Asian Journal of Water, Environment and Pollution. 2026;23(2):025310243.
doi: 10.36922/AJWEP025310243

REVIEW ARTICLE

Microplastics distribution in the soil: A review

Helen Shnada Auta[1,2], Innocent Ojeba Musa[3], Sesan Abiodun Aransiola[4], Hussaini Anthony Makun[2,5], Auwalu Hassan[6], Udeme Josiah Joshua Ijah[1], David Oyeyemi Aboyeji[1], Shahul Hamid Fauziah[7,8], Naga Raju Maddela[9], and Ram Prasad[10]*

[1]Department of Microbiology, School of Life Sciences, Federal University of Technology, Minna, Niger, Nigeria
[2]Department of Microbiology, Africa Centre of Excellence for Mycotoxin and Food Safety, Federal University of Technology, Minna, Niger, Nigeria
[3]Department of Microbiology, School of Science and Information Technology, Skyline University Nigeria, Kano, Kano, Nigeria
[4]Department of Microbiology, Faculty of Sciences, University of Abuja, Abuja, Nigeria.
[5]Department of Biochemistry, School of Life Sciences, Federal University of Technology, Minna, Niger, Nigeria
[6]Department of Biological Sciences, Faculty of Science, Federal University, Kashere, Gombe, Nigeria
[7]Institute of Biological Sciences, University of Malaya, Kuala Lumpur, Malaysia
[8]Centre for Research in Waste Management, Faculty of Science, University of Malaya, Kuala Lumpur, Malaysia
[9]Departamento de Ciencias Biológicas, Facultad de Ciencias de la Salud, Universidad Técnica de Manabí, Portoviejo, Manabí, Ecuador
[10]Department of Botany, School of Life Sciences, Mahatma Gandhi Central University, Motihari, Bihar, India
***Corresponding author**: Ram Prasad (ramprasad@mgcub.ac.in)

Received: August 1, 2025; 1st revised: October 3, 2025; 2nd revised: November 18, 2025; Accepted: December 26, 2025; Published online: January 2, 2026

Abstract: The pervasive use of plastics in modern society has led to significant environmental concerns about plastic pollution. As demand for plastic materials continues to rise, the improper disposal of plastic waste poses a substantial threat to both marine and terrestrial ecosystems. Microplastics, defined as plastic debris <5 mm in diameter, have emerged as a contaminant of global significance. While extensive research has focused on microplastic pollution in oceans, the impact on terrestrial environments remains understudied. The heterogeneous distribution of microplastics raises concerns about soil health, nutrient cycling, and crop productivity. Microplastics are not uniformly distributed across soil profiles. Instead, they often accumulate in topsoil layers where they interact with plant roots, microorganisms, and soil fauna. Their presence has been linked to changes in soil structure, reduced water holding capacity, and disruptions in microbial community dynamics. Understanding the patterns, pathways, and mechanisms governing microplastic distribution is therefore critical for developing informed mitigation strategies. If the food chain is disrupted, it can have negative impacts on soil biota, raising worries about human health. In this review, microplastics' impacts on soil biogeochemistry and their interactions with soil organisms are discussed, along with their properties, research trends, and other factors. Recent findings suggest that soil serves as a primary sink and transporter of microplastics, which can then enter aquatic ecosystems and affect soil biota, potentially disrupting the food chain and human health. We emphasize the need for ongoing study into the impact of microplastics on terrestrial ecosystems.

Keywords: Microplastics; Food insecurity; Soil; Air; Plants

1. Introduction

Plastic waste is a growing global issue. This waste stream has sparked considerable scientific attention due to its environmental impact. Since the dawn of the plastic age in 1950, when global production totaled 2 million tonnes (Mt), annual output has surged to over 460 Mt by 2024, resulting in a staggering cumulative total of approximately 12,200 Mt manufactured worldwide. Yet, despite this boom, recycling infrastructure and material design have failed to keep pace. Only about 9% of all plastics ever produced have been recycled, with 12% incinerated, leaving roughly 79%—or over 9,600 Mt—accumulated in landfills or released into the natural environment. This fate stems primarily from plastics not being engineered for recyclability and systemic gaps in global waste management, turning a versatile innovation into an enduring environmental hazard.[1-3] Around 12,000 Mt of plastic waste is expected to be disposed of in landfills by the year 2050.[4-9] Soils are highly important in ecological systems, as part of global material cycles (such as the carbon cycle), water filters (such as in groundwater treatment), and other areas. Soils worldwide are highly sensitive to human activities and pollutant inputs due to the extensive use of plastics.[10,11] According to the statistics from the Organization for Economic Co-operation and Development, global plastic production in the years 2000 and 2022 was 234 Mt and 475 Mt, respectively; this caused an increase in plastic waste from 156 Mt to 378 Mt in the said period.[12] It is noteworthy that 77% of this waste is either disposed of in landfills or accumulates in the soil.[13] Plastic particles in soil that are smaller than 5 mm are referred to as microplastics (MPs).[14]

Plastics break down into MPs (<5 mm) and nanoplastics (NPs; <1 μm) through biotic and abiotic degradation.[3,15-17] The term "microplastics" was coined in the 1970s to describe the minuscule plastic particles, granules, and threads found in water. Since the 1950s, plastic production has grown exponentially to fulfil market demand and is estimated to reach 1 billion tonnes by 2050, according to industry forecasts.[2,18] MPs can be divided into two categories: Primary MPs, which are purposefully designed to perform specific functions in products such as personal care items, and secondary MPs, which result from the degradation of larger plastics.[3,16,18] Physical degradation, caused by mechanical forces, such as wear and tear, is the most common source of MPs.[19-23] A wide range of human activities affects nature. The introduction of new compounds and the release of pollutants across diverse ecosystems worldwide are among these factors. Similar to other ecosystems, soil is particularly susceptible to the impacts of human activities. Nearly all (95%) of the world's food is land-based.[24]

2. Environmental burden of microplastics

Hundreds or thousands of organic subunits (monomers) are linked together via strong covalent chemical interactions to form synthetic polymers. Large-scale manufacture of polymers began in the 1950s, with Bakelite (a condensation reaction of phenol and formaldehyde) dating back to the early 20th century. Manufacturing has increased rapidly since then, reaching a peak of 380 Mt/year in 2015.[25,26] There are now thousands of commercially available polymer grades on the market. "Plastics" refers to low-cost, commodity thermoplastic polymers, which account for most of the market share. Polyvinyl chloride (PVC), polypropylene (PP), and polystyrene (PS) are numerous types of plastics found in our everyday lives.[27]

Plastics created from non-renewable petrochemicals, including all of the aforementioned commodity polymers, make up the vast majority of what is currently produced. Despite their low cost, each of these polymers has been meticulously crafted to possess specific physical properties. Rotation, injection, extrusion, compression, blowing, and thermoforming can all be used to shape them as desired.[28] To attain desired attributes (strength, porosity, opacity, and color), their material properties are altered during or after synthesis. Due to their high molecular weight, hydrophobic nature, and limited functional groups susceptible to microbial enzymes, light, water, etc., polyolefins are incredibly long-lasting.[29,30] They are suitable for food packing, sterile medical purposes, and construction, among other uses, but their recalcitrance and impermeability make them extremely long-lived if they are discarded. Stabilizers and antioxidants used to extend the working life of plastics also delay the degradation of plastic waste.[30-33]

There are several primary MP particles, including microbeads, microfibers, and pellets, that are <5.0 mm in diameter. Due to their small size, they are commonly used in the cosmetics and pharmaceutical industries.[16,20,34-36] In contrast, secondary MPs form when larger plastics are broken down chemically (by sunlight and water), biologically (by decomposition), and mechanically (by wear and tear).[11,32,37] The direct release of primary and secondary MPs has been documented from fishing and coastal activities, as well as from other sources, such as untreated sewage and processed effluents from both municipal and industrial wastewater treatment facilities.[10,21]

Geogenic heavy-metal background levels refer to the natural concentrations of trace elements (e.g., lead, cadmium, chromium, nickel, zinc, copper, and arsenic) in soil derived from parent rock through weathering[38] without significant anthropogenic input.[39] These baseline values vary regionally based on geology (e.g., ultramafic rocks enrich chromium and nickel; shale enriches cadmium and zinc). Understanding these natural levels is critical when studying MP contamination in soil for the following interconnected scientific, methodological, and interpretive reasons: MPs are rarely "pure" polymers in the environment. They act as vectors that adsorb heavy metals from surrounding soil or water due to their high surface area, functional groups (after weathering), and electrostatic properties.[40] Heavy metals bound to MPs may become more bioavailable to plants and soil organisms due to the Trojan horse effect (ingestion of MP–metal complexes) and desorption in the gut or rhizosphere.[41] If a soil has high geogenic cadmium, pollution with MPs that adsorb cadmium may push the total bioavailable load past critical thresholds; however, the pollution is only detectable if a background is established.[42]

Nigeria, like many countries, lacks national soil screening values for MPs. International guidelines (e.g., those of the European Union and Canada) are often adopted, but they assume low levels of naturally deposited metal. In tropical soils (e.g., oxisols and ultisols) or in mining-impacted regions (e.g., Jos Plateau and Zamfara), geogenic arsenic, lead, and mercury can naturally exceed safe limits.

