to microplastics. (Su *et al.*, 2023). Exposure to microplastics reduces soil NO<sub>3</sub> N concentration by 7.89% overall, but has no discernible effect on NH<sub>4</sub><sup>+</sup> N concentration. Subgroup analysis also showed that soil properties (soil texture, initial soil pH, initial soil organic carbon, soil total N concentration), microplastic characteristics, and experimental conditions (exposure time, experimental temperature, plant effects) all influenced the effects of microplastics on soil inorganic N. Exposure to microplastics over 27 °C increases the concentration of NO<sub>3</sub> N in the soil. Xiang *et al.*, 2023).

Throughout the vertical soil profile, soil depth was found to influence soil microbial abundance but not diversity. Depth, temperature, and nutrient status were the primary environmental factors influencing abundances in summer, while depth and temperature were the primary factors in winter. In the summer, depth had significant direct effects on microbial abundance as well as indirect effects through temperature and TN. Secondary regulators of microbial abundance included temperature, moisture, pH, and nutrients. (He *et al.*, 2022). In particular, the availability of soil nitrogen, especially in the form of nitrate, was mostly preserved even if the nitrification potential was not adversely impacted by the presence of MPs. The ammonification rate was consistently lower than the nitrification potential. However, the amounts of accessible nitrogen in PP-contaminated soils significantly decreased by the end of the incubation period. PP was generally shown to have the greatest detrimental impact on soil nitrogen processes. (Dindar, 2024).

## VI. THE PLASTISPHERE: A NOVEL MICROBIAL NICHE IN SOIL

### Microbial Colonization and Community Structure

The term "soil plastisphere" was established to characterize the soil domain directly influenced by plastics (including the microbial population inhabiting this environment) in order to aid understanding in the largely uncharted field. Plastics break up into nanoscale fragments that are different from their bulk counterparts due to their persistence. (Yu *et al.*, 2024). The plastisphere acts as a special microbial habitat (niche) that attracts the colonization of particular bacterial groups, such as diseases (such *Massilia* and *Pseudomonas*) and bacteria that may break down plastic.

Plastisphere functions as a distinct microbial habitat (niche) in the soil ecological systems, attracting particular bacteria and possibly disrupting the surrounding soil microbial community, thereby affecting the functional

properties of the soil ecological systems (Ran *et al.*, 2024). MPs may act as synthetic substrates for microbial colonization and plastisphere development when they penetrate natural settings, giving microorganisms new ecological niches. MP traits and soil environmental conditions may influence the development and succession of soil plastisphere communities. Numerous biological processes, particularly the co-transport of environmental pollutants, MP Biodegradation, and soil carbon cycling, are impacted by the soil plastisphere. (Chengqian Wang *et al.*, 2022). PBAT/PLA microplastics function as a filter, enriching taxa like Proteobacteria and Actinobacteria that can break down plastic polymers. PBAT/PLA plastisphere has more competitive interactions, lesser modularity, and fewer complex networks than PE plastisphere.

The PBAT/PLA plastisphere facilitated the abundance of genes linked to carbon and nitrogen cycle, as well as predicted metabolic pathways related in human illnesses, carbohydrate metabolism, amino acid metabolism, and xenobiotic biodegradation and metabolism. (Li *et al.*, 2023). The introduction of microplastics into the soil matrix creates a distinct microbial niche, fostering the development of unique biofilm communities that can significantly alter the environmental fate and behavior of the plastics themselves. The soil plastisphere can amplify the ecotoxicological risks posed by co-existing contaminants, including heavy metals, organic pollutants, pathogens, and antibiotic resistance genes. (Zhang *et al.*, 2025).

Plastisphere communities showed poorer correlations with environmental variables than soil communities. Fungal communities on soil microplastics were found to have limited dispersal, which may have ramifications for taxonomic isolation or even diversity loss. (Sun, Xie, *et al.*, 2024). Polyethylene microplastics have more uniform characteristics than the surrounding soil, the proportional importance of homogenous selection in plastic spheres was higher than that in soil samples. The degree of

variation between the plastsphere and soil bacterial communities was positively connected with the sampling sites' mean annual temperature and negatively correlated with the soil's pH and carbon content. (Sun, Wu, *et al.*, 2024).

#### *Microbial Community Responses to Microplastics*

MPs directly increase CO<sub>2</sub> and N<sub>2</sub>O emissions by changing microbial abundance, structure, activity, and gene expression. MPs also alter rhizosphere microbial growth, deplete soil nutrients, and cause plant toxicity, all of which have an indirect impact on greenhouse gas emissions (Chen *et al.*, 2025). Microorganisms can adapt to changes in substrates and soil qualities; they are susceptible to microplastics. Microorganisms play an important role in the biodegradation of plastic through the metabolic and mineralization processes. (1) microplastics' effects on microbial habitats through alterations in the physical, chemical, and biological characteristics of soil; (2) microplastics' effects on soil microbial communities and functions; and (3) soil microbial-mediated plastic degradation with probable mechanisms and possible remediation techniques. (Zhang *et al.*, 2021).

High-density polyethylene HDPE and PP microplastics exposure did not cause gut microbiota dysbiosis in *M. guillelmi*, but PP microplastics exposure significantly reduced bacterial diversity and changed bacterial community structure in the soil. (Cheng *et al.*, 2021). The addition of PE microplastics reduced the dissipation of ARGs in tetracycline-contaminated soils. In tetracycline-contaminated soils, multidrug, aminoglycoside, and cyclopeptide resistance genes were strongly positively correlated with Chloroflexi and Proteobacteria; in PE microplastic and tetracycline-contaminated soils, aminoglycoside resistance genes were strongly positively correlated with Actinobacteria. (Ya *et al.*, 2023). Numerous bacteria colonized microplastic surfaces, particularly pits and flakes, indicating active hydrolysis of plastic waste. Microplastics work as a "special microbial accumulator" in

agricultural soil, enriching certain taxa that break down polyethylene, such as Actinobacteria, Bacteroidetes, and Proteobacteria. (Zhang *et al.*, 2019).

It is suggested that the presence of microorganisms in the soil ecosystem may accelerate the soil bacterial community's succession rate, offering fresh perspectives on the evolutionary ramifications of microplastics in terrestrial environments (J. Wang *et al.*, 2020). The microbial diversity of MP-contaminated and plastsphere (MP-microbe consortium) soils was different and lower than that of non-contaminated soils. MPs significantly reduced the quantity of soil nitrifiers and ammonia oxidizers while increasing the relative abundance of soil nitrogen (N)-fixing and phosphorus (P)-solubilizing bacteria. In certain cases, MPs boosted nitrous oxide emissions and bioavailable N and P concentrations, depending on the type of soil. MPs controlled soil microbial functional activities. (Aralappanavar *et al.*, 2024).

In soils treated with PBAT-MPs and PLA-MPs, dissolved organic carbon (DOC) rose by 20.91% and 66.59%, respectively, whereas nitrate nitrogen (NO<sub>3</sub>N) dramatically dropped by 56.91% and 69.65%. PBAT-MPs and PLA-MPs mostly increased the abundance of functional genes linked to CNPS cycling by enhancing copiotrophic bacteria (Proteobacteria) and suppressing oligotrophic bacteria (Verrucomicrobiota, Gemmatimonadota) (Song *et al.*, 2024). Both MPs and nZnO dramatically changed the taxonomic, genetic, and functional diversity of soil microorganisms. Higher doses of MPs and nZnO increased CO<sub>2</sub> fixation and S metabolism but decreased gene abundance for nutritional cycles such C degradation and N cycling. The complexity, connectedness, and modularity of microbial networks were consistently reduced by nZnO.

Interestingly, compared to PE and PS, PLA (10%, w/w) showed more damage to fungal communities and more detrimental interactions between microorganisms and nutrient-cycling

genes, suggesting distinct dangers. (Sun *et al.*, 2025). MP abundance showed a negative correlation with soil enzymatic activity and P solubilization ( $R = 0.59$ ,  $p < 0.01$ ), and a positive correlation with P immobilization ( $R = 0.53$ ,  $p < 0.05$ ), suggesting reduced nutrient availability. Amplicon sequencing revealed that low-MP soils supported functionally significant groups, such as particular Acidobacteria and nitrifying archaea (e.g., Candidatus Nitrososphaera), while MP-rich soils were enriched in specific taxa within Firmicutes and Actinobacteria frequently linked to stress tolerance (Ibella *et al.*, 2026). The biodegradation of atrazine in soil was considerably inhibited by freeze-thaw cycles rather than microplastics; the average inhibition ratios for FTCs and microplastics were 33.69% and 4.99%, respectively.

The primary cause of the alterations in the microbial community structures in the soil and the atrazine breakdown was thawing temperature. Microplastics and FTCs do not have a synergistic effect on the short-term breakdown of atrazine in soil. (Xie *et al.*, 2025). Microplastics increase soil humification and CO<sub>2</sub> emissions. The application of microplastics reduced network complexity and stability, including network size, connectedness, and the number of module and keystone species, even though they had no discernible effect on the diversity and composition of the soil microbial community. (Shi, Sun and Wang, 2022). Microplastics have a significant impact on species in aquatic habitats. microplastic addition had a considerable impact on the quantity and composition of microarthropod and nematode communities. The effects of microplastics substantially cascade across the soil food webs, changing microbial behavior and possibly having additional effects on the cycling of nutrients and carbon in the soil. (Lin *et al.*, 2026). The number of microplastics, which are tiny particles generated as plastics break down, is rising in most ecosystems, including the soil. (K. Wang *et al.*, 2025).



**Fig. 3.** Concept diagram showing the effects of MPs on carbon and nitrogen cycling in the soil ecosystem.

## VII. EMERGING CONTAMINANTS: TIRE WEAR PARTICLES AND ASSOCIATED CHEMICALS

### Tire Wear Particles in Soil Ecosystems

Tire wear particles (TWPs) are a dominant source of microplastics and a vector for hazardous chemicals, including high concentrations of zinc and organic compounds like benzothiazole. TWPs at concentrations found in roadside soils (e.g., 1.5% w/w) induce significant toxicological effects in soil invertebrates, such as reduced reproduction, survival, and enzyme inhibition in species like *Folsomia candida* and *Porcellio scaber*. (Selonen *et al.*, 2021). Despite their significant contribution to global microplastic pollution, tire wear particles (TWPs) remain a critically underappreciated environmental contaminant. (Y. Wang *et al.*, 2025). Tire wear particles are found in all environmental compartments, including air, water, soils/sediments, and biota. Tire wear particles have maximum Predicted Environmental Concentrations (PECs) of 0.03 to 56 mg/l in surface waters and 0.3 to 155 g/kg d.w. in sediments.

