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Review Paper

Microplastics: The Invisible Invaders – Unveiling Sources, Journeys, Impacts, and Cutting-Edge Remedies in a Plastic-Choked World

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Abstract

Microplastics, synthetic polymeric particles under 5 mm, have permeated every environmental niche, from oceanic depths to terrestrial soils and human tissues, posing profound ecological and health risks. This comprehensive review synthesizes current knowledge on their classification, polymer types, primary and secondary sources, and entry pathways driven by human activities such as wastewater discharge, agricultural practices, and urban runoff. It explores transport mechanisms influenced by physical properties, biofouling, and environmental forces, leading to accumulation in hotspots like river deltas and agricultural lands. Ecological impacts include ingestion by wildlife, causing malnutrition and microbial disruptions, while human health concerns encompass chemical toxicity via food chains and systemic exposure, inducing oxidative stress. Detection technologies range from vibrational spectroscopy to AI-powered sensors, and remediation innovations span physical filtration, biological degradation, and nanotechnology hybrids. Challenges like scalability, fouling, and secondary pollution are addressed alongside policy frameworks, including microbead bans and the Global Plastic Treaty. Emphasizing the urgency of a circular economy and harmonized standards, this review calls for integrated strategies to mitigate this Anthropocene hallmark, safeguarding ecosystems and public health.

Introduction

Definition and Overview of Microplastics

Microplastics are defined as synthetic polymeric particles typically less than 5 mm in size (Chandra & Walsh, 2024; Gao et al., 2022). These particles can originate from the breakdown of larger plastic items (secondary microplastics) or be directly manufactured for industrial purposes (primary microplastics). They have been found in a variety of environments, including oceans, rivers, soil, atmosphere, and even drinking water. Due to their persistence in the environment and their ability to absorb harmful pollutants, microplastics pose a significant ecological threat, making the development of effective remediation technologies an urgent environmental priority.

Global Production and Prevalence

The global prevalence of microplastics is significant, driven by a massive increase in plastic production, which rose from 2 million tons in 1950 to approximately 400 million metric tons annually by 2023 (Kumar et al., 2025; Lu et al., 2025; Zielli et al., 2026). This production is projected to reach an

unprecedented 1,520 million metric tons by 2050 (Ramirez-Escarcega et al., 2025; Sepahvand et al., 2025). Much of this plastic is poorly managed; it is estimated that between 4.8 and 12.7 million metric tons of plastic waste enter the oceans from land-based sources every year (Joseph et al., 2025; Lu et al., 2025). Once in the environment, microplastics are ubiquitous, having been detected in all compartments, including remote Arctic ice (Li et al., 2025; Lin et al., 2025), the summit of Mount Everest, and deep-sea trenches thousands of meters below the surface (Kumar et al., 2025; Que et al., 2026; Sumaway et al., 2025).

Research Focus and Implications

Research focus is distributed across both aquatic and terrestrial environments. In aquatic environments, oceans, rivers, lakes, and estuaries serve as major transport pathways and reservoirs (Dinku et al., 2025; Joseph et al., 2025; Louvet et al., 2026). Rivers act as "highways" that move microplastics from land-based sources to the sea, where they can accumulate in the water column or settle into the deep-sea sediment (Kholis et al., 2026; Pilechi et al., 2022). Sinking behavior is influenced by particle density, shape, and biofouling, which increases the weight of buoyant polymers like polyethylene and polypropylene, causing them to descend (Dinku et al., 2025; Gkika et al., 2023). In terrestrial environments, soils are increasingly recognized as a major long-term sink for microplastics, receiving 4 to 23 times more annual plastic input than the oceans (Lu et al., 2025; Singh et al., 2025). Key entry routes into soil include the application of sewage sludge (biosolids), agricultural mulching films, and atmospheric deposition (Gao et al., 2025; Kumar et al., 2025). These particles can alter soil properties such as porosity, aggregation, and water retention, potentially hindering plant growth and microbial activity (Samandra et al., 2026; Zhao et al., 2026). These findings lay the groundwork for critical environmental engineering implications, including water purification and soil remediation efforts (Aragón et al., 2025; Gkika et al., 2023; Goh et al., 2025; Joseph et al., 2025; Li et al., 2025; Othman et al., 2021; Samandra et al., 2026). The detection of microplastics in human blood, lungs, and placenta further underscores the urgency of these remediation efforts to protect human health (Que et al., 2026; Sumaway et al., 2025).

Sources and Types of Microplastics

Classification and Physical Characteristics

Microplastics refer to a diverse range of small plastic particles, typically defined as those with diameters between 0.1 micrometers and 5 millimeters, though the term often encompasses those smaller than 5 mm (Avinash et al., 2023; Browne et al., 2011; Haque & Fan, 2023). Plastics can be categorized by size as follows: macroplastics (>25 mm), mesoplastics (25–5 mm), microplastics (5 mm to 0.1 micrometers), and nanoplastics (<0.1 micrometers) (Avinash et al., 2023; Browne et al., 2011; Haque & Fan, 2023). From an analytical standpoint, microplastics are usually defined as particles within the micrometer range (1 micrometer to 1 millimeter) (Li et al., 2025; Que et al., 2026; Sumaway et al., 2025). Based on their scale, these plastic contaminants are categorized as follows:

- Large Microplastics: Dimensions ranging from 1 mm to 5 mm (Gkika et al., 2023; Li et al., 2025; Samandra et al., 2026).
- Microplastics (Strict Sense): Particles between 1 µm and 1 mm (or 1000 µm) (Li et al., 2025; Samandra et al., 2026; Zielli et al., 2026).
- Nanoplastics: Particles generally defined as being smaller than 1 µm. Some sources specify a range of 1 nm to 1 µm for these ultra-fine particles (Gkika et al., 2023)(1-18-19).