It has been observed that MPs, due to their small volume and huge surface area, absorb a wide range of pollutants, including persistent organic pollutants. Environmentally persistent metals,[6,27,43] comprising both inorganic and organic pollutants, lead to the buildup of pollutants that pose numerous threats to the environment, flora, fauna, and human beings.[30,37] In addition, given MPs' long lifespans, extensive dispersal across habitats, and small size, they can interact with a broad spectrum of biota; however, information on MP exposure and the resulting consequences is currently scant in the literature.[1] Numerous scientists have extensively studied the impact of MPs on various marine and freshwater organisms over the last decade, but the situation is reversed for terrestrial plants. MP studies should include a thorough examination of plants, as they are primary producers in terrestrial ecosystems and are essential to environmental health.[31,44,45] To fill this research gap, we conducted an in-depth synthesis of recent scientific progress regarding the exposure-mediated impacts of MPs on plants, their sources, and recent trends in MP pollution, absorption, phytotoxicity, and remediation efforts.

2.1. Sources of microplastics

Plastic pollution worsens as production and use continue to rise, spreading it further despite certain regulations. Synthetic textiles, tires, personal care products, and other such items have been mentioned as possible sources of MPs (Figure 1). In other words, due to its lengthy shelf life, unsustainable use, and eventual deposition in landfills, plastic waste accumulates in the environment.[46-48] As plastics break down, their constituent chemicals and additives are emitted into the atmosphere.[49,50] These compounds are characterized by their stability under environmental conditions and can easily accumulate in soil and water. It is estimated that by 2050, there will be 500 Mt of plastic waste annually.[29,31,51] The United Nations Environment Programme reports that if current trends continue, the oceans may contain more plastic than fish by 2050 due to the predicted production of over 300 Mt of MPs, which will continue to pollute agricultural ecosystems as primary or secondary MPs.[45,51,52]

Environmental MPs comprise a diverse range of particles with different sizes, shapes, chemical compositions, and densities, arising from various sources.[53] Mulch made of plastic films, soil conditioners, and greenhouse materials are all direct sources of MPs in agriculture. MPs are spread indirectly through littering, reused water irrigation, and biosolids application.[32,47,54] Figure 2 summarizes the origin and distribution of primary and secondary MPs within environmental systems.

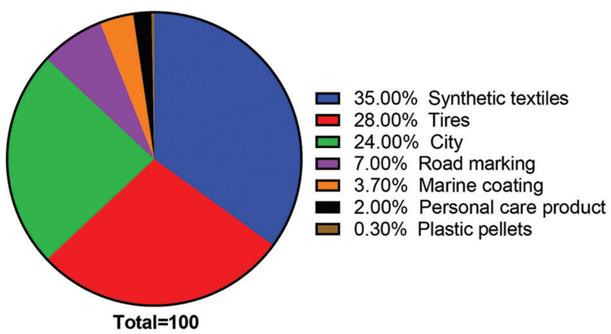

Figure 1. Potential sources of primary microplastics. Reprinted with modification from Boucher and Friot[55].

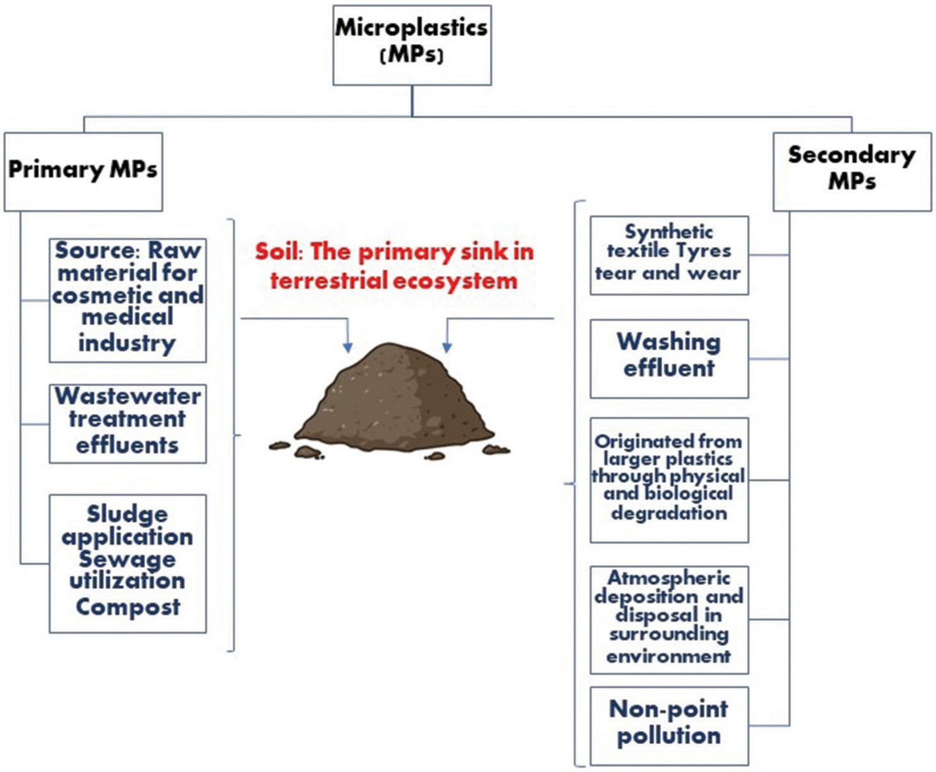

Figure 2. Microplastics types, sources, and accumulation in the terrestrial environment. Reprinted with modification from Kumari *et al.*[56].

2.2. Microplastics in agroecosystems

Studies in Europe, the United States, and Australia have estimated both annual and peak plastic inputs into agroecosystems.[28] Observational evidence suggests that each year, up to 2.5 Mt of MPs enter the oceans, largely originating from synthetic fibers released during laundry processes and from tire wear during driving, which together account for two-thirds of that quantity.[3,31,57,58] It is also estimated that approximately 95% of MPs passing through sewage treatment plants are retained during the treatment process and are broken down into biosolids. As a result, MPs enter agroecosystems through the use of biosolids as fertilizer (Figure 3).

Another major source of MP contamination is reclaimed water, which is commonly used for irrigation worldwide.[59,60] In addition, composts made from heterogeneous municipal solid waste or unsorted domestic rubbish are two common sources of plastic contamination in agroecosystems.[44] Physical degradation of plastics triggered by abrasion and fragmentation that occur during mixing and transportation exacerbates MP pollution. Studies found that biosolids were responsible for approximately 430,000 tonnes of MPs in Europe and about 300,000 tonnes in North America, contributing to contamination in agroecosystems.[1,54]

As oxygen availability and temperature increase, MPs are progressively fractured or weathered. Plastic contamination spreads across ecosystems, including groundwater and aquatic settings, as fragmented MPs travel vertically and horizontally within the soil profile and across the soil surface.[10,44,61] In addition, MPs are recognized for their persistence in soils. It was also discovered that polymers buried in soil for 32 years showed no signs of biodegradation.[3,62] Plastics are known to degrade over a period ranging from 20 to 500 years, depending on the material's composition, structural properties, and prevailing environmental conditions. Therefore, MP pollution warrants considerable attention.