Tire wear particles may pose a threat to aquatic life, as indicated by the upper limits of PEC/PNEC ratios in water and sediment being more than 1 (Wik, 2009). Numerous environmental systems, including soils, have been found to contain

microplastics, including tire wear particles. Tire particles can have a marginally bigger impact on soil systems than microplastics. (Tunali and Nowack, 2025). Quantitative assessments for the U.S. estimate total annual tire wear particle (TWP) release at roughly 79.5 kt. This mass partitions into key environmental compartments: 1.3–6.7 kt to the atmosphere, 23.0–34.0 kt to surface waters, and 18.5–30.2 kt to soils, with 16.7–29.2 kt captured by management systems.

A significant secondary pathway involves the land application of sewage sludge, which transfers 6.3–13.1 kt of urban TWPs to agricultural lands annually. (Zheng, Mehlig and Oxley, 2025). Tire wear particle (TWP) concentrations in these soils can be exceptionally high, reaching up to 26,400 mg/kg (2.6% by dry weight)—levels up to five times greater than previously reported in high-traffic areas. Variations in metal content are primarily explained by traffic density (11%) and soil organic matter (10%), which together with other factors account for nearly half (45%) of the observed variance, aligning concentrations with typical ranges for global urban and rural soils. (Elisabeth et al., 2023). Unique microbial community structures were produced by varying soil moisture conditions. Soil fungus was more susceptible to flooding, but soil bacteria were more susceptible to damp conditions.

It is found that the intake of TWPs considerably raised the emission of nitrous oxide (N<sub>2</sub>O) from dryland soil. Numerous taxa, such as Pyrinomonadaceae, Blastocatellaceae, and Cyanobacteriales, were shown to have TWP-biomarkers in soils and may have had a major impact on N<sub>2</sub>O emissions from drylands. Changes in the relative abundance of genes involved in ammonia oxidation (*amoA/B*), nitrite reduction (*nirS/K*), and N<sub>2</sub>O reduction (*nosZ*) in drylands were closely linked with their reactions to the TWPs input. (Xu et al., 2024). Soils treated with TWPs had elevated concentrations of polycyclic aromatic hydrocarbons (PAHs) and heavy metals. Exposure to TWPs had a substantial influence on soil enzyme activities, with urease and dehydrogenase activity declining by more than

50%, even though it had no effect on plant growth. Additionally, exposure to TWPs caused significant alterations in the metabolite profile of plants, such as changes in the amounts of sugars, carboxylic acids, and amino acids, suggesting changed metabolic pathways associated to nitrogen and amino acids.

The rhizospheric and bulk soil microbiota were also disturbed by TWP exposure, resulting in a decline in the number of bacterial (*Blastococcus*) and fungal (*Chaetomium*) taxa involved in nitrogen cycles and plant disease suppression (Jianling Wang et al., 2024). Tire particles from bicycles and electric scooters altered the bulk density and water-holding capacity of the soil, which had a negative impact on plant growth. Particles from car tires had leached a variety of organic chemicals and negatively impacted the growth of both adult and juvenile springtails. Tire particles produced in laboratories (from new tires) had the potential to negatively impact soil organisms by altering soil characteristics and leaching chemicals. (L. Kim et al., 2022). Environmentally persistent free radicals (EPFRs) are produced by aging processes of TWPs, especially UV-induced cleavage, and are frequently made worse by additions like carbon black and zinc oxide (ZnO).

Biodegradation may lessen hazards by decreasing contaminant bioavailability, photo aging increases soil toxicity through the production of reactive oxygen species (ROS), EPFRs, and additive release. (Zeb et al., 2026). Plant-soil systems may be impacted by tire wear particles (TP), which infiltrate soils through a variety of routes and build up over time. 3% TP decreased root and shoot biomass by 35% and 23%, respectively, although lower TP levels had some stimulating effects. Additionally, a 3% TP addition raised plant concentrations of zinc and copper while lowering plant nitrogen. Additionally, we observed a decrease in microbial biomass carbon (up to 20%), an increase in the microbial metabolic quotient (up to +62%), and notable alterations in the catabolic capacity of soil microbes in soils containing 3% TP. (Kundel et al.,

2025). In comparison to the pristine TWPs, the UV-aged TWPs' surface developed more holes and cracks. When exposed to both pristine and UV-aged TWPs, the variety and community structure of soil microorganisms changed, with the UV-aged TWPs considerably altering nirK-type soil denitrifying bacteria. Under UV-aged TWP exposure, *Streptomyces* was crucial in fostering the denitrification process and linking the nirK-type bacterial community. UV-aged TWPs increased the production of reactive oxygen species (ROS), encouraged soil microorganisms to secrete more extracellular polymer substances (EPS), and triggered the antioxidant defense system against oxidative damage caused by UV-aged TWPs. (Pu *et al.*, 2025).

Tire-leachate dramatically changes the dynamics of the soil, increasing the amount of nitrogen that is available in mung bean soil while immobilizing phosphorus in tomato soil. The effects of tire contamination are very species-dependent, with tomato growth being steady despite obvious internal stress and mung bean roots being sensitive and inhibited. The highly bioavailable leachate component poses the greatest damage to plant health (Wasnik *et al.*, 2026).

TWP amendment significantly changes the molecular characteristics of soil DOM, causing a significant drop in protein-, carbohydrate-, and lipid-like components, the breakdown of unstable dissolved organic matter with low aromaticity. Additionally, TWP intake immediately altered the characteristics of the soil, causing the aggregates to change: the proportion of small aggregates increased while the proportion of large aggregates dramatically reduced, lowering aggregate stability overall. Because of the disintegration of soil aggregates and the release of endogenous metals from TWPs, the bioaccessibility of heavy metals (HMs) (Cd, Cu, and Zn) extracted by CaCl<sub>2</sub> increased. On the other hand, during TWP stress, Pb tended to change into more stable fractions, which decreased its bioaccessibility. (Jiang *et al.*, 2026). The most likely tire-related intermediates found

in the roadside soil samples were ketones, carboxylic acids, epoxies, cyclohexane, and benzothiazolesulfenamide (BTS).

(Thomas *et al.*, 2022). Microbial activities were found to be dependent on soil storage conditions, including soil respiration and three enzyme activities ( $\beta$ -glucosidase, N-acetyl- $\beta$ -glucosaminidase, and phosphatase). The addition of TWPs raised soil respiration rates, and the ADTWP treatment showed greater deviations from the control group (no TWPs applied) than soils held under other conditions. Phosphatase activity showed an inverse pattern. Following the addition of TWPs, the phosphatase activity was higher in the AD soil and lower in the LS soil compared to the control group. (S. W. Kim *et al.*, 2022). Synthetic rubber polymers, reinforcing fillers, and chemical additives, such as heavy metals like zinc (Zn) and copper (Cu) and organic chemicals like polycyclic aromatic hydrocarbons (PAHs) and N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD), make up TWPs. TWPs have been demonstrated to disrupt microbial communities (with a 40–60% decrease in nitrogen-fixing bacteria), cause phytotoxicity through both physical root blockage and Zn-induced oxidative stress, and change important soil properties, such as a 25% reduction in porosity and a 20–35% decrease in organic matter decomposition. (Kang *et al.*, 2025).

TWP enhanced soil CO<sub>2</sub>, N<sub>2</sub>, and N<sub>2</sub>O emissions, which were linked to changes in soil dissolved organic matter (DOM) content and composition brought on by TWP and associated leachate. In particular, TWP exposure greatly enhanced the labile DOM components (H/C $\geq$ 1.5 and transformation $>$ 10), which were essential in forming the denitrifying community. Additionally, after TWP exposure, the abundances of denitrification genes (nirK/SandnosZ-I) and the particular denitrifying genus *Pseudomonas rose*. The effects of TWP on carbon and nitrogen cycling in soil, emphasizing that TWP exposure may worsen greenhouse gas emissions and fertilizer loss, posing detrimental consequences

on soil fertility in peri-urban settings and mitigating climate change (Kang *et al.*, 2025).

### **6PPD and 6PPD-Quinone in Soil Environments**

When rubber-related items are made or used, 6PPD, a common antioxidant and antiozonant, is produced. 6PPD and 6PPD-quinone have been found to be widely present in the environment due to the large manufacture and extensive use of rubber-related items. N-(1, 3-Dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD) is mostly utilized in the rubber sector as an antioxidant and antiozonant to stop deterioration. However, 6PPD can be ozonated to produce N-(1, 3-Dimethylbutyl) N'-phenyl-p-phenylenediamine quinone (6PPD-quinone), a very toxic transformation product that is harmful to both terrestrial and aquatic species. (Review *et al.*, 2024). Environmental elements including temperature, light, and storm occurrences, among others, would have an impact on the distribution and fate of 6PPD and 6PPD-quinone. (Chen *et al.*, 2023).

These substances, which come from tire abrasion, runoff, and biosolid application, go through oxidative changes fueled by ozone, UV light, and microbial activity. This leads to strong sorption to soil organic matter and extended persistence. They disturb plant physiology, soil fauna, and soil microbial populations, and crop uptake increases the danger of food chain contamination. Effective mitigation includes eco-friendly tire formulations, stormwater control, and bioremediation (Iqbal *et al.*, 2025). Numerous environmental media have been found to contain N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD) and its derivative 6PPDQ, which have detrimental effects on ecosystems and biological health. In comparison to typical e-waste recycling zones, dust samples from the surrounding e-waste recycling parks showed lower levels of 6PPDQ (median: 15.40 versus 46.37 ng/g,  $P < 0.05$ ). The dust samples had greater median concentrations of 6PPD and 6PPDQ than the soil samples ( $P < 0.001$ ). Seasonal variations were seen in the concentrations of 6PPD and 6PPDQ in the dust and soil, with the

winter months exhibiting the highest overall concentrations. 6PPDQ has a negative correlation with temperature and a positive correlation with 6PPD, O<sub>3</sub>, and radiation. 6PPD and 6PPDQ are more likely to build up in dust than in soil in residential areas. (Zhang *et al.*, 2024).