Physically, these particles appear in various morphologies, including fibers, fragments, films, pellets, spheres, and foams. Their colors are equally diverse, including white, transparent, blue, black, yellow, red, and green, which can influence how they are ingested by aquatic and terrestrial organisms (Burhani et al., 2024; Kholis et al., 2026). Microplastics exhibit a variety of shapes, ranging from spherical to elongated fibers, and come in an array of colors. However, those that differ from natural particles in shape, size, or color (such as blue or red fibers) are more frequently encountered in

environmental studies. Microplastics and mesoplastics can also be categorized based on their shape, including pellets, fragments, fibers, films, and foams. Morphological descriptions of microplastics provide insights into their origin, type, shape, color, and degradation stage. In leachate, microplastics are predominantly found as fibers, granules, and fragments, and fibers are also the most common form found in sewage sludge and wastewater (Golwala et al., 2021; Hidalgo-Ruz et al., 2012; Su et al., 2019).

Polymer Types and Composition

These particles originate from the bonding of hydrocarbon atoms in polymers. When plastics degrade or are disposed of improperly, they release various harmful compounds into the environment, such as phthalates, polybrominated diphenyl ethers, and tetrabromobisphenol (Avinash et al., 2023; Browne et al., 2011; Haque & Fan, 2023). The composition of microplastics typically reflects global production trends. The most prevalent polymer types found in environmental samples include:

- Polyethylene (PE): Found in plastic bags, films, and containers; categorized as LDPE (low-density) or HDPE (high-density)(Joseph et al., 2025; Kumar et al., 2024; Othman et al., 2021).
- Polypropylene (PP): Used in packaging, automotive parts, and disposable surgical masks (Ramirez-Escarcega et al., 2025; Shen et al., 2022). (Othman et al., 2021)
- Polyethylene Terephthalate (PET): Primarily used for beverage bottles and synthetic textiles (Pilechi et al., 2022; Ramirez-Escarcega et al., 2025).
- Polyvinyl Chloride (PVC): Common in construction materials and plumbing (23-29-40).
- Polystyrene (PS): Used for food packaging and insulation (Othman et al., 2021; Ramirez-Escarcega et al., 2025).
- Polyamide (PA/Nylon): Frequently derived from clothing and fishing nets (Goh et al., 2025; Othman et al., 2021).
- Technical Polymers: Others include Polyurethane (PU), Polymethyl Methacrylate (PMMA), and Acrylonitrile Butadiene Styrene (ABS) (Othman et al., 2021; Samandra et al., 2026; Zielli et al., 2026). Polymeric plastics like polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS) are among the most produced materials, and fragments of these polymers are found throughout the environment (Wang et al., 2021). Notably, the behaviors of these plastics in the environment vary. For instance, PVC, nylon, and PET tend to settle, whereas PP, PE, and PS are more likely to float or remain suspended in aquatic environments. However, processes such as biofouling and the absorption of organic materials can alter these behaviors, leading to different distribution patterns in various environmental compartments (Kaiser et al., 2017). As summarized in Table (1), the concentration of microplastics in soil systems is strongly governed by the intensity and type of human activities, highlighting the direct link between anthropogenic land use and terrestrial microplastic pollution.

Table 1- Physical Properties and Densities of Common Microplastic Polymers (Pilechi et al., 2022)

Polymer Type	Abbreviation	Density (kg/m³)	Typical Applications
Polyethylene	PE	910–950	Plastic bags, films, containers
Polypropylene	PP	900–920	Packaging, automotive parts, masks
Polystyrene	PS	1040–1090	Food packaging, insulation
Polyvinyl Chloride	PVC	1160–1300	Plumbing, construction materials
Polyethylene Terephthalate	PET	1340–1390	Beverage bottles, textiles
Polyamide (Nylon)	PA	1130–1150	Clothing, fishing nets

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Primary vs. Secondary Sources

Microplastics are categorized into primary and secondary types (Joseph et al., 2025; Li et al., 2025). Primary microplastics are intentionally produced in small sizes for specific uses, such as plastic pellets, microbeads in personal care products, particles in paints, and tire wear. Secondary microplastics form when larger plastic items break down through processes like photooxidation, mechanical wear, or biological degradation. Common sources of secondary microplastics include synthetic clothing fibers, urban waste (e.g., bags, plastic bottles), fishing debris, and agricultural films. Tire wear is considered a major contributor to microplastic pollution, particularly due to the increasing global vehicle population (An et al., 2020; Hidalgo-Ruz et al., 2012; Yurtsever, 2019).

Primary Microplastics (Intentionally Manufactured)

These are engineered at the micro-scale for specific industrial or consumer uses:

- Microbeads: Found in personal care products such as facial cleansers, toothpaste, and body washes (Joseph et al., 2025; Li et al., 2025; Othman et al., 2021).
- Industrial Abrasives: Used as scrubbers for cleaning or air-blasting (Burhani et al., 2024; Othman et al., 2021).
- Pre-production Pellets (Nurdles): Raw materials for plastic manufacturing that often spill during transport or production (Burhani et al., 2024; Louvet et al., 2026).

Secondary Microplastics (Fragmentation of Macroplastics)

These result from the degradation of larger plastic debris (macroplastics) due to environmental stressors:

- Weathering: Breakdown via ultraviolet (UV) radiation, mechanical forces (wave and wind action), and temperature fluctuations (Joseph et al., 2025; Sumaway et al., 2025).
- Synthetic Fibers: Released from clothing and textiles during laundry processes; a single wash can release up to 190,000 fibers (Goh et al., 2025; Shen et al., 2022).
- Tire Wear: Abrasion of tires on road surfaces produces significant quantities of synthetic rubber particles (Sepahvand et al., 2025; Singh et al., 2025).
- Agricultural Residue: Degradation of mulching films, greenhouse covers, and silage wraps (Kumar et al., 2025; Singh et al., 2025).

Human Activities and Environmental Entry

Microplastics have been detected in a wide range of environments: the hydrosphere, pedosphere, and atmosphere. Due to improper plastic disposal and inadequate waste management, they are now ubiquitous in seas, lakes, rivers, deltas, the atmosphere, sediments, landfills, and wastewater treatment plants. These particles pose significant risks to ecosystems and human health, especially through the food chain (Browne et al., 2011; Petersen & Hubbart, 2021; Wang et al., 2021). While much of the research has focused on marine systems, land-based sources of microplastics, such as solid waste, remain underexplored. Solid waste sources include buried waste, sewage sludge, and food waste. Microplastics from buried waste and sewage sludge can enter the environment through leachate and runoff, while those from food waste depend on disposal and treatment processes (Golwala et al., 2021).