There is limited information on the time required for the complete degradation of MPs. MPs play a significant role in soil properties by altering bulk density, water-holding capacity, and soil structural properties.[26,62] Soil quality varies widely depending on the type of MPs. A significant concern has been raised regarding interactions between MPs and soil contaminants, including organic pollutants, heavy metals, and antibiotics, that exert detrimental effects

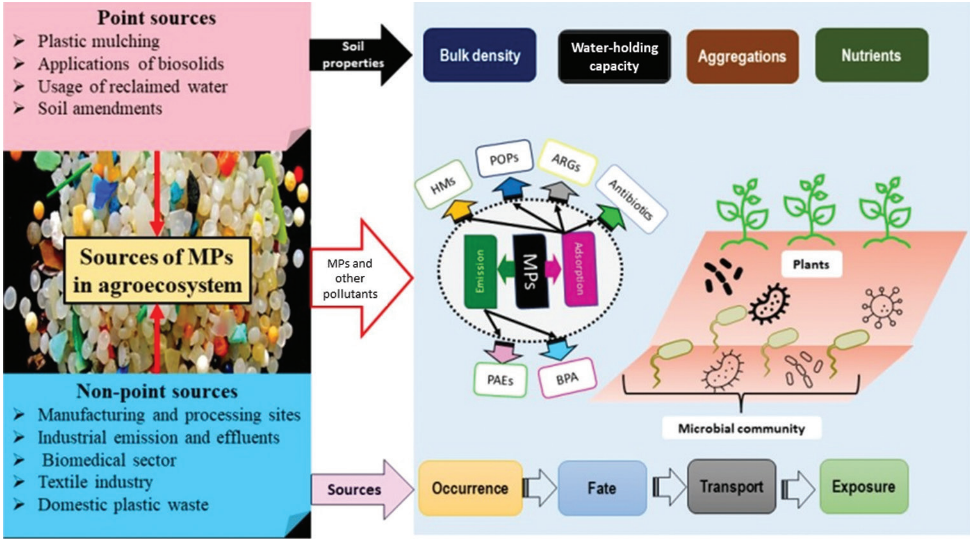

Figure 3. Soil characteristics, effects, and destiny of microplastics (MPs) in agroecosystems. Heavy metals (HMs), phthalic acid esters (PAEs), antibiotics and bacterial/phage resistance genes (ARG), antibiotics, bisphenol-A (BPA), and persistent organic pollutants (POPs) are the major environmental contaminants. Reprinted from Kumari *et al.*[56].

on native soil organisms.[37,47,63] MPs can modify the behavior of contaminants and serve as a major pathway for their migration across the underground environment.[63] In previous studies, MP fibers were applied to soil to reduce root penetration resistance, thereby enhancing root growth, decreasing soil bulk density, and improving soil aeration.[32,37,47] MPs were exposed to earthworms in another study, resulting in an unfavorable effect on soil porosity and moisture content, ultimately leading to reduced plant growth and development.[15,64,65] These studies suggest that changes in soil structure caused by MP contamination could affect microbial composition and function. Due to their widespread occurrence, variable sizes, source inputs, chemical composition, and complex interactions with both biotic and abiotic factors in agroecosystems, MP exposure exerts direct and indirect impacts on the food chain.[66,67] The abundance of MPs in agricultural soils in different countries is shown in Table 1.

3. Microplastics within terrestrial soil systems

3.1. Classification of microplastics

Microplastics are among the most recently emerging contaminants and pose a significant risk to both marine and terrestrial ecosystems.[74,75] During the initial phases of MP research, a broad range of plastic debris sizes (1–10 mm) was used to classify MPs without a standardized scheme.[66,76] This discrepancy in the size category caused problems when comparing MP data. Plastics are generally categorized by size into macroplastics (>20 mm), mesoplastics (5–20 mm), large MPs (1–5 mm), small MPs (1 µm–1 mm), and NPs (<1 nm) (Figure 4).[77,78] Primary and secondary MPs are divided by manufacturing process and fragmentation.[21,61,79] Primary MPs smaller than 5 mm are typically designed for specific purposes, including plastic granules and microbeads in home products, such as fabric softeners, and personal care products, such as toothpaste, facial cleansers, and cosmetics.[77] In most cases, sewage disposal systems are ineffective at removing these MPs from wastewater.[7,80] Secondary MPs form from larger plastics that are weathered or fragmented over time. Multiple variables, such as wind, temperature, and ultraviolet radiation, can cause the disintegration of large plastics and the subsequent generation of these MPs after they are released into the environment. These MPs include items such as tires, paints, vinyl materials, disposable products, and electronic devices.[15,81,82]

Secondary MPs are more commonly found in soil than primary MPs.[75,83] Landfills, soil conditioners, irrigation practices, road runoff, and atmospheric deposition are the most common sources of terrestrial pollution of MPs.[84,85] MPs are generated by diverse anthropogenic activities and subsequently deposited in agricultural and urban soils, where they might build up unintentionally. In agricultural soils, the primary source of MPs is from the use of organic waste materials, including sewage sludge and compost, as fertilizers.[52]

Table 1. Recent studies on microplastic identification in agricultural soils

Region	Source of MPs	Sampling depth	No. of soil samples (excluding control samples)	Main extraction method	Identification method	Unit	References
Chile	Sludge application	0–25 cm	93	Centrifuge, density separation by sodium chloride and zinc chloride	Stereo microscope	Particles/5 g dry weight	68
China	Pig manure	~20 cm	20	Continuous air-flow flotation separation, density separation by sodium chloride	Stereo microscope, ATR-FTIR, SEM	Particles/kg dry weight	69
China	Plastic mulching	20 cm	20	Wet sieving, density separation, and carbonation	SEM, ATR-FTIR	Numbers/kg dry mass	70
China	High vehicular traffic, municipal wastes, and agricultural practices	Top 5 cm	20	Density separation by zinc chloride	Stereo microscope, micro-Raman spectroscopy	Items/kg dry weight	71
Spain	Plastic mulching	0–10 cm	9	Centrifuge, ultrasonic bath	Stereo microscope	Particles/kg dry matter	69
Germany	Application of manure, littering, mulching, and silage	0–10 cm, 10–20 cm, and 20–30 cm	540	Wet sieving	Stereo microscope, FTIR	MP/kg dry weight	72
Taiwan	Historical fish farming, fruit protective foam, nearby roads, mulch, plastic debris	0–5 cm, 20–25 cm	150	Density separation by sodium chloride	Stereo microscope, ATR-FTIR	MP items/m^2	73

Abbreviations: ATR: Attenuated total reflectance; FTIR: Fourier-transformed infrared spectroscopy; MP: Microplastic; SEM: Scanning electron microscope.

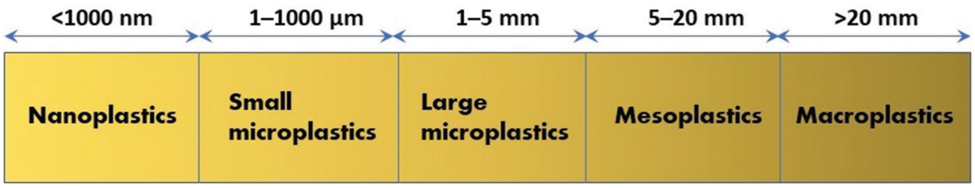

Figure 4. Size-based classification of plastic particulates. Data from Hanvey *et al.*[78].

In organic fertilizers and compost, as reported by several studies, MPs concentrations range from 14 to 1,200 particles/kg and 250–24,000 particles/kg, respectively.[84,86] Consequently, organic fertilizers can act as pathways for the introduction of MPs into the soil. A report by Lahive *et al.*[87] estimated that sewage sludge application to European and North American agricultural soils contributes up to 0.43 and 0.03 Mt MPs per annum, respectively. MPs have also been detected in soil from wastewater irrigation and plastic mulching film residues.[80,84] There are numerous other factors that contribute to MPs contamination in metropolitan areas besides agricultural runoff, including automobile tires and industrial plastics, as well as human waste, sewage effluent, and ambient dust.[29,79,88]

3.2. Study trend in soil microplastics

Carpenter and Smith[89] discovered plastic particles and fragments on the Sargasso Sea's surface in the early 1970s, and released the first scientific report on MP research. They expressed concern about the negative effects of pollution on fish populations. It has become increasingly popular to study the effects of plastic litter on marine ecosystems following the articles, and numerous other publications on MPs have been published since 1972.[3,19,27,82] Studies on MPs published between 2010 and 2022 have progressively increased. Although soil plays a crucial role in the accumulation and distribution of MPs into the water system, research on MPs in soil began relatively late. There have been few investigations into MPs in soils over the past decade, as reflected in the trend of research articles on MPs. After Van den Berg *et al.*[54] pointed out that MP accumulation has a profound impact on soil functions and biodiversity, a flurry of research on MP distribution and investigation in soils across the globe has emerged over the last 5 years, all aimed at understanding the impacts of MPs on soil biogeochemistry and the terrestrial ecosystem as a whole.

China has been the world's largest plastics manufacturer and user over the last decade. Various studies have been conducted in China, followed by the United States, Europe, and other Asian countries on soil MP pollution (Table 1). As most plastic debris is first exposed to soil, it is reasonable to assume that soil will contain more MP litter than the oceans in the future.[3,52,62,90] This indicates that more MPs polluting the soil will impair soil quality and health, with detrimental effects on food security and the ecosystem as a whole. As a result, numerous studies are needed to identify MPs' impacts.