The tire additive 6PPD and its biologically active derivative, 6PPD-quinone (6PPD-Q), are introduced into the environment via the pervasive release of tire and road wear particles (TRWPs), with soil acting as the main sink. 6PPD persisted significantly longer in anaerobic soils (average half-life 51.4 d) than in aerobic soils (0.7–1.5 d), suggesting that submerged soil or sediment compartments may be a more significant secondary source. Microorganisms facilitated the breakdown of 6PPD-Q in soils, with half-lives (13.5–14.2 d) longer than those of 6PPD under aerobic conditions. In soil under aerobic and anaerobic conditions, different transformation routes for 6PPD and 6PPD-Q were noted; 10 and 7 TPs were found, respectively.

N-phenyl-p-benzoquinone imine and 1, 3-dimethylbutyl amine, two of the detected TPs, are recognized to present possible concerns for human exposure. C-N cleavage, dehydrogenation, hydroxylation, and amination were the main transformation processes for 6PPD, whereas dephenylation, hydroxylation, methylation, and amination were the ones for 6PPD-Q. (Shen *et al.*, 2025). The breakdown of N-(1, 3-dimethylbutyl)-N-phenyl-p-phenylenediamine (6 PPD), which is frequently present in road dust as a result of tire wear, produces 6 PPD-Q (6 PPD-Quinone), an ozone-induced byproduct. Compared to bacteria, soil fungus is more sensitive to 6 PPD-Q accumulation, and related fungi (Basidio mycota) may serve as biomarkers for environmental 6 PPD-Q pollution. The bacterial microbial network is more stable and resilient in response to six PPD-Q inputs in the summer than it is in the winter.

However, the network structure of fungal communities is somewhat disrupted by 6 PPD-Q

accumulation, which results in a decrease in the variety of fungal microbial communities. The potential for nitrogen and phosphorus cycling in urban soil is weakened by long-term accumulation of 6 PPD-Q, but increased carbon cycling may accelerate the breakdown of 6 PPD-Q in urban soil. (Wu *et al.*, 2024). Their hazards could be mediated through biotransformation pathways of detoxification and/or bioactivation and associated metabolites. Certain derivatives exhibit increasing accumulation during the exposure length, according to kinetic profiling, which identifies varied temporal patterns among TPs. TPs showed earthworm toxicity comparable to 6PPD-Q, suggesting possible contributions to the noticeable negative effects shown in *C. elegans*. (W. Wang *et al.*, 2025).

The fate of 6PPD-Q in soils was dominated by biodegradation, whereas anaerobic flooding conditions were favorable for the formation of 6PPD-Q, which led to a roughly 3.8-fold greater accumulation of 6PPD-Q in flooded soils compared to wet soils after 60 days of aging. Ferreduction-coupled 6PPD improved the 6PPD-Q formation in flooded soils. (Xu *et al.*, 2023). National 6PPD-Q emissions rose by approximately 97.5% between 2013 and 2023, mostly due to vehicle growth. Partitioning of sources reveals significant contributions from soil reservoirs and highway traffic, highlighting the need to extend monitoring beyond urban water environments. the estimated daily intake of 6PPD-Q is higher in children (0.006–0.011ng/(kg·day)) compared to that in adults (0.003–0.005ng/(kg·day)), with the main exposure pathway shown to be dirt intake. (Xu, Su and Tang, 2026).

### **Polymer-Specific Effects on Soil Systems**

Microplastics (MPs) contamination impairs soil structure and function. In fine soils, low-density polymers (PE and PP) accumulated at 5–10 mg kg<sup>-1</sup> and increased stability by 20%. The clay fractions of coarse soils contained high-density polymers (PVC and PET), which decreased macro porosity by less than 15%. Hematite and hornblende retained less than 7% of low-density

MPs, while allophane and kaolinite absorbed 19% and 12%, respectively. Polymer density and mineral surface area mutually influence MP destiny and the ensuing variations in soil physical quality (Merino-guzm, 2025).

MPs dramatically raised dehydrogenase activity while decreasing phytase activity. MPs disrupted the rhizosphere microbial community's variety and structure, making it more vulnerable to polystyrene microplastics (PSMPs) and polypropylene microplastics (PPMPs). MP presence affected the soil-rhizosphere-plant system, which may have crucial consequences for evaluating MP environmental risk (Lian *et al.*, 2024). Pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) shows promise by identifying unique polymer fragments. Recent work has successfully identified polypropylene nanoplastics even in complex matrices like soil organic matter, though polystyrene analysis requires pretreatment. (Blanco *et al.*, 2021). These fossil fuel-derived plastics, such polyethylene, polystyrene, and polypropylene, are challenging for nature to decompose on its own. Fortunately, some bacteria have evolved the ability to degrade these durable manmade chemicals through evolutionary adaptation. Certain microbes have evolved the ability to breakdown these durable polymers.

Plant growth-promoting bacteria are helpful soil bacteria that have demonstrated potential for both encouraging plant growth and development and breaking down polymers. Enzymes found in some *Bacillus* and *Pseudomonas* species allow them to break down polyethylene. Similar complementary enzyme complexes that are appropriate for the breakdown of polypropylene are found in *Rhodococcus* species. These microorganisms start the breakdown of plastic by using oxidative and hydrolytic enzymes. The mineralization of the broken polymers is subsequently made easier by additional soil organisms. Polystyrene can be attacked by the nitrogen-fixing *Rhizobium*. Surface oxidation, which is facilitated by bacterial enzymes, is frequently the first stage in the multi-step

process. Numerous investigations have identified bacteria capable of consuming polyethylene, such as photosynthetic *Rhodospseudomonas* and *Brevibacillus borstelensis*. However, some *Streptomyces* can also depolymerize polypropylene. All things considered, using bacteria that consume plastic gives hope for

managing plastic waste while reducing environmental damage and accelerating the transition to a circular economy (H. Maqbool *et al.*, 2025).

Study Group (Authors, Year)	Focus Area	Approach	Key Findings
Abel et al. (2017); Baho et al. (2021); Dulanja et al. (2022)	Terrestrial ecosystems	Reviews	Identified microplastics as emerging pollutants affecting soil ecosystem stability and functions
Aralappanavar et al. (2024); Aijaz et al. (2024); Meng & Zhang (2025)	Soil properties & plant response	Reviews	Microplastics alter soil physical, chemical, and biological properties and influence plant growth
Chen et al. (2025); Omidoyin & Jho (2023); Zhang et al. (2021)	Soil microbial communities	Reviews + experiments	Microplastics modify microbial diversity, activity, and enzyme functions
Zhou et al. (2024); Zhu et al. (2022); Shi et al. (2022)	Nitrogen cycling	Experimental studies	Microplastics disrupt nitrogen transformations including nitrification and denitrification
Ma et al. (2023); Wang et al. (2022); Kumar et al. (2023)	Biogeochemical cycles (C, N, P)	Reviews/meta-analysis	Microplastics influence nutrient cycling through microbial and soil structural changes
Aminzadeh et al. (2025); Jiang et al. (2025); Maqbool et al. (2025)	Soil physics & transport	Experimental	Microplastics affect water flow, solute transport, and soil structure dynamics
Bosker et al. (2019); Lian et al. (2024); Song et al. (2024)	Plant–soil interactions	Experimental	Microplastics negatively impact seed germination, root growth, and rhizosphere processes
Li et al. (2022); Qiu et al. (2022); Su et al. (2023)	Meta-analysis studies	Meta-analysis	Overall negative impacts of microplastics on soil health and greenhouse gas emissions confirmed
Li et al. (2024); Gulizia et al. (2023); Cao et al. (2022)	Chemical leaching & additives	Experimental + reviews	Microplastics release toxic additives and act as vectors for pollutants
Hoang et al. (2025); Ren et al. (2021); Guo et al. (2020)	Fate, transport & environmental risk	Reviews	Microplastics migrate across soil and groundwater systems and pose ecological risks

## VIII. CONCLUSION

### Synthesis of Key Findings

The extensive body of literature reviewed herein demonstrates that microplastics represent a

significant and multifarious modulator of soil nutrient cycling within the Earth's Critical Zone, with effects that are profoundly influenced by hydrological connectivity. The pervasive contamination of terrestrial ecosystems by

microplastics, originating from sources such as agricultural mulch, sewage sludge, and atmospheric deposition, establishes a foundation for complex interactions that extend far beyond the physical presence of these particles in soil (Muñoz-alegría *et al.*, 2025); (Liu *et al.*, 2026). A critical insight emerging from this synthesis is the dual role of microplastics as both physical agents of change and chemical vectors. Physically, microplastics alter soil structure, porosity, bulk density, and aggregate stability in ways that are highly dependent on polymer type, size, concentration, and morphology (Tumwesigye *et al.*, 2023). Fibrous microplastics, for instance, exhibit different effects on void ratio and compression indices compared to granular particles, while low-density polymers like polyethylene and polypropylene accumulate differently than high-density polymers such as PVC and PET. These physical alterations directly impact soil hydraulic properties, including water holding capacity, saturated hydraulic conductivity, and preferential flow pathways (Nyika and Olumana, no date). The creation of low-permeability zones and the modification of pore structures fundamentally change water and solute transport dynamics, thereby influencing the very hydrological connectivity that governs nutrient movement through the Critical Zone (Sarkar *et al.*, 2023).

### **Hydrological Connectivity as a Master Variable**

The concept of hydrological connectivity emerges as a master variable mediating microplastic effects on nutrient cycling. Water serves not only as the primary transport medium for microplastics themselves—facilitating their vertical migration through the vadose zone, lateral transport via surface runoff, and eventual delivery to groundwater and aquatic systems—but also as the conduit through which microplastic-induced changes in soil physics translate into altered biogeochemical function. Preferential flow paths, whether created by microplastic incorporation or naturally occurring through macropores and desiccation cracks, become critical hotspots for both microplastic accumulation and nutrient transformation. The work is demonstrating in-situ vertical transport of mobile MP particles to depths of 2 meters through natural processes underscores the profound implications of

hydrological connectivity for the long-term fate of microplastics and their associated contaminants (Kumar *et al.*, 2026). Furthermore, the leaching dynamics of microplastic-derived dissolved organic matter (MP-DOM) and chemical additives are intrinsically linked to hydrological regimes. The work by (Liu *et al.*, 2024) revealing that MP-DOM composition evolves significantly across sequential leaching stages under different environmental conditions highlights the dynamic nature of microplastic chemical release. The finding that UV irradiation enhances trihalomethane precursor leaching more substantially than bulk DOC, and that polylactic acid-derived DOM exhibits fundamentally different properties compared to petroleum-based MP-DOM, suggests that the ecological impacts of microplastics will vary temporally and spatially as a function of hydrological exposure and weathering history.