Pollution in Aquatic Environments (Rivers, Lakes, Oceans)

- Wastewater Discharge: Conventional wastewater treatment plants (WWTPs) are not designed to remove microplastics; as a result, millions of particles are released daily into receiving waters (Kumar et al., 2024; Shen et al., 2022).

- Urban and Stormwater Runoff: Rain washes street litter, road markings, and tire wear into drainage systems and rivers (Goh et al., 2025).
- Maritime and Fishing Activities: Direct release from lost fishing gear (ghost nets), ship sewage, ship gray water, and ship ballast water (Kholis et al., 2026; Othman et al., 2021).
- Tourism: Littering by seasonal visitors on beaches and coastal regions (Elawady et al., 2025; Kholis et al., 2026).

Pollution in Terrestrial Environments (Soils)

- Sewage Sludge/Biosolids: Treated sludge from WWTPs is often applied as fertilizer in agriculture, directly introducing concentrated microplastics into the soil (Othman et al., 2021; Singh et al., 2025).
- Agricultural Management: The use of plastic mulch films and irrigation with contaminated wastewater (Gao et al., 2025; Kumar et al., 2025).
- Solid Waste Mismanagement: Improper littering, open dumping, and uncontrolled landfills contribute to widespread soil contamination (Goh et al., 2025; Kumar et al., 2025).
- Atmospheric Deposition: Airborne particles derived from urban and industrial zones settle onto the soil surface via wind and precipitation (Samandra et al., 2026; Singh et al., 2025).

Land-use patterns strongly control the distribution and accumulation of microplastics in soil environments. Fig (1) demonstrates that soils associated with intensive human activities—particularly agricultural, urban, and industrial areas in Australia—harbor significantly higher microplastic abundances than less impacted land-use categories, underscoring the critical role of anthropogenic pressure in terrestrial microplastic contamination (Samandra et al., 2026).

Transport and Accumulation of Microplastics

The transport of microplastics through the environment is complex and not yet fully understood. While microplastics may be transported as dust particles through the air, rivers are considered the primary pathway for their movement, like natural sediments (Rohais et al., 2024). The transport and accumulation of microplastics (MPs) are complex processes governed by the interplay between the physical properties of the particles, environmental forces, and biological interactions across aquatic and terrestrial systems (Joseph et al., 2025; Pilechi et al., 2022).

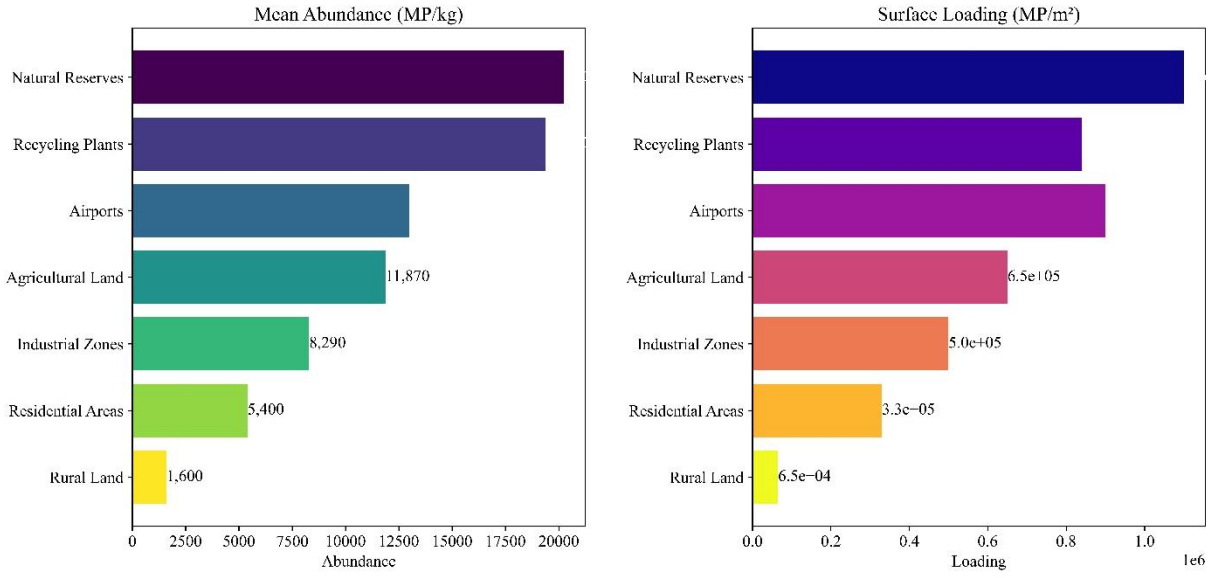


Fig. 1- Microplastic Abundance in Soils by Land-Use Category (Case Study: Australia) (Samandra et al., 2026).

Physical Properties Influencing Movement

The movement of microplastics is primarily driven by their density, size, and shape, which determines their buoyancy and settling velocity (Joseph et al., 2025; Pilechi et al., 2022):

- Density: Polymers denser than water (e.g., PVC, PET, and PS) tend to sink and accumulate in freshwater and marine sediments (Dinku et al., 2025; Silva & Marques, 2025). Conversely, low-density polymers (e.g., PE and PP) typically float on the surface or remain suspended in the water column (Dinku et al., 2025; Elawady et al., 2025).
- Size: Smaller particles (especially those <1 mm) are more susceptible to transport by wind and water currents (Joseph et al., 2025; Samandra et al., 2026). Decreasing particle size increases mobility, contributing to the widespread occurrence of microplastics in remote areas (Dinku et al., 2025; Samandra et al., 2026).
- Shape: Common morphologies include fibers, fragments, films, and pellets (Burhani et al., 2024; Pilechi et al., 2022). Fibers are notably prevalent in the atmosphere and water but are often more difficult to remove in treatment systems due to their tendency to escape filtration (Elawady et al., 2025; Shen et al., 2022). Irregularly shaped particles with sharp geometry are more likely to remain underwater, whereas spherical particles are more likely to remain on the surface (Zielli et al., 2026).