3.3. Analytical methods for soil microplastics

Research on MPs in soil has grown tremendously over the last 5 years, but the analytical methodologies used by research groups have differed widely.[52,91] The majority of analytical techniques used to identify and quantify MPs in soils are similar to those used for water and sediment. Soil sampling is the most critical step in the analysis of MPs in soil.[26,44,47,52] Organic matter (OM) digestion and filtration are required as part of the dissolution, separation, and extraction process.[47] Following air drying and sieving through a 5 mm metal screen, density separation is used to remove soil mineral fractions from MPs using saturated salt solutions. Plastics with differing densities necessitate different solutions. There are a few plastics with densities <1.2 g/cm^3 that can be separated using sodium chloride (Table 2).[92] Examples of these plastics include polyethylene (PE), PP, and PS, all of which have densities between 0.92 and 0.97 g/cm^3.[1,30,93,94] Zinc chloride solution (for MPs with density 1.5–1.7 g/cm^3) and other residues can also be used. As a result, there is a significant variation in the methodologies available for identifying and quantifying MPs in soil.[27,47,95]

Analytical process consistency and uniformity are critical for accurate measurement of MPs, particularly when non-standard protocols are used. As sodium chloride and zinc chloride are expensive, sodium iodide (1.8 g/cm^3) is recommended for better separation of more diverse types of plastics, including PVC (1.3–2.7% by volume) and PET (1.4–1.6 g/cm^3) in soil MPs analysis.[3,49,96]

Soil OM (SOM, 1.0–1.4 g/cm^3) has a density similar to PET and nylon,[50,84] making it difficult to separate MPs in organic-matter-rich soils by density. OM, minerals, and clay are components of soil and serve as habitats for soil biota. Minerals and other contaminants can interact with SOM.[6,34,62,91,92] MPs can be embedded in SOM, posing an exceptional challenge for the identification and quantification of MPs, because signals from Fourier-transformed infrared (FTIR) and Raman spectroscopy, which are generally utilized as identifiers, can be interfered with by SOM.[44,52,57,74] As a result, it is necessary to remove SOM from the samples. A variety of chemicals were used in previous study, including acid (e.g., nitric acid), alkaline (e.g., sodium hydroxide and potassium hydroxide), oxidizing agent (e.g., hydrogen peroxide [H_2O_2]), and enzyme (e.g., cellular enzymes,

Table 2. The density separation method to extract microplastics from soil

Polymer type	Extracting solution	Density
Polyethylene	Sodium chloride	1.2 g/cm^3
Polyvinyl chloride	Zinc chloride or sodium iodide	1.5–1.7 g/cm^3
Polyamide	Sodium iodide	1.8 g/cm^3

 doi: 10.36922/AJWEP025310243

such as cellulase, lipase, proteinase, amylase, and chitinase), to test various water, sediment, and biological samples.[3,52,93] Several studies, however, reported that acid, alkaline, and H_2O_2-treated plastic particles are damaged during digestion. An ideal digestion process for improving OM removal efficiency has recently been described using Fenton's reagent (a solution of H_2O_2 with ferrous iron) in combination with density separation.[28,52,87]

Several approaches for identifying and quantifying soil MPs have been developed after the extraction procedure. One of the most important steps in identifying MPs is visual sorting, followed by spectroscopic analysis of the surface texture and properties. Size, shape, and color can all be used to classify MPs based on their morphology; however, this method is notoriously unreliable.[2,97] Visual identification must be supplemented by other physical or chemical methods.[18,46,52,66] Raman and FTIR spectroscopy have been widely employed for the chemical identification of MPs, which can detect particles down to 10 μm and 1 μm, respectively.[45] While both spectroscopies are essential at the moment, their effectiveness is primarily determined by the efficiency with which OM can be removed from soil samples.[18,45,52,84] Thermal analysis techniques, such as pyrolysis and thermal extraction-desorption mass spectrometry, have been developed to rapidly and accurately identify and quantify MPs. Thermoanalytical techniques, such as thermogravimetric analysis coupled with mass spectrometry, have also been developed to help identify and quantify MPs.[98] However, they are unable to determine the number of MPs or their morphological features. Macroscopic near-infrared (NIR) process spectroscopy, combined with chemometrics (visible-NIR spectroscopy) and hyperspectral imaging, has recently been used to conduct analyses at lower cost and with greater speed than previous methods.[65,80,99]

3.4. Movement of microplastics in soil

A wide range of terrestrial habitats, such as farmlands,[2,32,80,94] urban/industrial areas,[2] and woods, have now been found to contain MP debris.[2,100] While MP abundance has been reported to vary with soil depth,[80] it is generally higher in shallow soils than in deep soils. MPs can enter the soil in a multitude of ways, and once there, they can either move into the deeper soil or disseminate to other areas.[10,80] For example, soil serves as both a major source and a substantial sink for mercury pollutants.[26,101]

Several mechanisms have been proposed for the transfer of MPs into the soil, including bioturbation by plant roots and soil fauna, agricultural operations, such as tillage and crop harvest, water infiltration, and wet–dry cycles that create soil cracking. These elements may help MPs move deeper into the environment. Soil MPs are thought to be transported or diffused by earthworms, particularly anecic species, through digging, ingestion, and throwing. Endogeic earthworm species, such as *Aporrectodea caliginosa*, engage in deeper soil mixing by creating both horizontal and vertical tunnels reaching depths of 20–30 cm. These worms exhibit a high efficiency in moving MPs downward, with 15–25% of ingested MP particles of similar size being transported beyond 10 cm into the subsoil, a result attributed to their soil-ingesting (geophagous) behavior and intense soil bioturbation. Field and laboratory studies estimate that their daily MP transfer is between 0.8 and 1.5 particles per worm, with up to 30% higher MP concentration in their deeper soil casts compared to surface-dwelling (epigeic) worms. A recent 2025 review emphasized that endogeic earthworms can facilitate vertical migration of MPs at rates 2–4 times higher than those of epigeic earthworms and amplify contamination in the soil profile by three to five times when both types co-occur.[3,58,102] MPs can also be dispersed and redistributed in soils by burrowing and feeding activities of mites, collembola, and mosquito larvae.[7,20,46] For soils to support the movement of MPs, they must have features, such as form, type, and surface condition, that are favorable for MP movement.[36,80,101] For example, de Souza Machado *et al*.[57] reported that soil aggregation has a huge impact on the mobility of microbeads in soils.

3.5. Effects of microplastics on soil biogeochemistry

For effective agricultural planning and food security, soil characteristics are important as they influence soil biogeochemistry.[103] A combination of solar ultraviolet radiation, higher oxygen availability, and higher temperature causes MPs to fragment or weather once they are deposited in the topsoil.[31,52,66] Plastic contamination can spread to different habitats, including deep soil, groundwater, and aquatic environments, as broken-down MPs migrate vertically and horizontally through the soil profile. In addition, the spread of MP pollution can be exacerbated by intensive human activities, which may affect soil biogeochemical and biodiversity features.[15,52] Only a few studies have examined the potential effects of MP contamination on soil biogeochemistry, alterations in the biota community, and human health implications.[3,80]

Soil structure can be altered by adding MPs to the matrix.[45,80] Soil porosity may be altered by MPs migrating into the soil profile, affecting water cycling and agglomeration, the critical characteristics for soil function.[95] It was discovered by de Souza Machado *et al.*[57] that all MP inputs resulted in changes to soil physical characteristics, such as water stability aggregates (polyamide, polyethersulfone, and PS), bulk density (high-density PE, polyethersulfone, PE terephthalate, PP, and PS), and increased water availability (all MPs). However, PE MP films increased water evaporation because MPs form a channel for water movement.[29] Soil MPs have a substantial impact on soil structure. However, the type of MPs, aggregate size fraction, and plant roots that contribute to water movement and associated microbiological activity in the subsurface vary across previous studies, complicating comparisons.[27,57,91]

The high carbon content in plastics[104] makes them difficult to break down. The presence of MPs in soil could be a source of carbon for bacteria, because MPs are gradually degraded.[53] Additional studies have shown that some plastic polymers contain nutrients that may affect soil biogeochemical processes, such as nitrogen in polyacrylonitrile and polyaramide, and fluorine in polytetrafluoroethylene. It is possible that several MPs, through the leaching process, could change the soil biogeochemical cycle, but this has yet to be proven.[27,29] The hydrophobicity of MPs, as well as their vast surface area, allows adsorption of a range of harmful chemicals, such as heavy metals,[59,60] hydrophobic organic compounds,[105] and antibiotics.[99] Leaching of MPs that have already absorbed these contaminants can negatively impact the soil environment. There may be a spike in soil pollution and a risk to the surrounding ecosystem.[80,91] Newly introduced MPs into contaminated soils, on the other hand, may serve as an effective adsorbent that reduces the mobility and bioavailability of pollutants. Polymers and interactions between MPs and soil media significantly influence sorption and desorption, yet these processes are highly variable.[19,91,106] More studies are required to investigate how MPs and contaminants interact with terrestrial ecosystems.