### **Biogeochemical Perturbations: Carbon and Nitrogen Cycling**

The evidence overwhelmingly indicates that microplastics perturb soil carbon and nitrogen cycling through multiple interconnected mechanisms. With respect to carbon, microplastics influence both CO<sub>2</sub> emissions and soil organic carbon (SOC) storage through direct (as carbon substrates) and indirect (via microbial community modulation) pathways. Biodegradable microplastics consistently demonstrate more pronounced effects on carbon mineralization compared to conventional polymers, with studies reporting increased CO<sub>2</sub> emissions, enhanced dissolved organic carbon concentrations, and altered microbial carbon use efficiency. The double-edged sword nature of biodegradable microplastics—simultaneously increasing CO<sub>2</sub> emissions while promoting microbial necromass accumulation in mineral-associated organic matter—illustrates the complexity of predicting net effects on soil carbon sequestration (Chang *et al.*, 2024). The meta-analytical finding that MP-DOM is nearly eight times more labile than natural organic matter and exhibits nearly four-fold lower sorption to mineral particles carries profound implications for soil carbon stability. This reduced mineral protection, combined with enhanced microbial accessibility, suggests that microplastic

contamination may accelerate the turnover of native soil organic carbon while simultaneously introducing a novel, highly bioavailable carbon source. The resulting priming effects could fundamentally alter the balance between carbon storage and mineralization in terrestrial ecosystems (Ullah et al., 2025). Nitrogen cycling perturbations are equally complex and consequential. Microplastics consistently reduce soil nitrate concentrations while having variable effects on ammonium, with the magnitude and direction of these effects modulated by polymer type, concentration, soil properties, and environmental conditions such as temperature. The mechanisms underlying these observations are multifaceted, encompassing changes in nitrogen transformation rates (nitrification, denitrification, ammonification, nitrogen fixation), shifts in the abundance and composition of nitrogen-cycling microbial guilds, and direct effects of leached plastic additives such as phthalates. The finding that plasticizers, rather than the polymer matrix itself, may be primarily responsible for observed effects on nitrogen cycling emphasizes the need to consider the full chemical complexity of microplastic contaminants (Bhattacharjee et al., 2025). The increased N<sub>2</sub>O emissions consistently observed with microplastic exposure represent a particular concern given the potent greenhouse gas potential of N<sub>2</sub>O. The meta-analytical finding of 140.6% increase in N<sub>2</sub>O emissions associated with enhanced denitrification suggests that microplastic contamination may contribute to positive climate feedbacks. The interaction between microplastics and other factors such as temperature, biochar application, and soil moisture regimes further complicates predictive capabilities (Rillig et al., 2021).

### ***The Plastisphere: A Novel Ecological Interface***

The formation of the plastisphere—the distinct microbial habitat on microplastic surfaces—represents a paradigm-shifting concept in soil microbial ecology. The consistent enrichment of specific taxa, including potential plastic-degraders (Actinobacteria, Proteobacteria, Bacteroidetes) and, concerningly, potential pathogens (Massilia, Pseudomonas, pathogenic Alternaria), indicates that microplastics function not merely as inert contaminants but as active agents reshaping

microbial community structure and function. The finding that plastisphere communities exhibit lower diversity, reduced network complexity, and different assembly mechanisms (greater stochasticity) compared to bulk soil communities suggests that microplastics create novel selective environments that may have cascading effects on ecosystem function (Rillig et al., 2021). The functional implications of plastisphere formation are only beginning to be understood. Enhanced abundance of genes associated with xenobiotic biodegradation, human diseases, and altered carbon and nitrogen cycling within plastisphere communities' points to the potential for microplastics to serve as hotspots for both beneficial (plastic degradation) and detrimental (pathogen enrichment, antibiotic resistance gene dissemination) processes. The finding that the plastisphere can modulate the environmental behavior of co-existing contaminants, including heavy metals, organic pollutants, and antibiotic resistance genes, positions microplastics as critical interfaces governing the fate and toxicity of complex pollutant mixtures in agricultural soils (Li et al., 2025).

### ***Emerging Contaminants: Tire Wear Particles and 6PPD-Quinone***

The recognition of tire wear particles as a dominant and underappreciated component of microplastic pollution represents a critical advance in the field. The quantitative estimates of TWP release—approximately 79.5 kt annually in the U.S., with significant partitioning to soils (18.5–30.2 kt) and additional inputs via sewage sludge application (6.3–13.1 kt)—reveal the magnitude of this contamination pathway. The exceptionally high concentrations detected in roadside soils (up to 26,400 mg/kg) and the demonstrated toxicity to soil invertebrates establish TWPs as a significant and urgent concern (Ghanadi et al., 2025; Li et al., 2025). The discovery of 6PPD-quinone as a highly toxic transformation product of the tire antioxidant 6PPD has catalyzed research into the fate and effects of these compounds in terrestrial environments. The finding that 6PPD persists significantly longer in anaerobic soils (half-life 51.4 d) compared to aerobic conditions (0.7–1.5 d) and that anaerobic flooding actually promotes 6PPD-Q formation, has profound

implications for the many agricultural soils subject to periodic saturation. The demonstrated sensitivity of soil fungi to 6PPD-Q accumulation, the disruption of fungal network structure, and the weakening of nitrogen and phosphorus cycling potential in contaminated urban soils suggest that tire-derived contaminants may have ecosystem-level consequences that extend far beyond their initial deposition zones. The estimated 97.5% increase in national 6PPD-Q emissions between 2013, coupled with the recognition of soil as a major reservoir and the higher estimated daily intake in children compared to adults, elevates 6PPD-Q from an aquatic ecotoxicological concern to a broader human and environmental health issue requiring urgent attention.

### **Context-Dependency and Knowledge Gaps**

A recurring theme throughout this review is the profound context-dependency of microplastic effects. Soil properties (texture, pH, organic matter content, nutrient status), microplastic characteristics (polymer type, size, shape, concentration, weathering state, additive content), environmental conditions (temperature, moisture, freeze-thaw cycles, UV exposure), and biological factors (microbial community composition, presence of soil fauna, plant species) all interact to determine the net effects on nutrient cycling. The differential vulnerability of nutrient-rich versus nutrient-poor soils, the temperature-dependent effects on nitrogen bioavailability, and the polymer-specific impacts on soil physical properties all underscore the impossibility of simple, universal predictions (Sousa et al., 2025). Significant knowledge gaps remain. The vertical dimension of microplastic effects—from surface soils through the vadose zone to groundwater—remains underexplored relative to surface processes. The deep Critical Zone, where microbes mediate essential biogeochemical cycles but where access is limited, represents a particular frontier. The temporal dynamics of microplastic effects, including aging processes, leaching kinetics, and the evolution of plastisphere communities over environmentally relevant timescales, are poorly constrained. The interactive effects of microplastics with other global change factors—warming, altered precipitation regimes, elevated CO<sub>2</sub>, co-

contaminants—remain largely unknown. Perhaps most critically, the translation of observed effects on nutrient cycling to consequences for ecosystem services, agricultural productivity, and human well-being remains poorly quantified (Schefer et al., 2025).

This comprehensive review establishes microplastics as significant and complex modulators of soil nutrient cycling within the Earth's Critical Zone, with hydrological connectivity serving as a master variable governing their transport, transformation, and ecological effects. The evidence synthesized herein supports several overarching conclusions: First, microplastics are ubiquitous in terrestrial ecosystems, with agricultural soils serving as major sinks. Their physical presence fundamentally alters soil structure, porosity, aggregate stability, and hydraulic properties in polymer- and concentration-dependent manners. These physical modifications, in turn, influence water and solute transport, creating feedback loops that affect both microplastic fate and nutrient dynamics.

Second, microplastics perturb soil carbon and nitrogen cycling through multiple interconnected mechanisms, including direct contributions as carbon substrates, indirect effects via microbial community modulation, and the release of chemical additives. Biodegradable microplastics generally exert more pronounced effects than conventional polymers, increasing CO<sub>2</sub> emissions while simultaneously altering microbial carbon use efficiency and necromass accumulation. Nitrogen cycling is consistently disrupted, with reduced nitrate concentrations, enhanced N<sub>2</sub>O emissions, and shifts in the abundance and activity of nitrogen-transforming microbial guilds.

Third, the formation of the plastisphere creates novel microbial niches with distinct community composition, reduced diversity, and altered functional potential compared to bulk soil. Plastisphere communities may accelerate plastic degradation while simultaneously enriching potential pathogens and facilitating the dissemination of antibiotic resistance genes,

positioning microplastics as critical interfaces governing the fate of co-occurring contaminants.

Fourth, tire wear particles and their associated chemicals, particularly 6PPD-quinone, represent emerging contaminants of high concern. Their substantial emissions, accumulation in roadside and agricultural soils, demonstrated toxicity to soil biota, and potential for human exposure necessitate urgent research and management attention.

Fifth, the effects of microplastics on nutrient cycling are profoundly context-dependent, modulated by soil properties, microplastic characteristics, environmental conditions, and biological factors. This context-dependency, combined with significant knowledge gaps regarding deep Critical Zone processes, temporal dynamics, and interactive effects with global change factors, limits predictive capabilities and underscores the need for continued research.

The Earth's Critical Zone—the thin living skin spanning from vegetation canopy to groundwater that sustains terrestrial life—is increasingly contaminated by microplastics that modify the very biogeochemical processes upon which ecosystem function depends. As plastic production continues to increase and environmental contamination accumulates, understanding and mitigating the effects of microplastics on soil nutrient cycling under varying hydrological regimes becomes not merely an academic exercise but a pressing environmental imperative. The findings synthesized herein suggest that microplastics, through their physical, chemical, and biological effects on soil, have the potential to fundamentally alter nutrient dynamics in ways that may compromise soil health, agricultural productivity, and climate regulation. Addressing this challenge will require integrated research approaches that bridge disciplines, consider the full complexity of the Critical Zone, and ultimately inform policy and management strategies to protect this vital resource.