The behavior of microplastics in the environment is influenced by their physical properties, including polymer type, density, size, and shape. These factors affect buoyancy, drag force, and gravitational forces, all of which influence particle movement. Additionally, the degradation of polymers can affect the effective size of the particles, further complicating their transport. Pollution and deep mixing processes can also influence the long-range movement of microplastics (Shamskhany et al., 2021). In addition to physical properties, biological, chemical, and physical interactions affect the transport and fate of microplastics. Microplastics may remain in one location, incorporated into soil and sediments, or they may cycle between different environments, influenced by weather conditions, currents, and environmental factors (Horton & Dixon, 2018).

Transport Pathways

Microplastics utilize several primary conduits to migrate through ecosystems:

- Riverine Transport: Rivers act as the primary "highways" or conduits for transporting land-based plastic waste to the oceans (Joseph et al., 2025). An estimated 1.15 to 2.41 million tons of plastic flow from rivers to the sea annually (Kumar et al., 2025).
- Atmospheric Deposition: Airborne microplastics originate from tire wear, synthetic textile abrasion, and industrial emissions (Joseph et al., 2025; Kumar et al., 2025). These particles can be transported over vast distances by wind and return to the Earth's surface via dry deposition (gravitational settling) or wet deposition (scavenging by precipitation) (Gao et al., 2025).
- Soil Infiltration and Runoff: In terrestrial environments, microplastics enter the soil via sewage sludge application, plastic mulching, and irrigation (Gao et al., 2025; Singh et al., 2025). They can infiltrate deeper soil layers through urban runoff, vertical leaching, and bioturbation by soil fauna like earthworms, potentially reaching groundwater systems (Gao et al., 2025; Singh et al., 2025).

To better understand the fate and transport of microplastics in fluvial systems, predictive modelling approaches have been employed to simulate their distribution across river compartments. As shown in Fig (2), the model captures the movement and accumulation of microplastics along river pathways, providing quantitative support for fate-based assessments of freshwater-to-marine microplastic fluxes.

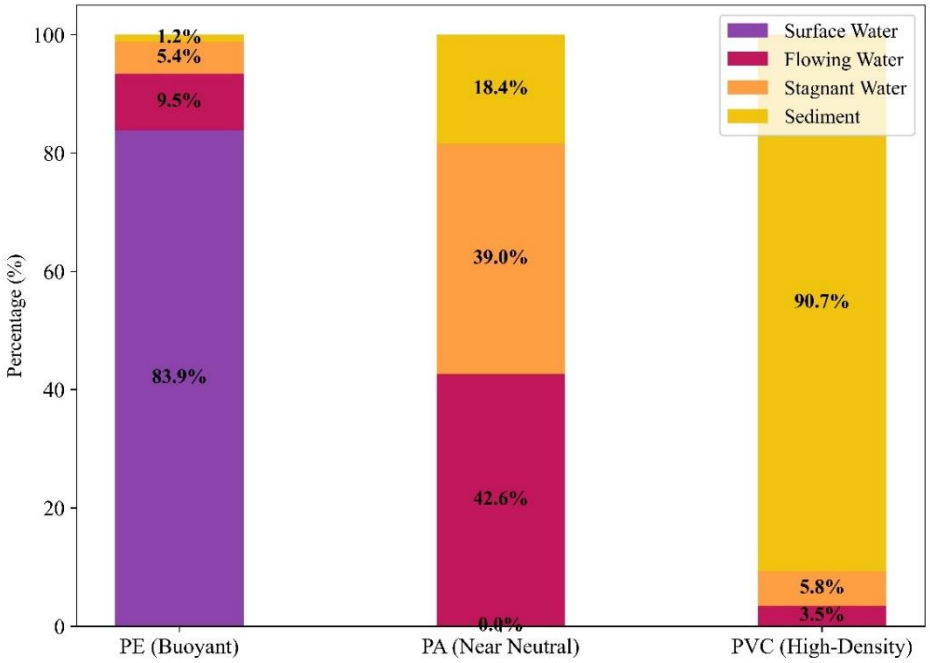


Fig. 2- Predictive Distribution Model of Microplastics in River Compartments (Domercq et al., 2022).

Biological Factors and Biofouling

Biofouling—the colonization of microplastic surfaces by microbial communities (biofilms)—significantly alters particle dynamics (Domercq et al., 2022; Joseph et al., 2025):

- Altered Density: Biofilm formation increases the effective density and weight of microplastics, causing buoyant polymers to sink into deep-sea habitats or sediments (Domercq et al., 2022; Joseph et al., 2025; Kumar et al., 2025).
- Surface Modification: Biofouling changes the hydrophobicity and surface charge of particles, which influences their aggregation with natural suspended particulate matter (SPM) and their interaction with aquatic organisms (Domercq et al., 2022; Pilechi et al., 2022).

Accumulation Hotspots

Specific environments serve as long-term repositories for microplastic accumulation:

- Aquatic Hotspots: These include oceanic gyres (garbage patches), river deltas, and deep-sea trenches. Semi-enclosed seas, such as the Mediterranean, are also significant hotspots (Elawady et al., 2025).
- Terrestrial Hotspots: Agricultural soils are major sinks due to the long-term use of plastic mulches and biosolid fertilizers. Urban roadsides accumulate high concentrations of tire wear and road paint particles (Samandra et al., 2026; Singh et al., 2025).

Environmental and Health Impacts

Microplastic (MP) pollution has become a significant global threat to ecosystems and human health due to its persistence and capacity to interact with various biological systems (Gao et al., 2025; Lin et al., 2025). These particles, now recognized as indicators of the Anthropocene (or "Plasticene"), infiltrate every environmental compartment, leading to complex hidden damage (Muthulakshmi et al., 2023; Sepahvand et al., 2025).

Ecological Effects on Aquatic and Terrestrial Wildlife

Microplastics exert both physical and chemical pressures on a wide range of organisms:

- Ingestion in Aquatic Species: Marine life, from zooplankton and corals to fish and apex predators, mistakenly ingest MPs due to their attractive colors and buoyancy (Kholis et al., 2026). This leads to digestive blockages, internal injuries, reduced feeding

efficiency, and malnutrition (Anene et al., 2025; Gao et al., 2025; Sharma & Vidyarthi, 2024). Specifically, corals have been observed preferentially ingesting MPs over natural food, causing mesenteric atrophy and disrupting their symbiotic relationship with algae (Elawady et al., 2025; Gao et al., 2025).