3.6. Microplastics interactions with soil microorganisms

Recent studies have focused on MP contamination in aquatic ecosystems rather than terrestrial ecosystems. Feeding activity is a major factor in the breakdown of MPs in soil. MPs are swallowed by creatures that cannot break down MPs in most cases.[107] Studies on organisms in the aquatic environment reported that consumption of MPs may lead to a decrease in growth and reproduction, as well as death, in aquatic organisms,[87,108-110] due to nutritional imbalances, organ dysfunction, and impaired immune responses and metabolism.[3,79,107] There is evidence that human health could be adversely affected by the bioaccumulation of MPs and their subsequent trophic transfer within terrestrial food chain systems.[50,80] Studies by Guo *et al.*[80] and Cox *et al.*[5] estimated that humans ingest between 39,000 and 52,000 MP particles annually on average from ingestion of seafood, salt, sugar, and chicken, among other foods.

Although soil microorganisms make up a significant portion of all terrestrial species, little is known about the effects MPs have on them. It is reasonable to expect that the presence of MPs can modify soil structure and function, negatively impacting the microbial ecosystem's composition and diversity, particularly nitrogen-fixing microorganisms, fungi, mycorrhizal, and pathogens in the rhizosphere.[3,50,53] Rillig *et al.*[53] reported that dehydrogenases, leucine aminopeptidases, alkaline phosphatases, fluorescein diacetate hydrolase, and cellobiohydrolases have all been found to be influenced by the presence of MPs in the soil, along with their enzymatic activities. The change dependant on the MPs, enzymes, and whether or not plants are present.[57,65]

The microbiological homes formed by MPs in soil are known as plastispheres.[74,107] The degradation of MPs can be facilitated by diverse bacterial and fungal communities inhabiting this environment. Consequently, microbial biodegradation can release toxic compounds contained or absorbed by MPs into the surrounding environment; therefore, further investigation into the impact on soil ecology is needed.

3.7. Pathways of microplastic uptake in plants

Over the past decade, plant scientists have increasingly investigated the mechanisms underlying MP uptake in plants. To a limited extent, MPs have been shown to penetrate plant cells and seeds, but only for specific MP sizes and types.[2,51,62] Due to the high molecular weight and low solubility of MPs in cellulose-rich plant cell walls, it is generally considered that plants cannot absorb them. When MPs are degraded to the nanoscale, however, several studies have shown an increase in their uptake.[7,61,63] As a result, NPs can potentially enter plant cells. In addition, it has been demonstrated that several engineered nanomaterials, including metals, metal oxides, and carbon allotropes, can enter plants through roots and be distributed across various tissues, indicating a significant potential for NP uptake in plants.[74]

Previous studies showed a marked accumulation of PS within the root intercellular spaces following the exposure of rice plants to 20 nm PS nanoparticles.[20,61,62] After 72 h of exposure, nanopolychlorinated PS (50 nm) was detected in the primary roots of onion, indicating that it can penetrate biological barriers and enter root cells.[34-36,54,76] Similar to PS NPs (0.2 nm), lettuce and wheat roots were observed to absorb and transfer PS NPs into shoots. As a result, the accumulated NPs affected crop health by altering cellular membranes and biochemistry. Therefore, further study of the interactions and fate of MPs and NPs in agroecosystems is essential to ensure safe food production.

3.8. Microplastics and plants

Microplastics have been shown to affect the morphophysiological characteristics of plants, both directly and indirectly, through their exposure. However, the impacts of MP or NP exposure differ considerably, depending on both the plant species and the characteristics of the plastic. This section discusses the impacts of MPs on plant germination, growth, and indicators of biochemical processes.

Plants need to absorb water during germination to initiate the metabolic events necessary for germination.[20,58] The germination rate of *Lepidium sativum* was found to be reduced when exposed to MPs or NPs.[50] Furthermore, PS MP exposure to herbaceous species, such as *Trifolium repens*, *Orychophragmus violaceus*, and *Impatiens balsamina*, reduced germination rates at various particle sizes and concentrations.[50] Germination percentage, vigor, and the germination index declined under stress induced by PS MPs, but only at higher concentrations (1,000 mg/L) in rice seedlings.[45,58,94]

More studies are required to investigate the impacts of NPs and MPs on terrestrial plant development. Further research is required to validate these findings and better understand the mechanisms through which MPs may affect plants.[55] Study by Qi *et al.*[101] investigated the effects of LDPE and starch-based biodegradable MP films of varying sizes on potted wheat. MP films were reported to have a significant impact on wheat growth in both the vegetative and reproductive stages. It was also reported that biodegradable plastic mulch films had a greater impact on wheat development than LDPE. MPs have also been reported to negatively influence plant biomass, tissue elemental composition, root traits, and soil microbial activity in *Allium fistulosum*.[3,94]

Increasing amounts of contaminants are found in soils due to human activity, and these pollutants are often released into the environment. MPs and NPs are among the novel potential contaminants.[16,32] Plastic particulates now meet the definition of recognized pollutants, such as heavy metals, which originate from both geological and human sources. Due to their role as a temporary reservoir for sediments, nutrients, and pollutants, floodplain landscapes and soils provide a key environment for the accumulation and interaction of plastics.[26]

Weber *et al.*[44] computed total plastic and heavy metal concentrations and investigated soil properties in both soil material and MP particles, spatially linking both types of contaminants. For example, the Lahn River watershed has low-to-moderate levels of heavy metal contamination, with plastic debris distributed to a depth of nearly 2 m, and macroplastic particles contained a significant amount of heavy metals. Two types of correlation were discovered: spatial and statistical.

4. Conclusion

Environmentalists are increasingly concerned about the growing prevalence of MPs as environmental toxins. A number of studies have attempted to determine the extent to which soil can operate as a primary reservoir and a vehicle for the spread of microscopic particles. Generally, MPs are found in landfills and agricultural mulching films, as well as generated via tire abrasion and air deposition. Incorporating MPs into the soil can have a substantial effect on soil structure and soil function, as well as the quantity of organisms in the soil. To safeguard human health and ensure the integrity of the food production system, soil scientists advocate prioritizing research on the adverse effects of plastics—particularly their contributions to soil contamination and the alterations of microbial habitats—rather than emphasizing the occasionally reported beneficial aspects of MPs, such as increasing carbon pools, fertility, or microbial activity. It is also important to note that the impact of MPs on soil can vary greatly depending on the type of MP, its size, form, and purpose of use. Further studies should be conducted to enhance our understanding of MP movement and degradation processes, as well as their interactions with a wide range of soil factors and soil species, to prevent widespread contamination of MPs in the terrestrial ecosystem and reduce their threats. This review of MP distribution in soil provides a comprehensive overview of current knowledge, highlighting the sources, distribution characteristics, migration, and degradation mechanisms of MPs in soil ecosystems. The review discussed the impacts of MPs on soil physical and chemical properties, their effects on soil biota, and the potential risks to human health. It is recommended to explore the sources of MPs in soil, such as sewage sludge, plastic mulch, litter, and tire wear, and their distribution patterns across different soil environments. The methods used to extract and quantify MPs in soil, including density fractionation, oxidation, and spectroscopic analysis, should also be investigated to highlight their challenges and limitations. These studies can provide insights into understanding the dynamics of MPs in soil ecosystems and mitigating their potential risks.

Acknowledgments

The authors gratefully acknowledge the support and contributions of all individuals and institutions that facilitated the completion of this study. Finally, we extend our appreciation to all sources of scholarly materials and data that informed this work.

Funding

None.

Conflict of interest

Ram Prasad is an Editorial Board Member of this journal, but was not in any way involved in the editorial and peer-review process conducted for this paper, directly or indirectly. Separately, other authors declared that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Author contributions

Conceptualization: Helen Shnada Auta, Innocent Ojeba Musa, Sesan Abiodun Aransiola

Writing–original draft: Hassan Anthony, Udeme Josiah Joshua Ijah, David Oyeyemi Aboyeji, Shahul Hamid Fauziah

Writing–review & editing: Naga Raju Maddela, Ram Prasad, Innocent Ojeba Musa, Auwalu Hassan

Availability of data

All the data included in this article.