## REFERENCES

1. Abel, A. *et al.* (2017) "Microplastics as an emerging threat to terrestrial ecosystems,"

- (September). Available at: <https://doi.org/10.1111/gcb.14020>.
2. Aijaz, M.N.H.N., Akhtar, K.A.M. and Babur, W.A.L.M. (2024) *Impact of microplastics on soil ( physical and chemical ) properties , soil biological properties / soil biota , and response of plants to it: a review, International Journal of Environmental Science and Technology*. Springer Berlin Heidelberg. Available at: <https://doi.org/10.1007/s13762-024-05656-y>.
3. Akob, D.M. and Küsel, K. (2011) "Where microorganisms meet rocks in the Earth's Critical Zone," pp. 3531–3543. Available at: <https://doi.org/10.5194/bg-8-3531-2011>.
4. Aminzadeh, M. *et al.* (2025) "Microplastic-induced alterations in water flow and solute transport dynamics in soil," *Scientific Reports*, 15(1), p. 42941. Available at: <https://www.nature.com/articles/s41598-025-30476-6>.
5. Aralappanavar, V.K. *et al.* (2024) "Effects of microplastics on soil microorganisms and microbial functions in nutrients and carbon cycling – A review," *Science of the Total Environment*, 924(October 2023). Available at: <https://doi.org/10.1016/j.scitotenv.2024.171435>.
6. Baho, D.L., Bundschuh, M. and Futter, M.N. (2021) "Microplastics in terrestrial ecosystems: Moving beyond the state of the art to minimize the risk of ecological surprise," (January), pp. 3969–3986. Available at: <https://doi.org/10.1111/gcb.15724>.
7. Banwart, S.A. *et al.* (no date) "Soil Functions: Connecting Earth ' s Critical Zone," pp. 333–359.
8. Blancho, F. *et al.* (2021) "Nanoplastics Identification in Complex Environmental Matrices: Strategies for Polystyrene and Polypropylene." Available at: <https://doi.org/10.1021/acs.est.1c01351>.
9. Bosker, T. *et al.* (2019) "Chemosphere Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant *Lepidium sativum*," *Chemosphere*, 226, pp. 774–781. Available at: <https://doi.org/10.1016/j.chemosphere.2019.03.163>.
10. Bullard, J.E. *et al.* (2021) "Preferential transport of

- microplastics by wind," *Atmospheric Environment*, 245(August 2020), p. 118038. Available at: <https://doi.org/10.1016/j.atmosenv.2020.118038>.
11. Cao, Y. *et al.* (2022) "Microplastics: A major source of phthalate esters in aquatic environments," *Journal of Hazardous Materials*, 432(February), p. 128731. Available at: <https://doi.org/10.1016/j.jhazmat.2022.128731>.
  12. Carpanez, T.G., Castro, L.M.C. and Santos, C.R.D.O.S. (2025) "Source, dynamics, and risks of microplastics and nanoplastics in agricultural groundwater systems," 97, pp. 1–15. Available at: <https://doi.org/10.1590/0001-3765202420241393>.
  13. Casazza, M. *et al.* (2018) "Aerosol pollution, including eroded soils, intensifies cloud growth, precipitation, and soil erosion: A review," *Journal of Cleaner Production*, 189, pp. 135–144. Available at: <https://doi.org/10.1016/j.jclepro.2018.04.004>.
  14. Chen, G. *et al.* (2025) "Effects of microplastics on microbial community and greenhouse gas emission in soil: A critical review," *Ecotoxicology and Environmental Safety*, 289(August 2024), p. 117419. Available at: <https://doi.org/10.1016/j.ecoenv.2024.117419>.
  15. Chen, X. *et al.* (2023) "Analysis, environmental occurrence, fate and potential toxicity of tire wear compounds 6PPD and 6PPD-quinone," *Journal of Hazardous Materials*, 452(January), p. 131245. Available at: <https://doi.org/10.1016/j.jhazmat.2023.131245>.
  16. Cheng, Y. *et al.* (2021) "Chemosphere The effects of high-density polyethylene and polypropylene microplastics on the soil and earthworm *Metaphire guillelmi* gut microbiota," *Chemosphere*, 267, p. 129219. Available at: <https://doi.org/10.1016/j.chemosphere.2020.129219>.
  17. Deng, Y. *et al.* (2024) "Characteristics and Migration Dynamics of Microplastics in Agricultural Soils," pp. 1–16.
  18. Dindar, E. (2024) "The Effect of N Mineralization, Nitrification and Ammonification Rates in Soils Contaminated with Microplastics," *Water, Air, & Soil Pollution*, 235(11), pp. 1–19. Available at: <https://doi.org/10.1007/s11270-024-07500-y>.
  19. Ding, J. *et al.* (2024) "Aging in soil increases the disturbance of microplastics to the gut microbiota of soil fauna," *Journal of Hazardous Materials*, 461(August 2023), p. 132611. Available at: <https://doi.org/10.1016/j.jhazmat.2023.132611>.
  20. Ding, L. *et al.* (2020) "Science of the Total Environment The occurrence and distribution characteristics of microplastics in the agricultural soils of Shaanxi Province, in north-western China," *Science of the Total Environment*, 720, p. 137525. Available at: <https://doi.org/10.1016/j.scitotenv.2020.137525>.
  21. Do, A.T.N., Ha, Y. and Kwon, J. (2022) "Leaching of microplastic-associated additives in aquatic environments: A critical review ☆," *Environmental Pollution*, 305(April), p. 119258. Available at: <https://doi.org/10.1016/j.envpol.2022.119258>.
  22. Dong, Y. *et al.* (2025) "Soil & Tillage Research Microplastics decrease soil compressibility but have no major impact on soil physical properties," 253(February). Available at: <https://doi.org/10.1016/j.still.2025.106688>.
  23. Dulanja, P. *et al.* (2022) "Effects of microplastics on the terrestrial environment: A critical review," *Environmental Research*, 209(June 2021), p. 112734. Available at: <https://doi.org/10.1016/j.envres.2022.112734>.
  24. Elisabeth, S.R. *et al.* (2023) "Science of the Total Environment High levels of tire wear particles in soils along low traffic roads," 903(August). Available at: <https://doi.org/10.1016/j.scitotenv.2023.166470>.
  25. Fang, J. *et al.* (2024) "Interference of microplastics on autotrophic microbiome in paddy soils: Shifts in carbon fixation rate, structure, abundance, co-occurrence, and assembly process," *Journal of Hazardous Materials*, 474(March), p. 134783. Available at: <https://doi.org/10.1016/j.jhazmat.2024.134783>.
  26. Feng, X. *et al.* (2025) "Trends and mechanisms in agricultural mulch film microplastic pollution: a critical review. Review article .," 10.
  27. Gao, B. *et al.* (2022) "Interactive effects of microplastics, biochar, and earthworms on CO<sub>2</sub> and N<sub>2</sub>O emissions and microbial functional

- genes in vegetable-growing soil," *Environmental Research*, 213(June), p. 113728. Available at: <https://doi.org/10.1016/j.envres.2022.113728>.
28. Gao, S. *et al.* (2025) "Microplastics Trigger Soil Dissolved Organic Carbon and Nutrient Turnover by Strengthening Microbial Network Connectivity and Cross-Trophic Interactions." Available at: <https://doi.org/10.1021/acs.est.4c12546>.
29. "Global Change Biology - 2025 - Shi - A Double-Edged Sword of Biodegradable Microplastics on the Soil Microbial Carbon Pump.pdf" (no date).
30. Gulizia, A.M., Philippa, B., *et al.* (2023) "Plasticiser leaching from polyvinyl chloride microplastics and the implications for environmental risk assessment," *Marine Pollution Bulletin*, 195(August), p. 115392. Available at: <https://doi.org/10.1016/j.marpolbul.2023.115392>.
31. Gulizia, A.M., Patel, K., *et al.* (2023) "Science of the Total Environment Understanding plasticiser leaching from polystyrene microplastics," *Science of the Total Environment*, 857(June 2022), p. 159099. Available at: <https://doi.org/10.1016/j.scitotenv.2022.159099>.
32. Guo, J. *et al.* (2020) "Source, migration and toxicology of microplastics in soil," *Environment International*, 137(July 2019), p. 105263. Available at: <https://doi.org/10.1016/j.envint.2019.105263>.
33. Han, N. *et al.* (2022) "Science of the Total Environment Horizontal transport of macro- and microplastics on soil surface by rainfall induced surface runoff as affected by vegetations," *Science of the Total Environment*, 831(April), p. 154989. Available at: <https://doi.org/10.1016/j.scitotenv.2022.154989>.
34. He, D. *et al.* (2018) "Trends in Analytical Chemistry Microplastics in soils: Analytical methods, pollution characteristics and ecological risks," *Trends in Analytical Chemistry*, 109, pp. 163–172. Available at: <https://doi.org/10.1016/j.trac.2018.10.006>.
35. He, D. *et al.* (2020) "Microplastics in Terrestrial Ecosystems: A Scientometric Analysis," pp. 1–15.
36. He, J. *et al.* (2022) "Catena Soil depth and agricultural irrigation activities drive variation in microbial abundance and nitrogen cycling," 219(August). Available at: <https://doi.org/10.1016/j.catena.2022.106596>.
37. Helm, P., Athey, S. and Rochman, C.M. (2020) "Microplastics entering northwestern Lake Ontario are diverse and linked to urban sources Jelena Grbi," 174. Available at: <https://doi.org/10.1016/j.watres.2020.115623>.
38. Henkel, C. and Hofmann, T. (2022) "Polyvinyl Chloride Microplastics Leach Phthalates into the Aquatic Environment over Decades." Available at: <https://doi.org/10.1021/acs.est.2c05108>.
39. Hoang, V.H. *et al.* (2025) "Microplastic characteristics, transport, risks, and remediation in groundwater: a review," *Environmental Chemistry Letters*, 23(3), pp. 817–837. Available at: <https://doi.org/10.1007/s10311-025-01825-8>.
40. Holbrook, W.S. *et al.* (2019) "Links between physical and chemical weathering inferred from a 65-m-deep borehole through Earth's critical zone," (February), pp. 1–11. Available at: <https://doi.org/10.1038/s41598-019-40819-9>.
41. Huang, M. *et al.* (2023) "Microplastics in soil ecosystems: soil fauna responses to field applications of conventional and biodegradable microplastics," *Journal of Hazardous Materials*, 441(July 2022), p. 129943. Available at: <https://doi.org/10.1016/j.jhazmat.2022.129943>.
42. Idbella, M. *et al.* (2026) "Microplastic pollution drives soil bacterial community shifts and alters phosphorus cycling across land use gradients," *Journal of Hazardous Materials*, 501(September 2025), p. 140968. Available at: <https://doi.org/10.1016/j.jhazmat.2025.140968>.
43. Iqbal, H. *et al.* (2025) "6PPD and 6PPD-Q in terrestrial environments: Environmental fate, ecological effects, and mitigation approaches ☆," *Applied Soil Ecology*, 216(38), p. 106492. Available at: <https://doi.org/10.1016/j.apsoil.2025.106492>.
44. Islam, T. and Cheng, H. (2024) "Science of the Total Environment Existence and fate of microplastics in terrestrial environment: A global fretfulness and abatement strategies," *Science of the Total Environment*, 953(August), p. 176163. Available at: <https://doi.org/10.1016/j.scitotenv.2024.176163>.
45. Jiang, H. *et al.* (2025) "Journal of Environmental