- Terrestrial Impacts: In terrestrial systems, MPs are ingested by soil fauna like earthworms, causing enterocyte damage and thinning of the intestinal wall (Gao et al., 2025; Lu et al., 2025). Higher up the food chain, apex predators such as gray wolves and Persian leopards accumulate MPs through the consumption of contaminated prey, with higher loads often found in generalist predators closer to human infrastructure (Sepahvand et al., 2025). Poultry also ingests MPs from plastic litter or contaminated feed, leading to accumulation in the gizzard, liver, and muscle tissues, which eventually move into the human food chain (Joseph et al., 2025; Sharma & Vidyarthi, 2024).
- Biodiversity and Microbial Communities: MPs significantly disrupt soil microbial dynamics, particularly nitrogen-fixing bacterial communities. Specific polymers like polyester can reduce soil aggregation and nodule formation in legume plants like red clover, while polypropylene can decrease total bacterial abundance (Zhao et al., 2026).

Human Health Risks and Toxicity

Human exposure occurs through ingestion, inhalation, and dermal contact.

- Food Chain Entry: MPs have been detected in a vast array of consumables, including seafood, salt, sugar, honey, milk, beer, and tea (Kumar et al., 2025; Kumar et al., 2024). A single plastic teabag can release billions of micro- and nanoplastics into a single cup (Kumar et al., 2024).
- Chemical Additives and Toxicity: MPs act as vectors for over 16,000 chemicals, including hazardous additives like phthalates, bisphenol A (BPA), and organophosphate esters (OPEs) (Anene et al., 2025; Elawady et al., 2025). These chemicals are often endocrine disruptors linked to reproductive toxicity, reduced fertility, and developmental abnormalities. Furthermore, MPs absorb environmental toxins like heavy metals and persistent organic pollutants (POPs), amplifying their bioavailability to humans.
- Systemic Exposure: Biomonitoring has confirmed MPs in human blood, lungs, placenta, feces, urine, and arterial plaques (Anene et al., 2025; Joseph et al., 2025). Mechanistic studies suggest they induce oxidative stress, inflammatory cytokine release, mitochondrial impairment, and potentially carcinogenic effects (Gao et al., 2025; Joseph et al., 2025).

The detection of microplastics in human tissues and organs provides compelling evidence of direct human exposure. As shown in Table (2), these findings highlight the potential for widespread systemic distribution of microplastics within the human body, underscoring the urgency of assessing long-term health implications.

Table 2- Detection of Microplastics in Human Tissues and Organs (Joseph et al., 2025; Zielli et al., 2026).

Tissue / Organ	Detected Polymers	Detection Method	Potential Health Implications
Blood	PE, PP, PS, PET, PVC	Py-GC/MS, Raman	Circulatory transport; immune activation
Lungs	PP, PET, PA, PE	μFTIR, Raman	Inflammation; oxidative stress; fibrosis
Placenta	PS, PP, PE, PVC	μFTIR, Raman	Barrier disruption; fetal health risk
Stool	PET, PE, PP, PS	FTIR	Gut dysbiosis; intestinal permeability
Breast Milk	PE, PVC, PP, PU	FTIR, Raman	Risk to neonatal development
Liver & Spleen	PS, PVC, PMMA, PET	Py-GC/MS	Hepatotoxicity; lipid metabolism effects

Specific Concerns in Water and Soil Environments

The impact of MPs is uniquely manifested across these two primary sinks:

- Drinking Water Contamination: Both tap and bottled water are major sources of MP ingestion (Burhani et al., 2024; Kumar et al., 2024). Studies have found up to 5,400 particles/kg in salt and significant concentrations in mineral water, raising concerns for vulnerable populations such as infants consuming formula prepared with contaminated water (Burhani et al., 2024; Gao et al., 2025).
- Soil Fertility and Plant Uptake: In terrestrial environments, MPs alter physical soil properties, including porosity, bulk density, and water retention, often leading to drier, less fertile soil (Samandra et al., 2026; Singh et al., 2025; Zhao et al., 2026). MPs and even smaller Nano plastics are absorbed by plant roots and translocated through the vascular system to edible tissues (Singh et al., 2025). This uptake can inhibit seed germination, reduce chlorophyll content, and hinder nutrient absorption, ultimately lowering crop yield and quality. For example, polystyrene MPs have been shown to reduce biomass in crops like lettuce and rice (Gao et al., 2025; Singh et al., 2025).

Detection and Monitoring Technologies

Engineering tools for identifying and monitoring microplastic (MP) pollution span advanced spectroscopic characterization, standardized field sampling, spatial distribution modeling, and emerging real-time sensors. Infrared spectroscopy is widely regarded as the most reliable method for identifying the chemical composition of microplastics. To estimate their abundance, researchers typically use units such as "number per square meter" for sediment and sea surface studies and "number per cubic meter" for water column studies (Hidalgo-Ruz et al., 2012).

Analytical Techniques and Characterization

Accurate identification relies on physical and chemical profiling to distinguish polymers from natural debris.

- Vibrational Spectroscopy: Fourier Transform Infrared (FTIR) spectroscopy is the most established tool for identifying unique molecular vibrational signatures (Elawady et al., 2025; Lin et al., 2025). Micro-FTIR (μFTIR) enables spatially resolved detection of particles down to 10–20 μm (Dinku et al., 2025; Lin et al., 2025). Raman spectroscopy offers superior spatial resolution, detecting particles as small as 1 μm, and is less hindered by water interference, making it ideal for aqueous matrices (Lin et al., 2025; Zielli et al., 2026). Surface-Enhanced Raman Spectroscopy (SERS) uses metallic nanostructures to amplify signals, extending detection limits to the nanoscale (Li et al., 2025).
- Laser Direct Infrared (LDIR): This high-throughput system uses a quantum cascade laser for automated identification of chemical composition, size, and shape, typically in the 20–500 μm range (Que et al., 2026).
- Thermoanalytical Methods: Pyrolysis–GC/MS (Py-GC–MS) and Thermal Extraction Desorption (TED-GC–MS) provide mass-based quantification by breaking polymers into volatile fragments. These methods are destructive but can analyze particles smaller than the optical detection limits (Elawady et al., 2025; Li et al., 2025).
- Microscopy: Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS) are used for high-resolution surface characterization and elemental identification (e.g., verifying PVC by detecting chlorine) (Li et al., 2025).