References

1. Büks F, Loes van Schaik N, Kaupenjohann M. What do we know about how the terrestrial multicellular soil fauna reacts to microplastic? *Soil.* 2020;6:245-267. doi: 10.5194/soil-6-245-2020
2. Choi YR, Kim YN, Yoon JH, Dickinson N, Kim KH. Plastic contamination of forest, urban, and agricultural soils: A case study of Yeoju City in the Republic of Korea. *J Soils Sed.* 2021;21:1962-1973. doi: 10.1007/s11368-020-02759-0
3. Hu C, Lu B, Guo W, *et al*. Distribution of microplastics in mulched soil in Xinjiang, China. *Int J Agric Biol Eng.* 2021;14:196-204. doi: 10.25165/j.ijabe.20211402.6165
4. Chen Y, Leng Y, Liu X, Wang J. Microplastic pollution in vegetable farmlands of suburb Wuhan, central China. *Environ Pollut.* 2020;257:113449. doi: 10.1016/j.envpol.2019.113449
5. Cox KD, Covernton GA, Davies HL, Dower JF, Juanes F, Dudas SE. Human consumption of microplastics. *Environ Sci Technol.* 2019;53:7068-7074. doi: 10.1021/acs.est.9b01517
6. Crossman J, Hurley RR, Futter M, Nizzetto L. Transfer and transport of microplastics from biosolids to agricultural soils and the wider environment. *Sci Total Environ.* 2020;724:138334. doi: 10.1016/j.scitotenv.2020.138334
7. You X, Wang S, Li G, Du L, Dong X. Microplastics in the soil: A review of distribution, anthropogenic impact, and interaction with soil microorganisms based on meta-analysis. *Sci Total Environ.* 2022;832:154975. doi: 10.1016/j.scitotenv.2022.154975
8. Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. *Sci Adv.* 2017;3:e1700782. doi: 10.1126/sciadv.1700782
9. UNEP. United Nations Environmental Program. *From Pollution to Solution: A global Assessment of Marine Litter and Plastic Pollution*; 2021. Available from: https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution [Last accessed on 2025 Nov 17].
10. Bian W, An L, Zhang S, *et al*. The long-term effects of microplastics on soil organomineral complexes and bacterial communities from controlled-release fertilizer residual coating. *J Environ Manage.* 2022;304:114193. doi: 10.1016/j.jenvman.2021.114193
11. Wang C, Zhao J, Xing B. Environmental source, fate, and toxicity of microplastics. *J Hazard Mater.* 2021;407:124357. doi: 10.1016/j.scitotenv.2019.134841
12. Guo JJ, Li F, Xiao HC, *et al*. Polyethylene and polypropylene microplastics reduce chemisorption of cadmium in paddy soil and increase its bioaccessibility and bioavailability. *J Hazard Mater.* 2023;449:130994.

doi: 10.1016/j.jhazmat.2023.130994

13. Yu Z, Xu X, Guo L, Jin R, Lu Y. Uptake and transport of micro/nanoplastics in terrestrial plants: Detection, mechanisms, and influencing factors. *Sci Total Environ.* 2024;907:168155. doi: 10.1016/j.scitotenv.2023.168155
14. Thompson RC, Olsen Y, Mitchell RP, *et al*. Lost at sea: Where is all the plastic? *Science.* 2004;304:838-838. doi: 10.1126/science.1094559
15. Lebreton L, Andrady A. Future scenarios of global plastic waste generation and disposal. *Palgrave Commun.* 2019;5:6. doi: 10.1057/s41599-018-0212-7
16. Meixner K, Kubiczek M, Fritz I. Microplastic in soil-current status in Europe with special focus on method tests with Austrian samples. *AIMS Environ Sci.* 2020;7:179-191. doi: 10.3934/environsci.2020011
17. Zhao S, Zhang Z, Chen L, *et al*. Review on migration, transformation and ecological impacts of microplastics in soil. *Appl Soil Ecol.* 2022;176:104486. doi: 10.1016/j.apsoil.2022.104486
18. Auta HS, Emenike CU, Fauziah SH. Distribution and importance of microplastics in the marine environment: A review of the sources, fate, effects, and potential solutions. *Environ Int.* 2017;102:165-176. doi: 10.1016/j.envint.2017.02.013
19. Koutnik VS, Leonard J, Alkidim S, *et al*. Distribution of microplastics in soil and freshwater environments: Global analysis and framework for transport modeling. *Environ Pollut.* 2021;274:116552. doi: 10.1016/j.envpol.2021.116552.23
20. Sun Q, Li J, Wang C, *et al*. Research progress on distribution, sources, identification, toxicity, and biodegradation of microplastics in the ocean, freshwater, and soil environment. *Front Environ Sci Eng.* 2022;16:1. doi: 10.1007/s11783-021-1429-z
21. Tian L, Chen Q, Jiang W, *et al*. A carbon-14 radiotracer-based study on the phototransformation of polystyrene nanoplastics in water versus in air. *Environ Sci Nano.* 2019;6:2907-2917. doi: 10.1039/C9EN00662A
22. Zhu K, Jia H, Sun Y, *et al*. Long-term phototransformation of microplastics under simulated sunlight irradiation in aquatic environments: Roles of reactive oxygen species. *Water Res.* 2020;173:115564. doi: 10.1016/j.watres.2020.115564
23. Narciso-Ortiz L, Aguirre-García GJ, Peña-Montes C, Lizardi-Jiménez MA. The deficit of regulation of plastic waste and microplastics in Latin America: About health and bioaccumulation in México. *Environ Sci Pollut Res.* 2025;32:25437-25449. doi: 10.1007/s11356-025-37151-3
24. FAO. Food and Agriculture Oranization of United Nation. *New FAO Report on Land and Water Resources Paints an Alarming Picture*; 2021. Available from: https://www.fao.org/newsroom/detail/new-fao-report-on-land-and-water-resources-paints-alarming-picture-091221/en#:~:text=Human%2Dinduced%20soil%20degradation%20affects,percent%20between%202000%20and%202017 [Last accessed on 2025 Sep 29].
25. Ren X, Tang J, Wang L, Liu Q. Microplastics in soil-plant system: Effects of nano/microplastics on plant photosynthesis, rhizosphere microbes and soil properties in soil with different residues. *Plant Soil.* 2021;462:561-576. doi: 10.1007/s11104-021-04869-1
26. Zhou Y, Liu X, Wang J. Characterization of microplastics and the association of heavy metals with microplastics in suburban soil of central China. *Sci Total Environ.* 2019;694:133798. doi: 10.1016/j.scitotenv.2019.133798
27. Li S, Ding F, Flury M, *et al*. Macro-and microplastic accumulation in soil after 32 years of plastic film mulching. *Environ Pollut.* 2022;300:118945. doi: 10.1016/j.envpol.2022.118945
28. Forster NA, Wilson SC, Tighe MK. Examining sampling protocols for microplastics on recreational trails. *Sci Total Environ.* 2022;818:151813. doi: 10.1016/j.scitotenv.2021.151813
29. Möller JN, Heisel I, Satzger A, *et al*. Tackling the challenge of extracting microplastics from soils: A protocol to purify soil samples for spectroscopic analysis. *Environ Toxicol Chem.* 2022;41:844-857. doi: 10.1002/etc.5024
30. Yuan W, Christie-Oleza JA, Xu EG, *et al*. Environmental fate of microplastics in the world's third-largest river: Basin-wide investigation and microplastic community analysis. *Water Res.* 2022;210:118002. doi: 10.1016/j.watres.2021.118002
31. Harms IK, Diekötter T, Troegel S, Lenz M. Amount, distribution and composition of large microplastics in typical agricultural soils in Northern Germany. *Sci Total Environ.* 2021;758:143615. doi: 10.1016/j.scitotenv.2020.143615
32. Zhuoran L, Min J, Yingxin Z, Xu Z, Zhifan Y. Visual analysis of global microplastics research status and hotspots. *Environ Chem.* 2022;41:1124-1136. doi: 10.19741/j.issn.1673-4831.2022.0937
33. Choudhary A, Thakur D, Kumar R, *et al*. Exploring microplastic pollution from origin to environmental impact and remediation approaches. *Dis Environ.* 2025;3:219. doi: 10.1007/s44274-025-00402-8
34. Han X, Lu X, Vogt RD. An optimized density-based approach for extracting microplastics from soil and sediment samples. *Environ Pollut.* 2019;254:113009. doi: 10.1016/j.envpol.2019.113009
35. Rezaei M, Riksen MJ, Sirjani E, Sameni A, Geissen V. Wind erosion as a driver for transport of light density