- Chemical Engineering Transport of polystyrene microplastics in saturated and unsaturated paddy soils: Effect of freeze-thaw cycles under different physicochemical conditions," *Journal of Environmental Chemical Engineering*, 13(6), p. 120137. Available at: <https://doi.org/10.1016/j.jece.2025.120137>.
46. Jiang, S. *et al.* (2026) "Impact of Tire Wear Particle ( TWP ) -Derived Dissolved Organic Matter ( DOM ) on Soil Properties and Heavy Metal Mobility," pp. 1–18.
47. Ju, T. *et al.* (2025) "Microplastics Disrupt Soil Aggregate Stability and Associated Nutrient Dynamics in Mulched Salt-Affected Agricultural Soils." Available at: <https://doi.org/10.1021/acs.est.5c01063>.
48. Kang, J. *et al.* (2025) "Tyre Wear Particles in the Environment: Sources , Toxicity , and Remediation Approaches," pp. 1–31.
49. Kee, J. *et al.* (2020) "Science of the Total Environment Microplastics in the freshwater and terrestrial environments: Prevalence , fates , impacts and sustainable solutions," *Science of the Total Environment*, 719, p. 137512. Available at: <https://doi.org/10.1016/j.scitotenv.2020.137512>.
50. Khurana, S. *et al.* (2022) "Predicting the impact of spatial heterogeneity on microbially mediated nutrient cycling in the subsurface," pp. 665–688.
51. Kim, L. *et al.* (2022) "Toxicity assessment of tire particles released from personal mobilities ( bicycles , cars , and electric scooters ) on soil organisms," 437(April).
52. Kim, S.W. *et al.* (2022) "Soil Storage Conditions Alter the Effects of Tire Wear Particles on Microbial Activities in Laboratory Tests." Available at: <https://doi.org/10.1021/acs.estlett.2c00585>.
53. Kumar, A. *et al.* (2023) "Trends in Analytical Chemistry Microplastics in terrestrial ecosystems: Un-ignorable impacts on soil characterises , nutrient storage and its cycling," *Trends in Analytical Chemistry*, 158, p. 116869. Available at: <https://doi.org/10.1016/j.trac.2022.116869>.
54. Kundel, D. *et al.* (2025) "Driving soils to change: Tyre wear particles modulate microbial-mediated soil functions and performance of vegetable crops," 214(March).
55. Li, G. *et al.* (2024) "Divergent responses in microbial metabolic limitations and carbon use efficiency to variably sized polystyrene microplastics in soil," (July 2023), pp. 2658–2671. Available at: <https://doi.org/10.1002/ldr.5090>.
56. Li, H. *et al.* (2022) "Microplastic effects on soil system parameters: a meta - analysis study," *Environmental Science and Pollution Research*, 4, pp. 11027–11038. Available at: <https://doi.org/10.1007/s11356-021-18034-9>.
57. Li, K. *et al.* (2023) "The platisphere of biodegradable and conventional microplastics from residues exhibit distinct microbial structure, network and function in plastic-mulching farmland," *Journal of Hazardous Materials*, 442(September 2022), p. 130011. Available at: <https://doi.org/10.1016/j.jhazmat.2022.130011>.
58. Li, Q. *et al.* (2025) "iScience and its own transport in soil," *ISCIENCE*, 28(9), p. 113193. Available at: <https://doi.org/10.1016/j.isci.2025.113193>.
59. Li, Y. *et al.* (2024) "Science of the Total Environment Leaching of chemicals from microplastics: A review of chemical types , leaching mechanisms and influencing factors," *Science of the Total Environment*, 906(August 2023), p. 167666. Available at: <https://doi.org/10.1016/j.scitotenv.2023.167666>.
60. Lian, Y. *et al.* (2024) "Effects of polystyrene , polyethylene , and polypropylene microplastics on the soil-rhizosphere-plant system: Phytotoxicity , enzyme activity , and microbial community," *Journal of Hazardous Materials*, 465(38), p. 133417. Available at: <https://doi.org/10.1016/j.jhazmat.2023.133417>.
61. Lin, D. *et al.* (2026) "Microplastics negatively affect soil fauna but stimulate microbial activity: insights from a field-based microplastic addition experiment," (January). Available at: <https://doi.org/10.1098/rspb.2020.1268/875431/rspb.2020.1268.pdf>.
62. Lin, H. *et al.* (2006) "Hydropedology: Synergistic integration of pedology and hydrology," 42, pp. 1–13. Available at: <https://doi.org/10.1029/2005WR004085>.
63. Liu, D. *et al.* (2024) "Occurrence and emission characteristics of microplastics in agricultural surface runoff under different natural rainfall and

- short-term fertilizer application," *Journal of Hazardous Materials*, 477(April), p. 135254. Available at: <https://doi.org/10.1016/j.jhazmat.2024.135254>.
64. Liu, F., Lorenz, C. and Zhao, G. (2025) "From land to sea: Hydrological source tracking of microplastics in coastal sediments," 283(May).
65. Liu, R. *et al.* (2022) "Research Progress of Microplastic Pollution in the Vadose Zone," pp. 1–13.
66. Lohmann, P. *et al.* (no date) "Seasonal Patterns of Dominant Microbes Involved in Central Nutrient Cycles in the Subsurface."
67. Luo, Y. *et al.* (2023) "Science of the Total Environment Microplastics are transferred by soil fauna and regulate soil function as material carriers," *Science of the Total Environment*, 857(October 2022), p. 159690. Available at: <https://doi.org/10.1016/j.scitotenv.2022.159690>.
68. Ma, R. *et al.* (2023) "Microplastics affect C, N, and P cycling in natural environments: Highlighting the driver of soil hydraulic properties," *Journal of Hazardous Materials*, 459(August), p. 132326. Available at: <https://doi.org/10.1016/j.jhazmat.2023.132326>.
69. Maguire, L.W. and Gardner, C.M. (2023) "Science of the Total Environment Fate and transport of biological microcontaminants bound to microplastics in the soil environment," *Science of the Total Environment*, 892(March), p. 164439. Available at: <https://doi.org/10.1016/j.scitotenv.2023.164439>.
70. Maqbool, A. *et al.* (2025) "Effect of Preferential Microplastics Leaching Through Macropores on Vertical Soil Particle Transport," pp. 1–14. Available at: <https://doi.org/10.1111/ejss.70140>.
71. Maqbool, H. *et al.* (2025) "Exploring the Role of Plant Growth - Promoting Bacteria in Biodegradation of Plastic: A Review," *Water, Air, & Soil Pollution*, 236(6), pp. 1–26. Available at: <https://doi.org/10.1007/s11270-025-07972-6>.
72. Meng, S. and Zhang, Z. (2025) "Effects of microplastics on soil environment and land plant growth: a review," *Environmental Monitoring and Assessment* [Preprint]. Available at: <https://doi.org/10.1007/s10661-025-14316-8>.
73. Menon, M. *et al.* (2014) "SoilTrEC: a global initiative on critical zone research and integration," pp. 3191–3195. Available at: <https://doi.org/10.1007/s11356-013-2346-x>.
74. Merino-guzm, C. (2025) "Polymer-specific impacts of microplastics on mineral retention and soil stability," 378(February), pp. 1–7. Available at: <https://doi.org/10.1016/j.envpol.2025.126487>.
75. Nie, W. *et al.* (no date) "Economic Valuation of Earth 's Critical Zone: A Pilot Study of the Zhangxi Catchment, China," pp. 1–19.
76. Ning, K. *et al.* (2025) "Arbuscular mycorrhizal fungi and glomalin mediate the effects of microplastics on soil carbon storage," *Journal of Hazardous Materials*, 500(October), p. 140426. Available at: <https://doi.org/10.1016/j.jhazmat.2025.140426>.
77. Olesen, K.B. *et al.* (2019) "Microplastics in a Stormwater Pond."
78. Omidoyin, K.C. and Jho, E.H. (2023) "Effect of microplastics on soil microbial community and microbial degradation of microplastics in soil: A review," 28(6), pp. 0–3.
79. Pu, Y. *et al.* (2025) "Journal of Environmental Chemical Engineering Effects of UV-aged tire wear particles ( TWP ) on soil microorganisms: Microbial community, microbial metabolism, cell defense and repair, and transmission of ARGs," *Journal of Environmental Chemical Engineering*, 13(2), p. 115624. Available at: <https://doi.org/10.1016/j.jece.2025.115624>.
80. Qiang, L. *et al.* (2023) "Ecotoxicology and Environmental Safety Plastic mulching, and occurrence, incorporation, degradation, and impacts of polyethylene microplastics in agroecosystems," *Ecotoxicology and Environmental Safety*, 263(January), p. 115274. Available at: <https://doi.org/10.1016/j.ecoenv.2023.115274>.
81. Qiao, J. *et al.* (2018) "Catena Estimating the spatial relationships between soil hydraulic properties and soil physical properties in the critical zone ( 0 – 100 m ) on the Loess Plateau, China: A state-space modeling approach," *Catena*, 160(October 2017), pp. 385–393. Available at: <https://doi.org/10.1016/j.catena.2017.10.006>.
82. Qiao, Z. *et al.* (2025) "Vadose Zone Geochemical Heterogeneity Governs Vertical Microbial