Sampling and Extraction Methods

Standardized collection is essential for comparing contamination levels across different environments.

- Water Sampling: Methods include using Rosette Water Samplers at various depths or plankton nets (e.g., 0.8 cm mesh) for surface and riverine transport (Kholis et al., 2026) (19-4). Subsurface sediments are often collected using Van Veen, Ekman, or Ponar grab samplers (Kholis et al., 2026).
- Soil and Sediment Sampling: Tools such as stainless-steel shovels and hand corers are used to collect stratified layers (Samandra et al., 2026).
- Laboratory Extraction: The process typically involves density separation using salt solutions (NaCl, $ZnCl_2$, or NaI) to float

plastic particles away from heavier sediment (Dinku et al., 2025). Chemical digestion (using KOH, H_2O_2, or enzymes such as proteinase K) is performed to remove interfering organic matter prior to filtration (Dinku et al., 2025; Sepahvand et al., 2025).

Quantification Units and Data Reporting

Microplastic abundance is expressed using several metrics to reflect environmental loading:

- Areal Units: Particles per m^2 or g/m^2 (surface loading) (Samandra et al., 2026).
- Mass/Volumetric Units: Particles per m^3, items per L, particles per kg of dry sediment/soil, or µg/g for mass-based concentrations (Elawady et al., 2025; Samandra et al., 2026).

Monitoring Strategies and Spatial Modeling

Engineering applications utilize data-driven approaches to track pollutant movement and identify hotspots.

- GIS and Remote Sensing: Geographic Information Systems (GIS) are integrated with satellite data (e.g., Sentinel-2) to monitor large-scale distributions of floating debris. Spatial modeling correlates MP loads with proximity to anthropogenic features like roads and villages.
- Numerical Fate Models: The SimpleBox4Plastic (SB4P) model estimates MP masses across air, water, and soil compartments (Papavasiliou et al., 2025). CaMPSim-3D is a numerical framework integrating Lagrangian particle tracking with hydrodynamic systems to predict MP transport in rivers and estuaries (Silva & Marques, 2025).

Emerging Engineering Applications

New technologies are moving detection from the laboratory to real-time, in situ deployment.

- Biosensors and Smart Sensors: Electrochemical biosensors utilize voltammetry and impedance to provide real-time monitoring of microplastics and adsorbed pollutants (Elawady et al., 2025). Plasmonic sensors integrated with machine learning can classify particle types and sizes in aqueous environments with high accuracy (Elawady et al., 2025; Lin et al., 2025).
- AI-Powered Vision: Real-time artificial intelligence systems, such as the YOLOv5 framework combined with camera systems, are used for automated counting and size estimation of microplastics in dynamic riverine environments (Elawady et al., 2025).
- Point-of-Care (PoC) Tools: Miniaturized devices and smartphone-assisted platforms are being developed for rapid contamination assessment in the field (Lin et al., 2025).

Innovations in Remediation Technologies

Physical Removal Technologies

Physical methods are typically the primary defence against microplastic pollution, focusing on separating, extracting, or immobilising microplastics through mechanical processes. These techniques have shown high removal efficiencies, even though they were not originally designed specifically for microplastics (Carr et al., 2016).

Filtration and Membrane Technologies

Advanced membrane technologies, including ultrafiltration, microfiltration, and membrane bioreactors, demonstrate removal efficiencies that often exceed 99% (Gao et al., 2022). These membranes, which have fine pore sizes, can trap even the smallest microplastic particles. However, they are susceptible to fouling and typically involve high operational costs. Other filtration technologies used in tertiary treatment, such as disc filters (DF), rapid sand filtration (RSF), dissolved air flotation (DAF), and membrane bioreactors (MBR), have also achieved efficiencies of up to 99.9% (Chandra & Walsh, 2024; Gkika et al., 2023; Song & Park, 2024).

Adsorption-Based Removal

Functional materials like graphene composites, metal-organic frameworks (MOFs), biochar, live and biomass alga, and layered double hydroxides are highly effective adsorbents for types of pollution (Hafshejani et al., 2016; Hafshejani et al., 2015; Hoveizavi et al., 2024; Hooshmand et al., 2024; Menati et al., 2024; Hafshejani & Saeidinia; 2025). Their performance is significantly enhanced through

magnetisation or chemical modification, making them a powerful solution in the fight against microplastic pollution (Tiwari et al., 2020).

Magnetic Separation

Iron-based nanoparticles and magnetic carbon nanotubes play a crucial role in the efficient and selective separation of microplastics from various environments. This is especially important when faced with hydrophobic coatings that often hinder traditional separation methods (Li et al., 2025; Tang et al., 2021). These advanced materials utilise their magnetic properties to allow for rapid and effective extraction processes. By incorporating these nanoparticles and nanotubes, we not only significantly reduce the time required for separation but also achieve a remarkable decrease in energy consumption. This makes them invaluable resources in addressing the pressing issue of microplastic pollution while minimising environmental impact.

Gravitational and Density-Based Separation

In conventional wastewater treatment plants (WWTPs), the processes of sedimentation and skimming harness the intriguing properties of microplastics (MPs) through their varying densities and buoyancy. High-density particles settle robustly in grit chambers, making their descent like stones sinking to the bottom of a pond. Meanwhile, the low-density plastics rise to the surface, buoyed by their lightweight nature, floating alongside greasy residues and oily film, creating a troublesome scum that requires removal. During the initial stages of treatment, techniques such as screening, scum extraction, and gravity-assisted separation come into play, effectively capturing and eliminating between 35% to 98% of these pesky MPs (Carr & Thompson, 2019; Sarkar et al., 2022).