microplastics. *Sci Total Environ.* 2019;669:273-281. doi: 10.1016/j.scitotenv.2019.02.382
36. Schell T, Rico A, Vighi M. Occurrence, fate and fluxes of plastics and microplastics in terrestrial and freshwater ecosystems. *Rev Envion Contam Toxicol.* 2020;250:1-43. doi: 10.1007/398_2019_40
37. Schöpfer L, Menzel R, Schnepf U, *et al*. Microplastics effects on reproduction and body length of the soil-dwelling nematode *Caenorhabditis elegans*. *Front Environ Sci.* 2020;8:41. doi: 10.3389/fenvs.2020.00041
38. Yang L, Zhang Y, Kang S, Wang Z, Wu C. Microplastics in soil: A review on methods, occurrence, sources, and potential risk. *Sci Total Environ.* 2021;780:146546. doi: 10.1016/j.scitotenv.2021.146546
39. Kabata-Pendias A. *Trace Elements in Soils and Plants*. United States: CRC Press; 2000. doi: 10.1016/j.scitotenv.2019.02.382
40. Pan I, Umapathy S, Issac PK, Rahman MM, Guru A, Arockiaraj J. The bioaccessibility of adsorped heavy metals on biofilm-coated microplastics and their implication for the progression of neurodegenerative diseases. *Environ Monit Assess.* 2023;195:1264. doi: 10.1007/s10661-023-11890-7
41. Mohamed Nor NH, Kooi M, Diepens NJ, Koelmans AA. Lifetime accumulation of microplastic in children and adults. *Environ Sci Technol.* 2021;55:5084-5096. doi: 10.1021/acs.est.0c07384
42. Yu H, Hou J, Dang Q, Cui D, Xi B, Tan W. Decrease in bioavailability of soil heavy metals caused by the presence of microplastics varies across aggregate levels. *J Hazard Mater.* 2020;395:122690. doi: 10.1016/j.jhazmat.2020.122690
43. Chandel R, Singh L, Khan NA, Thakur S. Microbial remediation of microplastic-contaminated soil, focusing on mechanisms, benefits, and research gaps. *NPJ Emerg Contam.* 2025;1:14. doi: 10.1038/s44454-025-00014-0
44. Weber CJ, Opp C, Prume JA, Koch M, Andersen TJ, Chifflard P. Deposition and *in-situ* translocation of microplastics in floodplain soils. *Sci Total Environ.* 2022;819:152039. doi: 10.1016/j.scitotenv.2021.152039
45. Yu L, Zhang J, Liu Y, Chen L, Tao S, Liu W. Distribution characteristics of microplastics in agricultural soils from the largest vegetable production base in China. *Sci Total Environ.* 2021;756:143860. doi: 10.1016/j.scitotenv.2020.143860
46. Al-Jaibachi R, Cuthbert RN, Callaghan A. Examining effects of ontogenic microplastic transference on *Culex* mosquito mortality and adult weight. *Sci Total Environ.* 2019;651:871-876. doi: 10.1016/j.scitotenv.2018.09.236
47. Huang B, Sun L, Liu M, *et al*. Abundance and distribution characteristics of microplastic in plateau cultivated land of Yunnan Province, China. *Envron Sci Pollut Res.* 2021;28:1675-1688. doi: 10.1007/s11356-020-10527-3
48. Xu M, Du W, Ai F, *et al*. Polystyrene microplastics alleviate the effects of sulfamethazine on soil microbial communities at different CO_2 concentrations. *J Hazard Mater.* 2021;413:125286. doi: 10.1016/j.jhazmat.2021.125286
49. Braun M, Mail M, Heyse R, Amelung W. Plastic in compost: Prevalence and potential input into agricultural and horticultural soils. *Sci Total Environ.* 2021;760:143335. doi: 10.1038/s44454-025-00014-0
50. Nematollahi MJ, Keshavarzi B, Mohit F, Moore F, Busquets R. Microplastic occurrence in urban and industrial soils of Ahvaz metropolis: A city with a sustained record of air pollution. *Sci Total Environ.* 2022;819:152051. doi: 10.1016/j.scitotenv.2021.152051
51. Chae Y, An YJ. Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review. *Environ Pollut.* 2018;240:387-395. doi: 10.1016/j.envpol.2018.05.008
52. He D, Luo Y, Lu S, Liu M, Song Y, Lei L. Microplastics in soils: Analytical methods, pollution characteristics and ecological risks. *TrAC Trends Anal Chem.* 2018;109:163-172. doi: 10.1016/j.trac.2018.10.006
53. Rillig MC, Lehmann A, de Souza Machado AA, Yang G. Microplastic effects on plants. *New Phytol.* 2019;223:1066-1070. doi: 10.1111/nph.15794
54. Van den Berg P, Huerta-Lwanga E, Corradini F, Geissen V. Sewage sludge application as a vehicle for microplastics in eastern Spanish agricultural soils. *Environ Pollut.* 2020;261:114198. doi: 10.1016/j.envpol.2020.114198
55. Boucher J, Friot D. *Primary Microplastics in the Oceans: A Global Evaluation of Sources*. Vol. 10. Switzerland: IUCN Gland; 2017. doi: 10.2305/IUCN.CH.2017.01.en
56. Kumari A, Rajput VD, Mandzhieva SS, *et al*. Microplastic pollution: An emerging threat to terrestrial plants and insights into its remediation strategies. *Plants.* 2022;11:340. doi: 10.3390/plants11030340
57. de Souza Machado AA, Lau CW, Kloas W, *et al*. Microplastics can change soil properties and affect plant performance. *Environ Sci Technol.* 2019;53:6044-6052. doi: 10.1021/acs.est.9b01339
58. Wang K, Chen W, Tian J, *et al*. Accumulation of microplastics in greenhouse soil after long-term plastic film mulching in Beijing, China. *Sci Total Environ.* 2022;828:154544. doi: 10.1016/j.scitotenv.2022.154544

59. Dai Y, Shi J, Zhang N, Pan Z, Xing C, Chen X. Current research trends on microplastics pollution and impacts on agro-ecosystems: A short review. *Sep Sci Technol.* 2022;57:656-669. doi: 10.1080/01496395.2021.1927094
60. Rodríguez-Seijo A, Santos B, da Silva EF, Cachada A, Pereira R. Low-density polyethylene microplastics as a source and carriers of agrochemicals to soil and earthworms. *Environ Chem.* 2018;16:8-17. doi: 10.1071/EN18162
61. Xi B, Wang B, Chen M, *et al*. Environmental behaviors and degradation methods of microplastics in different environmental media. *Chemosphere.* 2022;299:134354. doi: 10.1016/j.chemosphere.2022.134354
62. Lang M, Wang G, Yang Y, *et al*. The occurrence and effect of altitude on microplastics distribution in agricultural soils of Qinghai Province, northwest China. *Sci Total Environ.* 2022;810:152174. doi: 10.1016/j.scitotenv.2021.152174
63. Hale RC, Seeley ME, La Guardia MJ, Mai L, Zeng EY. A global perspective on microplastics. *J Geophys Res Oceans.* 2020;125:e2018JC014719. doi: 10.1029/2018JC014719
64. Li X, Chen L, Mei Q, *et al*. Microplastics in sewage sludge from the wastewater treatment plants in China. *Water Res.* 2018;142:75-85. doi: 10.1016/j.watres.2018.05.034
65. Shan J, Zhao J, Zhang Y, Liu L, Wu F, Wang X. Simple and rapid detection of microplastics in seawater using hyperspectral imaging technology. *Anal Chim Acta.* 2019;1050:161-168. doi: 10.1016/j.aca.2018.11.008
66. Gao D, Li XY, Liu HT. Source, occurrence, migration and potential environmental risk of microplastics in sewage sludge and during sludge amendment to soil. *Sci Total Environ.* 2020;742:140355. doi: 10.1016/j.scitotenv.2020.140355
67. Liu K, Wang X, Song Z, Wei N, Li D. Terrestrial plants as a potential temporary sink of atmospheric microplastics during transport. *Sci Total Environ.* 2020;742:140523. doi: 10.1016/j.scitotenv.2020.140523
68. Lee H, Kim S, Sin A, *et al*. Pretreatment methods for monitoring microplastics in soil and freshwater sediment samples: A comprehensive review. *Sci Total Environ.* 2023;871:161718. doi: 10.1016/j.scitotenv.2023.161718
69. Fakour H, Lo SL, Yoashi NT, *et al*. Quantification and analysis of microplastics in farmland soils: Characterization, sources, and pathways. *Agriculture.* 2021;11:330. doi: 10.3390/agriculture11040330
70. Kong M, Huang MJ, Zhang ZX, Long J, Siddique KH, Zhang DM. Effects of plastic film mulching on soil microbial carbon metabolic activity and functional diversity at different maize growth stages in cool, semi-arid regions. *Front Microbiol.* 2024;15:1492149. doi: 10.3389/fmicb.2024.1492149
71. Jahedi F, Dehbandi R, Talepour N, *et al*. Abundance, distribution, and ecological risks of microplastics in urban and agricultural topsoil of Mian-Ab Plain, Iran. *Dis Appl Sci.* 2025;7:667. doi: 10.1007/s42452-025-07190
72. Steinmetz Z, Schröder H. Plastic debris in plastic-mulched soil-a screening study from western Germany. *PeerJ.* 2022;10:e13781. doi: 10.7717/peerj.13781
73. Muhib MI, Rahman MM. Microplastics contamination in fish feeds: Characterization and potential exposure risk assessment for cultivated fish of Bangladesh. *Heliyon.* 2023;9:e19789. doi: 10.1016/j.heliyon.2023.e19789
74. Frias JP, Nash R. Microplastics: Finding a consensus on the definition. *Mar Pollut Bull.* 2019;138:145-147. doi: 10.1016/j.marpolbul.2018.11.022
75. Horton AA, Jürgens MD, Lahive E, van Bodegom PM, Vijver MG. The influence of exposure and physiology on microplastic ingestion by the freshwater fish *Rutilus rutilus* (roach) in the River Thames, UK. *Environ Pollut.* 2018;236:188-194. doi: 10.1016/j.envpol.2018.01.044
76. Haixin Z, Yimei H, Shaoshan A, *et al*. Land-use patterns determine the distribution of soil microplastics in typical agricultural areas on the eastern Qinghai-Tibetan Plateau. *J Hazard Mater.* 2022;426:127806. doi: 10.1016/j.jhazmat.2021.127806
77. Gesamp G. *Sources, Fate and Effects of Microplastics in the Marine Environment: Part Two of a Global Assessment.* London: IMO; 2016. p. 220.
78. Hanvey JS, Lewis PJ, Lavers JL, Crosbie ND, Pozo K, Clarke BO. A review of analytical techniques for quantifying microplastics in sediments. *Anal Methods.* 2017;9:1369-1383. doi: 10.1039/C6AY02707E
79. Wright SL, Ulke J, Font A, Chan KLA, Kelly FJ. Atmospheric microplastic deposition in an urban environment and an evaluation of transport. *Environ Int.* 2020;136:105411. doi: 10.1016/j.envint.2019.105411
80. Guo JJ, Huang XP, Xiang L, *et al*. Source, migration and toxicology of microplastics in soil. *Environ Int.* 2020;137:105263. doi: 10.3390/toxics13100901
81. Gana M, Isibor PO, Damisa JI, Iseghohi F, Musa IO, Oyewole OA. Nanoparticle-based remediation and environmental cleanup. In: *Environmental Nanotoxicology: Combatting the Minute Contaminants*. Berlin: Springer; 2024. p. 161-181.
82. Mbachu O, Jenkins G, Pratt C, Kaparaju P. A new contaminant superhighway? A review of sources, measurement techniques and fate of atmospheric