- Assembly in Lakeshore Agricultural Lands." Available at: <https://doi.org/10.1029/2025JG008815>.
83. Qiu, Y. *et al.* (2022) "Soil microplastic characteristics and the effects on soil properties and biota: A systematic review and meta-analysis ☆," *Environmental Pollution*, 313(September), p. 120183. Available at: <https://doi.org/10.1016/j.envpol.2022.120183>.
84. Ran, T. *et al.* (2024) "Ecotoxicology and Environmental Safety Soil plastisphere interferes with soil bacterial community and their functions in the rhizosphere of pepper (*Capsicum annuum* L.)," *Ecotoxicology and Environmental Safety*, 270(August 2023), p. 115946. Available at: <https://doi.org/10.1016/j.ecoenv.2024.115946>.
85. Rao, C. *et al.* (2025) "Preferential Flow Drives Coupled Nitrogen Migration and Transformation in the Vadose Zone: Microbial Hotspots and Functional Gene Dynamics." Available at: <https://doi.org/10.1021/acs.est.5c03358>.
86. Rasmussen, L.A. *et al.* (2024) "Retention of microplastics and tyre wear particles in stormwater ponds," *Water Research*, 248(November 2023), p. 120835. Available at: <https://doi.org/10.1016/j.watres.2023.120835>.
87. Rehman, A. *et al.* (2025) "Unveiling the microplastics degradation and its transformative effects on soil nutrient dynamics and plant health – A systematic review," *Sustainable Production and Consumption*, 54(July 2024), pp. 25–42. Available at: <https://doi.org/10.1016/j.spc.2024.12.018>.
88. Ren, Z. *et al.* (2021) "Microplastics in the soil-groundwater environment: Aging, migration, and co-transport of contaminants – A critical review," *Journal of Hazardous Materials*, 419(March), p. 126455. Available at: <https://doi.org/10.1016/j.jhazmat.2021.126455>.
89. Review, A.N. *et al.* (2024) "toxics," pp. 1–11.
90. Riveros, G. *et al.* (2022) "Microplastic pollution on the soil and its consequences on the nitrogen cycle: a review," *Environmental Science and Pollution Research*, pp. 7997–8011. Available at: <https://doi.org/10.1007/s11356-021-17681-2>.
91. Salam, M. *et al.* (2023) "Effects of micro ( nano ) plastics on soil nutrient cycling: State of the knowledge," *Journal of Environmental Management*, 344(April), p. 118437. Available at: <https://doi.org/10.1016/j.jenvman.2023.118437>.
92. Sarker, A. *et al.* (2020) "Science of the Total Environment A review of microplastics pollution in the soil and terrestrial ecosystems: A global and Bangladesh perspective," *Science of the Total Environment*, 733, p. 139296. Available at: <https://doi.org/10.1016/j.scitotenv.2020.139296>.
93. Selonen, S. *et al.* (2021) "Exploring the impacts of microplastics and associated chemicals in the terrestrial environment – Exposure of soil invertebrates to tire particles," 201(March). Available at: <https://doi.org/10.1016/j.envres.2021.111495>.
94. Severe, E. *et al.* (2025) "The Transport of Microplastics from Soil in Response to Surface Runoff and Splash Erosion." Available at: <https://doi.org/10.1021/acs.est.5c04795>.
95. Sewwandi, M. *et al.* (2024) "Trends in Analytical Chemistry Microplastics in urban stormwater sediments and runoff: An essential component in the microplastic cycle," *Trends in Analytical Chemistry*, 178(June 2023), p. 117824. Available at: <https://doi.org/10.1016/j.trac.2024.117824>.
96. She, Y., Qi, X. and Li, Z. (2024) "Insights into soil autotrophic ammonium oxidization under microplastics stress: Crossroads of nitrification , comammox , anammox and Feammox," *Journal of Hazardous Materials*, 478(August), p. 135443. Available at: <https://doi.org/10.1016/j.jhazmat.2024.135443>.
97. Shen, D. *et al.* (2025) "Transformations of 6PPD and 6PPD-quinone in soil under redox-driven conditions: Kinetics , product identification , and environmental implications," *Environment International*, 200(May), p. 109532. Available at: <https://doi.org/10.1016/j.envint.2025.109532>.
98. Shen, M. *et al.* (2022) "Science of the Total Environment Recent advances in impacts of microplastics on nitrogen cycling in the environment: A review," 815. Available at: <https://doi.org/10.1016/j.scitotenv.2021.152740>.
99. Shi, J. *et al.* (2022) "Microplastic presence significantly alters soil nitrogen transformation and decreases nitrogen bioavailability under contrasting temperatures," *Journal of Environmental Management*, 317(June), p.

115473. Available at:  
<https://doi.org/10.1016/j.jenvman.2022.115473>.
100. Shi, J. *et al.* (2023) "Effects of Microplastics on Soil Carbon Mineralization: The Crucial Role of Oxygen Dynamics and Electron Transfer." Available at:  
<https://doi.org/10.1021/acs.est.3c02133>.
101. Shi, J., Tanentzap, A.J., *et al.* (2025) "Microplastics Generate Less Mineral Protection of Soil Carbon and More CO<sub>2</sub> Emissions," 2409585. Available at:  
<https://doi.org/10.1002/advs.202409585>.
102. Shi, J., Zhang, Q., *et al.* (2025) "Science of the Total Environment Microplastic induces microbial nitrogen limitation further alters microbial nitrogen transformation: Insights from metagenomic analysis," *Science of the Total Environment*, 967(February), p. 178825. Available at:  
<https://doi.org/10.1016/j.scitotenv.2025.178825>.
103. Shi, J., Sun, Y. and Wang, X. (2022) "Microplastics reduce soil microbial network complexity and ecological deterministic selection," 24, pp. 2157–2169. Available at:  
<https://doi.org/10.1111/1462-2920.15955>.
104. Singh, J. *et al.* (2022) "Bioresource Technology Biodegradation of plastics for sustainable environment," *Bioresource Technology*, 347(November 2021), p. 126697. Available at:  
<https://doi.org/10.1016/j.biortech.2022.126697>.
105. Song, T. *et al.* (2024) "Effect of conventional and biodegradable microplastics on the soil-soybean system: A perspective on rhizosphere microbial community and soil element cycling," *Environment International*, 190(February), p. 108781. Available at:  
<https://doi.org/10.1016/j.envint.2024.108781>.
106. Su, P. *et al.* (2023) "Microplastics stimulated nitrous oxide emissions primarily through denitrification: A meta-analysis," *Journal of Hazardous Materials*, 445(November 2022), p. 130500. Available at:  
<https://doi.org/10.1016/j.jhazmat.2022.130500>.
107. Sullivan, P.L. *et al.* (2022) "Earth-Science Reviews Embracing the dynamic nature of soil structure: A paradigm illuminating the role of life in critical zones of the Anthropocene," 225(November 2021). Available at:  
<https://doi.org/10.1016/j.earscrev.2021.103873>.
108. Sun, J. *et al.* (2025) "Metagenomic analysis reveals soil microbiome responses to microplastics and ZnO nanoparticles in an agricultural soil," *Journal of Hazardous Materials*, 492(January), p. 138164. Available at:  
<https://doi.org/10.1016/j.jhazmat.2025.138164>.
109. Sun, Y. *et al.* (2023) "Trends in Analytical Chemistry Current advances in interactions between microplastics and dissolved organic matters in aquatic and terrestrial ecosystems," 158. Available at:  
<https://doi.org/10.1016/j.trac.2022.116882>.
110. Sun, Y., Wu, M., *et al.* (2024) "Homogenization of bacterial plastisphere community in soil: a continental-scale microcosm study," 4(December 2023), pp. 1–12.
111. Sun, Y., Xie, S., *et al.* (2024) "Terrestrial plastisphere as unique niches for fungal communities," pp. 1–11. Available at:  
<https://doi.org/10.1038/s43247-024-01645-8>.
112. Temam, R. and Mortula, M. (2023) "Leaching of microplastics from PVC pipes under stagnant conditions," *Desalination and Water Treatment*, 311(November 2022), pp. 243–252. Available at:  
<https://doi.org/10.5004/dwt.2023.29979>.
113. Thomas, J. *et al.* (2022) "Method Development for Separation and Analysis of Tire and Road Wear Particles from Roadside Soil Samples." Available at:  
<https://doi.org/10.1021/acs.est.2c03695>.
114. Tunali, M. and Nowack, B. (2025) "Ecotoxicology and Environmental Safety Towards including soil ecotoxicity of microplastics and tire wear particles into life cycle assessment," *Ecotoxicology and Environmental Safety*, 303(May), p. 118856. Available at:  
<https://doi.org/10.1016/j.ecoenv.2025.118856>.
115. Ulrich, N. *et al.* (2025) "The vertical migration of a pesticide mixture in sandy soil is strongly driven by their sorption behavior and can be altered by Polyethylene Microplastics," 494(May). Available at:  
<https://doi.org/10.1016/j.jhazmat.2025.138511>.
116. Wan, Y. *et al.* (2019) "Science of the Total Environment Effects of plastic contamination on