Nature-Based Solutions

Constructed wetlands and floating treatment wetlands harness the intricate networks of plant-root systems, combined with the natural process of sedimentation, to efficiently capture microplastics. Through the remarkable process of phytoremediation, these innovative systems not only remove harmful pollutants from water but also revitalise the ecosystem, showcasing nature's power in combating environmental challenges (Ahmad et al., 2024).

Engineering-based removal technologies play a critical role in mitigating water pollution (Naghsh Javaheri et al., 2020; Etemadiasl et al., 2023). As shown in Table 3, the efficiency of physical removal systems differs significantly among filtration, membrane processes, electrocoagulation, and hybrid technologies, emphasizing the importance of technology selection and system optimization.

Table 3- Efficiency of Engineering Technologies in Microplastic Removal (Song & Park, 2024)

Removal Method	Primary Mechanism	Efficiency (%)	Engineering Considerations
Membrane Bioreactor (MBR)	Size sieving + Biodegradation	> 99.4	High cost; risk of membrane fouling
Ultrafiltration (UF)	Pore size separation	100	Effective for nanoscale particles
Electrocoagulation (EC)	Charge neutralization	82–99	Uses Al/Fe electrodes; energy efficient
Adv. Oxidation (AOP)	Chemical degradation	~ 75	Potential to create smaller fragments
Rapid Sand Filtration	Physical entrapment	29–44	Low efficiency for particles < 10 µm

Biological and Biochemical Technologies

Biological solutions effectively harness the power of natural microbial and enzymatic processes to break down microplastics—tiny plastic particles less than five millimetres in size—into benign byproducts such as carbon dioxide and water. These eco-friendly approaches play a vital role in sustainable environmental remediation by addressing the pervasive issue of plastic pollution. While these methods demonstrate significant potential, they do face challenges, particularly regarding the rate at which they can degrade microplastics and their scalability for widespread application. Increasing the efficiency of these biological processes requires ongoing research and development to optimise conditions for microbial activity and enzyme effectiveness. By overcoming these limitations, we can enhance the practicality of biological solutions and move toward a cleaner, healthier planet (Lu et al., 2025; Othman et al., 2021; Shen et al., 2022).

Microbial Degradation

Certain bacterial strains, such as Ideonella sakaiensis, have the remarkable ability to break down polyethylene terephthalate (PET), while fungi like Aspergillus niger are adept at degrading polyethylene (Yuan et al., 2020). These microorganisms use complex enzymatic reactions to dismantle harmful plastics, converting them into harmless byproducts such as carbon dioxide (CO_2), water (H_2O), and biomass. This process not only showcases the incredible potential of nature but also provides promising solutions for tackling plastic pollution in our environment.

Enzymatic Hydrolysis

Enzymes such as PETase, MHETase, cutinase, laccase, and hydrolases are powerful tools in the fight against plastic pollution. They can break down plastics by severing ester and carbon-carbon bonds (Dhali et al., 2024; Khairul Anuar et al., 2022). What makes these enzymes particularly remarkable is their ability to function under mild conditions, which makes them effective and environmentally friendly solutions for sustainable remediation strategies. By utilizing enzymatic hydrolysis, we can significantly enhance our efforts to reduce plastic waste and protect the environment.

Biofilm-Assisted Capture

In wastewater treatment plants (WWTPs), biofilms play a critical role in tackling microplastic pollution. These natural formations develop on the surfaces of microplastics, significantly changing their density and enhancing their sedimentation (Harrison et al., 2018). Although biofilms do not always completely break down plastics, their ability to effectively capture and immobilize these particles is essential. Additionally, the formation of floc and the active ingestion of microplastics by protozoa during secondary treatments significantly improve the removal process (Sarkar et al., 2022). By harnessing the power of biofilms, we can enhance the efficiency of wastewater treatment, contributing to a cleaner and more sustainable environment.

Genetic and Synthetic Biology Approaches

Innovative research in synthetic biology is leading the way in transforming the capabilities of microbes. By utilizing gene editing and pathway engineering, scientists are enhancing the efficiency and precision of these tiny organisms. This groundbreaking work involves fine-tuning enzymes and strategically assembling microbial consortia, enabling them to effectively address various types of plastic. The implications of these advancements are significant, as they offer promising solutions for tackling plastic pollution (Cai et al., 2023).

Nanotechnology Applications

Nanotechnology offers a promising solution for addressing the issue of microplastic remediation. It enables precise targeting and has a high surface reactivity, which allows for its integration into hybrid systems. This approach not only improves effectiveness but also fosters further advancements in environmental technology.

Nano-Adsorbents and Membranes

Carbon nanotubes, graphene oxide, and nano-enabled membranes are advanced materials that possess exceptionally large

surface areas and customizable surface chemistries. These qualities make them highly effective in capturing a wide variety of microplastic particles from complex environmental mixtures. These nanomaterials can be engineered to interact with different types of microplastics, which enhances their ability to filter out contaminants from water and soil. Their effectiveness in trapping microplastics results from their unique structural properties, which promote strong adsorption, thereby contributing to more efficient environmental cleanup strategies (Kumar et al., 2020).

Photocatalysis

Semiconducting nanoparticles, particularly titanium dioxide (TiO_2) and zinc oxide (ZnO), play a vital role in the photocatalytic degradation of plastic materials when they are illuminated by ultraviolet (UV) or visible light. This innovative process involves the absorption of light energy by these nanoparticles, which stimulates chemical reactions that break down large plastic polymers into smaller, less harmful molecules, thus reducing their environmental impact (Sacco et al., 2023; Uheida et al., 2021). Despite the promising nature of this approach in addressing plastic waste, several challenges limit its practical application. One major issue is the penetration depth of light, as not all areas of plastic materials receive sufficient exposure to activate the photocatalytic process effectively. Additionally, the high cost associated with producing and implementing these semiconductor materials can hinder their widespread use. Overcoming these obstacles is essential for harnessing the full potential of photocatalytic degradation in real-world applications aimed at minimizing plastic pollution (Ramirez-Escarcega et al., 2025).