microplastics. *Water Air Soil Pollut.* 2020;231:85.
doi: 10.1007/s11270-020-4459-4

83. Townsend KR, Lu HC, Sharley DJ, Pettigrove V. Associations between microplastic pollution and land use in urban wetland sediments. *Environ Sci Pollut Res.* 2019;26:22551-22561.
doi: 10.1007/s11356-019-04885-w
84. Bläsing M, Amelung W. Plastics in soil: Analytical methods and possible sources. *Sci Total Environ.* 2018;612:422-435.
doi: 10.1016/j.scitotenv.2017.08.086
85. Mehra S, Sharma K, Sharma G, Singh M, Chadha P. Sources, fate, and impact of microplastics in aquatic environment. In: *Emerging Contaminants*. London: IntecOpen; 2020.
doi: 10.5772/intechopen.93805
86. Redondo-Hasselerharm P, Gort G, Peeters E, Koelmans A. Nano-and microplastics affect the composition of freshwater benthic communities in the long term. *Sci Adv.* 2020;6:eaay4054.
doi: 10.1126/sciadv.aay4054
87. Lahive E, Walton A, Horton AA, Spurgeon DJ, Svendsen C. Microplastic particles reduce reproduction in the terrestrial worm *Enchytraeus crypticus* in a soil exposure. *Environ Pollut.* 2019;255:113174.
doi: 10.1016/j.envpol.2019
88. Grbić J, Helm P, Athey S, Rochman CM. Microplastics entering northwestern Lake Ontario are diverse and linked to urban sources. *Water Res.* 2020;174:115623.
doi: 10.1016/j.watres.2020.115623
89. Carpenter EJ, Smith K Jr. Plastics on the sargasso sea surface. *Science.* 1972;175:1240-1241.
doi: 0.1126/science.175.4027.1240
90. James E, Turner A. Mobilisation of antimony from microplastics added to coastal sediment. *Environ Pollut.* 2020;264:114696.
doi: 10.1016/j.envpol.2020.114696
91. Bai X, Li C, Ma L, Xin P, Li F, Xu Z. Quantitative analysis of microplastics in coastal tidal-flat reclamation in Dongtai, China. *Front Environ Sci Eng.* 2022;16:107.
doi: 10.1007/s11783-022-1528-5
92. Ding L, Zhang S, Wang X, *et al*. The occurrence and distribution characteristics of microplastics in the agricultural soils of Shaanxi Province, in north-western China. *Sci Total Environ.* 2020;720:137525.
doi: 10.1016/j.scitotenv.2020.137525
93. Allen S, Allen D, Phoenix VR, *et al*. Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nat Geosci.* 2019;12:339-344.
doi: 10.1038/s41561-019-0335-5
94. Feng S, Lu H, Liu Y. The occurrence of microplastics in farmland and grassland soils in the Qinghai-Tibet plateau: Different land use and mulching time in facility agriculture. *Environ Pollut.* 2021;279:116939.
doi: 10.1016/j.envpol.2021.116939
95. Wang T, Wang L, Chen Q, Kalogerakis N, Ji R, Ma Y. Interactions between microplastics and organic pollutants: Effects on toxicity, bioaccumulation, degradation, and transport. *Sci Total Environ.* 2020;748:142427.
doi: 10.1016/j.scitotenv.2020.142427
96. Wang W, Ge J, Yu X, Li H. Environmental fate and impacts of microplastics in soil ecosystems: Progress and perspective. *Sci Total Environ.* 2020;708:134841.
doi: 10.1016/j.scitotenv.2019.134841
97. Triebskorn R, Braunbeck T, Grummt T, *et al*. Relevance of nano-and microplastics for freshwater ecosystems: A critical review. *TrAC Trends Anal Chem.* 2019;110:375-392.
doi: 10.1016/j.trac.2018.11.023
98. O'Connor D, Pan S, Shen Z, *et al*. Microplastics undergo accelerated vertical migration in sand soil due to small size and wet-dry cycles. *Environ Pollut.* 2019;249:527-534.
doi: 10.1016/j.envpol.2019.03.092
99. Corradini F, Bartholomeus H, Lwanga EH, Gertsen H, Geissen V. Predicting soil microplastic concentration using vis-NIR spectroscopy. *Sci Total Environ.* 2019;650:922-932.
doi: 10.1016/j.scitotenv.2018.09.101
100. Klein M, Fischer EK. Microplastic abundance in atmospheric deposition within the Metropolitan area of Hamburg, Germany. *Sci Total Environ.* 2019;685:96-103.
doi: 10.1016/j.scitotenv.2019.05.405
101. Qi R, Jones DL, Li Z, Liu Q, Yan C. Behavior of microplastics and plastic film residues in the soil environment: A critical review. *Sci Total Environ.* 2020;703:134722.
doi: 10.1016/j.scitotenv.2019.134722
102. Geyer R. Production, use, and fate of synthetic polymers. In: *Plastic Waste and Recycling*. Amsterdam: Elsevier: 2020. p. 13-32.
103. Koriyev MR, Fonseka PU, Umurzakova UN, *et al*. Soil salinity status in Namagan region, Uzbekistan. *Suranaree J Sci Technol.* 2024;31.
doi: 10.55766/sujst-2024-05-e05652
104. Jiang X, Wang T, Jiang M, *et al*. Assessment of plastic stocks and flows in China: 1978-2017. *Resour Conserv Recycl.* 2020;161:104969.
doi: 10.1016/j.resconrec.2020.104969
105. Yang X, Lwanga EH, Bemani A, *et al*. Biogenic transport of glyphosate in the presence of LDPE microplastics: A mesocosm experiment. *Environ Pollut.* 2019;245:829-835.
doi: 10.1016/j.envpol.2018.11.044
106. Wang HT, Ding J, Xiong C, *et al*. Exposure to microplastics lowers arsenic accumulation and alters gut bacterial communities of earthworm *Metaphire californica*. *Environ Pollut.* 2019;251:110-116.
doi: 10.1016/j.envpol.2019.04.054

107. Wang J, Liu X, Li Y, *et al*. Microplastics as contaminants in the soil environment: A mini-review. *Sci Total Environ.* 2019;691:848-857. doi: 10.1016/j.scitotenv.2019.07.209
108. Da Costa JP, Santos PS, Duarte AC, Rocha-Santos T. (Nano) plastics in the environment-sources, fates and effects. *Sci Total Environ.* 2016;566:15-26. doi: 10.1016/j.scitotenv.2016.05.041
109. Lönnstedt OM, Eklöv P. Retracted: Environmentally relevant concentrations of microplastic particles influence larval fish ecology. *Science.* 2016;352:1213-1216. doi: 10.1126/science.aad8828
110. Setälä O, Norkko J, Lehtiniemi M. Feeding type affects microplastic ingestion in a coastal invertebrate community. *Mar Pollut Bull.* 2016;102:95-101. doi: 10.1016/j.marpolbul.2015.11.053