- water evaporation and desiccation cracking in soil," *Science of the Total Environment*, 654, pp. 576–582. Available at: <https://doi.org/10.1016/j.scitotenv.2018.11.123>.
117. Wang, Chunhui *et al.* (2022) "Microplastic Pollution in the Soil Environment: Characteristics , Influencing Factors , and Risks," pp. 1–14.
118. Wang, Chengqian *et al.* (2022) "Soil plastisphere: Exploration methods , influencing factors , and ecological insights," *Journal of Hazardous Materials*, 430(February), p. 128503. Available at: <https://doi.org/10.1016/j.jhazmat.2022.128503>.
119. Wang, C., Zhao, J. and Xing, B. (2021) "Environmental source , fate , and toxicity of microplastics," *Journal of Hazardous Materials*, 407(May 2020), p. 124357. Available at: <https://doi.org/10.1016/j.jhazmat.2020.124357>.
120. Wang, F. *et al.* (2024) "Science of the Total Environment Microplastics and biochar interactively affect nitrous oxide emissions from tobacco planting soil," *Science of the Total Environment*, 952(August), p. 175885. Available at: <https://doi.org/10.1016/j.scitotenv.2024.175885>.
121. Wang, J. *et al.* (2020) "Science of the Total Environment LDPE microplastics significantly alter the temporal turnover of soil microbial communities," *Science of the Total Environment*, 726, p. 138682. Available at: <https://doi.org/10.1016/j.scitotenv.2020.138682>.
122. Wang, J *et al.* (2022) "Runoff and discharge pathways of microplastics into freshwater ecosystems: A systematic review and meta-analysis," pp. 1473–1492. Available at: <https://doi.org/10.1139/facets-2022-0140>.
123. Wang, Jiaxin *et al.* (2024) "Insights into effects of conventional and biodegradable microplastics on organic carbon decomposition in different soil aggregates ☆," *Environmental Pollution*, 359(March), p. 124751. Available at: <https://doi.org/10.1016/j.envpol.2024.124751>.
124. Wang, Jianling *et al.* (2024) "Integrating metabolomics and high-throughput sequencing to investigate the effects of tire wear particles on mung bean plants and soil microbial communities," *Environmental Pollution*, 340(P1), p. 122872. Available at: <https://doi.org/10.1016/j.envpol.2023.122872>.
125. Wang, K. *et al.* (2025) "Microplastics and soil microbiomes," *BMC Biology*, 23(1). Available at: <https://doi.org/10.1186/s12915-025-02387-5>.
126. Wang, Q. *et al.* (2025) "Lytic virus – bacteria interactions play a primary role in enhancing soil organic carbon and total nitrogen storage in polyethylene microplastics-amended soils," *Chemical Engineering Journal*, 523(September), p. 168373. Available at: <https://doi.org/10.1016/j.cej.2025.168373>.
127. Wang, W. *et al.* (2020) "Science of the Total Environment Environmental fate and impacts of microplastics in soil ecosystems: Progress and perspective," *Science of the Total Environment*, 708, p. 134841. Available at: <https://doi.org/10.1016/j.scitotenv.2019.134841>.
128. Wang, W. *et al.* (2025) "Wei Wang, § Gefei Huang, § Fangfang Miao, Zhongying Zhao, and Zongwei Cai \*." Available at: <https://doi.org/10.1021/acs.est.5c02072>.
129. Wang, Xin *et al.* (2022) "Science of the Total Environment Recent advances on the effects of microplastics on elements cycling in the environment," *Science of the Total Environment*, 849(August), p. 157884. Available at: <https://doi.org/10.1016/j.scitotenv.2022.157884>.
130. Wang, X. *et al.* (2026) "Journal of Environmental Chemical Engineering Sequential leaching dynamics of dissolved organic matter from microplastics: Implications for trihalomethane formation and microbial growth potential," *Journal of Environmental Chemical Engineering*, 14(1), p. 120578. Available at: <https://doi.org/10.1016/j.jece.2025.120578>.
131. Wang, Y. *et al.* (2025) "Trends in Analytical Chemistry Tire wear particles in aquatic ecosystems: Current knowledge and future perspectives," *Trends in Analytical Chemistry*, 183(August 2024), p. 118095. Available at: <https://doi.org/10.1016/j.trac.2024.118095>.
132. Wasnik, S. *et al.* (2026) "NanoImpact Impact of tire particles and tire leachate contaminants on plant physiology and soil health: Case study in mung bean and tomato," *NanoImpact*, 41(November 2025), p. 100601. Available at: <https://doi.org/10.1016/j.impact.2025.100601>.
133. Weber, C.J. *et al.* (2022) "Deposition and in-

- situ translocation of microplastics in floodplain soils," *Science of the Total Environment*, 819. Available at: <https://doi.org/10.1016/j.scitotenv.2021.152039>.
134. Wik, A. (2009) "Occurrence and effects of tire wear particles in the environment – A critical review and an initial risk assessment," 157, pp. 1–11. Available at: <https://doi.org/10.1016/j.envpol.2008.09.028>.
135. Wilkinson, M.T., Richards, P.J. and Humphreys, G.S. (2009) "Earth-Science Reviews Breaking ground: Pedological , geological , and ecological implications of soil bioturbation," *Earth Science Reviews*, 97(1–4), pp. 257–272. Available at: <https://doi.org/10.1016/j.earscirev.2009.09.005>.
136. Wu, W. *et al.* (2024) "The spatio-temporal accumulation of 6 PPD-Q in greenbelt soils and its effects on soil microbial communities ☆," *Environmental Pollution*, 358(May), p. 124477. Available at: <https://doi.org/10.1016/j.envpol.2024.124477>.
137. Xiang, Y. *et al.* (2023) "Effects of microplastics exposure on soil inorganic nitrogen: A comprehensive synthesis," *Journal of Hazardous Materials*, 460(July). Available at: <https://doi.org/10.1016/j.jhazmat.2023.132514>.
138. Xie, Y. *et al.* (2025) "Eco-Environment & Health Freeze-thaw cycles and biodegradable microplastics alter the microbial degradation of atrazine in mollisols," 4(October). Available at: <https://doi.org/10.1016/j.eehl.2025.100196>.
139. Xu, F., Su, M. and Tang, S. (2026) "Spatiotemporal Distribution of 6PPD - Q in China Revealed by a National-Scale Quantification Framework." Available at: <https://doi.org/10.1021/acs.est.5c12242>.
140. Xu, Q. *et al.* (2023) "Qiao Xu, Gang Li, \* Li Fang, Qian Sun, Ruixia Han, Zhe Zhu, and Yong-Guan Zhu \*." Available at: <https://doi.org/10.1021/acs.est.2c08672>.
141. Xu, Q. *et al.* (2024) "Science of the Total Environment Soil moisture-dependent tire wear particles aging processes shift soil microbial communities and elevated nitrous oxide emission on drylands," *Science of the Total Environment*, 952(August), p. 175948. Available at: <https://doi.org/10.1016/j.scitotenv.2024.175948>.
142. Ya, H. *et al.* (2021) "Recent advances on ecological effects of microplastics on soil environment," *Science of the Total Environment*, 798, p. 149338. Available at: <https://doi.org/10.1016/j.scitotenv.2021.149338>.
143. Ya, H. *et al.* (2023) "Chemosphere Co-existence of polyethylene microplastics and tetracycline on soil microbial community and ARGs," *Chemosphere*, 335(March), p. 139082. Available at: <https://doi.org/10.1016/j.chemosphere.2023.139082>.
144. Yan, Z. *et al.* (2024) "Effects of biodegradable microplastics and straw addition on soil greenhouse gas emissions," *Environmental Pollution*, 356(June), p. 124315. Available at: <https://doi.org/10.1016/j.envpol.2024.124315>.
145. Yang, H. *et al.* (2022) "Distribution, sources, migration, influence and analytical methods of microplastics in soil ecosystems," *Ecotoxicology and Environmental Safety*, 243(August), p. 114009. Available at: <https://doi.org/10.1016/j.ecoenv.2022.114009>.
146. Yang, Z., Sha, Y. and Kumar, A. (2025) "Degradable microplastics induce more soil organic carbon loss via priming effects: a viewpoint," *Plant and Soil*, 511(1), pp. 99–102. Available at: <https://doi.org/10.1007/s11104-023-06141-0>.
147. Yu, H. *et al.* (2022) "Microplastics as an Emerging Environmental Pollutant in Agricultural Soils: Effects on Ecosystems and Human Health," 10(March), pp. 1–18. Available at: <https://doi.org/10.3389/fenvs.2022.855292>.
148. Yu, Y. *et al.* (2024) "Nano Today Nanoplastics in soil plastisphere: Occurrence , bio-interactions and environmental risks," *Nano Today*, 58(April), p. 102409. Available at: <https://doi.org/10.1016/j.nantod.2024.102409>.
149. Yu, Z. *et al.* (2021) "Sources , migration , accumulation and influence of microplastics in terrestrial plant communities," *Environmental and Experimental Botany*, 192, p. 104635. Available at: <https://doi.org/10.1016/j.envexpbot.2021.104635>.
150. Zeb, A. *et al.* (2026) "A critical review of tire

- wear particles aging and ecotoxicological consequences in terrestrial environments: Insights into environmentally persistent free radicals," *Journal of Hazardous Materials*, 501(38), p. 140641. Available at: <https://doi.org/10.1016/j.jhazmat.2025.140641>.
151. Zhang, H. (2025) "Biodegradable film mulching alters soil C, N, P and S cycling via mediating microbial communities in dryland," 2025(September). Available at: <https://doi.org/10.1002/jsfa.70193>.
152. Zhang, M. et al. (2019) "Science of the Total Environment Microplastics from mulching film is a distinct habitat for bacteria in farmland soil," *Science of the Total Environment*, 688, pp. 470–478. Available at: <https://doi.org/10.1016/j.scitotenv.2019.06.108>.
153. Zhang, S. et al. (2025) "A new perspective on understanding soil microplastics: Composition, influencing factors of the soil plastisphere, and its impacts on the environmental behavior of co-existing contaminants," *Chemical Engineering Journal*, 518(January), p. 164640. Available at: <https://doi.org/10.1016/j.cej.2025.164640>.
154. Zhang, X. et al. (2021) "Systematical review of interactions between microplastics and microorganisms in the soil environment," *Journal of Hazardous Materials*, 418(March), p. 126288. Available at: <https://doi.org/10.1016/j.jhazmat.2021.126288>.
155. Zhang, Z. et al. (2024) "Science of the Total Environment Spatiotemporal variation of 6PPD and 6PPDQ in dust and soil from e-waste recycling areas," *Science of the Total Environment*, 923(March), p. 171495. Available at: <https://doi.org/10.1016/j.scitotenv.2024.171495>.
156. Zheng, C., Mehlig, D. and Oxley, T. (2025) "Quantifying pathways of tyre wear into the environment," *Environmental Research*, 285(P1), p. 122288. Available at: <https://doi.org/10.1016/j.envres.2025.122288>.
157. Zhou, Y. et al. (2021) "Microplastic contamination is ubiquitous in riparian soils and strongly related to elevation, precipitation and population density," *Journal of Hazardous Materials*, 411(November 2020), p. 125178. Available at: <https://doi.org/10.1016/j.jhazmat.2021.125178>.
158. Zhou, Z. et al. (2024) "Science of the Total Environment Differential impacts of polyethylene microplastic and additives on soil nitrogen cycling: A deeper dive into microbial interactions and transformation mechanisms," *Science of the Total Environment*, 942(March), p. 173771. Available at: <https://doi.org/10.1016/j.scitotenv.2024.173771>.
159. Zhu, F. et al. (2022) "Microplastics altered soil microbiome and nitrogen cycling: The role of phthalate plasticizer," *Journal of Hazardous Materials*, 427(October 2021), p. 127944. Available at: <https://doi.org/10.1016/j.jhazmat.2021.127944>.