Magnetic Nanoparticles

Functionalized magnetic nanoparticles offer a promising solution for the targeted and efficient removal of microplastics from various environments. These nanoparticles can be engineered with specific ligands or hydrophobic domains, which enhance their ability to attract and bind to microplastic particles. This selective affinity enables effective capture of microplastics, making the process both efficient and reusable. By utilizing the magnetic properties of these nanoparticles, they can be easily retrieved from mixtures after capturing the microplastics, thereby minimizing waste and facilitating recycling efforts (Li et al., 2025; Sumaway et al., 2025).

Hybrid Nano-Bio Systems

New and innovative methods are emerging that combine the unique properties of nanomaterials with the biological effectiveness of enzymes and microbial cells to significantly improve degradation processes. This synergy utilizes the catalytic capabilities of nanoparticles, which can accelerate chemical reactions, while also taking advantage of the specificity of biological agents to target specific substances. By integrating these two approaches, researchers aim to develop hybrid systems that enhance both the efficiency and effectiveness of breaking down complex pollutants and organic materials. These advancements, as noted by Mandeep and Shukla (2020), represent a promising direction in the fields of environmental remediation and bioengineering.

Challenges, Policies, and Future Directions

The transition from laboratory-scale research to real-world mitigation of microplastic (MP) pollution is hindered by significant engineering barriers, high economic costs, and a complex regulatory landscape.

Engineering Barriers and Technical Limitations

- High Costs and Scalability: Advanced detection methods like micro-FTIR and Raman spectroscopy are labor-intensive, time-consuming, and require expensive instrumentation, making high-throughput monitoring impractical (Elawady et al., 2025; Joseph et al., 2025). Similarly, while photocatalytic degradation and membrane bioreactors (MBR) show high efficiency, their implementation is restricted by high

capital and operational costs, particularly regarding energy consumption (Goh et al., 2025; Ramirez-Escarcega et al., 2025).

- Filter Fouling: A primary challenge in filtration systems (MF, UF, RO) is membrane fouling and pore clogging, where the accumulation of microplastics and organic matter reduces flux and necessitates frequent maintenance or replacement (Aragón et al., 2025; Gkika et al., 2023).
- Secondary Pollution from Nanotechnology: The use of magnetic nanoparticles for MP capture risks secondary contamination if the magnetic sorbents are not fully recovered from the effluent (Li et al., 2025). Furthermore, photocatalysis may unintentionally generate smaller, more bioavailable, and potentially more toxic fragments or chemical byproducts if mineralization is incomplete (Ramirez-Escarcega et al., 2025).
- Slow Biodegradation: Biological removal methods suffer from slow degradation rates (often requiring months or years) and are highly sensitive to environmental factors, making them less reliable for rapid, large-scale treatment (Domercq et al., 2022; Li et al., 2025; Lu et al., 2025).

Policy Frameworks and Global Regulations

- Microbead Bans: Many countries, including the USA, UK, Canada, and several EU member states, have enacted bans on the intentional use of plastic microbeads in "rinse-off" personal care products and cosmetics (Elawady et al., 2025; Kumar et al., 2025).
- UN Guidelines and International Treaties: The United Nations Sustainable Development Goal (SDG) 14.1 specifically targets the reduction and prevention of marine pollution, including marine debris, by 2025 (Sumaway et al., 2025). Efforts are also underway to develop a legally binding Global Plastic Treaty to address the full lifecycle of plastics (Sumaway et al., 2025)
- Regional Directives: The EU Single-Use Plastic Directive (SUPD) and the Marine Strategy Framework Directive set ambitious targets for waste reduction, mandatory recycled content, and standardized monitoring of microplastic trends in aquatic bodies (Elawady et al., 2025).

Roles in Waste Management and Agricultural Control

- Extended Producer Responsibility (EPR): This policy instrument holds manufacturers accountable for the entire lifecycle of their products, incentivizing the design of more durable, reusable, and recyclable items to minimize environmental leakage (Goh et al., 2025; Kumar et al., 2025).
- Agricultural Regulations: Stricter management is required for agricultural plastics, such as mulching films and greenhouse covers, which are major sources of soil contamination (Kumar et al., 2025; Sepahvand et al., 2025). Additionally, the application of sewage sludge (biosolids) as fertilizer is a significant pathway for microplastics to enter terrestrial ecosystems, necessitating improved sludge treatment or regulation (Goh et al., 2025; Kumar et al., 2025).
- Improved Recycling and Bio-alternatives: Shifting toward a circular economy involves advancing chemical recycling and developing biodegradable alternatives (e.g., PLA, PHA, or starch-based materials) that can naturally decompose without leaving persistent residues (Goh et al., 2025; Kumar et al., 2025)

Despite these developments, the absence of universally accepted standards for monitoring or limiting MPs continues to hamper coordinated global efforts (Silva & Marques, 2025). Establishing internationally harmonized protocols for sampling and reporting is essential to clarify true environmental loads and support effective legislation (Dinku et al., 2025; Zielli et al., 2026).

Conclusions

Microplastics represent a pervasive and multifaceted environmental challenge, originating from diverse sources and polymers, transported through complex pathways, and accumulating in critical hotspots across aquatic and terrestrial ecosystems. As detailed in this review, their ecological impacts- ranging from wildlife ingestion and microbial disruptions to soil fertility alterations-coupled with human health risks such as systemic exposure and chemical toxicity, underscore the urgent need

for action. Advances in detection technologies, from spectroscopic methods to AI-driven sensors, provide robust tools for monitoring, while remediation innovations in physical, biological, and nanotechnology approaches offer promising solutions, albeit with challenges like scalability and secondary pollution. Policy frameworks, including bans, international treaties, and extended producer responsibility, are essential for prevention, yet require harmonization to be effective. Future research should prioritize integrated, circular economy strategies to reduce plastic production at the source, enhance biodegradation, and mitigate long-term risks, ultimately safeguarding biodiversity and public health in a plastic-dominated world.

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Conflict of Interest

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Confirmation

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contribution

First Author: Fatemeh Elyasi, Investigation, Writing – Original.
Second Author: Laleh Divband Hafshejani, Visualization, Writing – Review & Editing.
Third Author: Parvaneh Tishehzan Conceptualization, Writing – Review & Editing.

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