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Emerging Contaminants: Microplastics and their Impacts on the Environment

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ABSTRACT

Microplastics (MPs), generally defined as plastic particles smaller than 5 mm in their largest dimension. They are pervasive environmental contaminants due to their persistence, occurrence and diverse physicochemical properties. Their widespread distribution across terrestrial, aquatic and atmospheric compartments, together with their interactions with biological organisms and chemical contaminants has raised concerns regarding ecological integrity and human health. This review synthesizes the current knowledge on definition and classification of microplastics, sources, environmental transport and fate, analytical approaches for their detection and characterization, biological uptake, trophic transfer, ecological effects and human exposure. Evidence indicates that microplastics can originate from both primary and secondary sources and be redistributed through hydrological, atmospheric and biological pathways with particle size, polymer density, morphology, weathering, biofouling and aggregation influencing their environmental fate. Across diverse organisms, exposure has been associated with impaired feeding, growth and reproduction, oxidative stress, inflammation and cellular damage. MPs may also interact with chemical contaminants and plastisphere-associated microorganisms. Trophic transfer across food webs has been documented, whereas evidence for biomagnification remains limited and inconsistent. Human exposure occurs primarily through ingestion and inhalation, and particles have been reported in blood, lung, placental and other tissues; however, relationship with specific diseases remains unestablished. Major knowledge gaps include methodological heterogeneity, limited detection of nanoplastics, insufficient environmentally realistic long-term studies, uncertainty regarding trophic transfer and its implication for biomagnification. Future research should prioritize harmonized and improved analytical and quality-assurance protocols, long-term realistic exposure experiments, mechanistic toxicity studies and integrated human-health risk assessment.

Keywords Microplastics, Nanoplastics, Environmental fate, Polymer identification, Ecotoxicology, Human exposure, Plastisphere.

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INTRODUCTION

Global plastic production now exceeds 400 million tons annually and is projected to rise further with expanding industrialization and consumer demand (Geyer *et al.* 2017; Borrelle *et al.* 2020). Plastics are synthetic or semi-synthetic polymeric materials whose durability, flexibility, low density and resistance to degradation underpin their use in packaging, construction, healthcare, agriculture and transportation, and equally explain their persistence in the environment for decades or centuries. Rather than mineralizing completely, discarded items fragment progressively under ultraviolet radiation, mechanical abrasion, thermal stress and biological weathering, generating microplastics and ultimately nanoplastics, both now recognized as contaminants of emerging concern (Jambeck *et al.* 2015; Andrady, 2017; Gigault *et al.* 2018).

Microplastics, generally defined as plastic particles smaller than 5 mm in diameter, have become a major focus of environmental research because of their persistence, widespread occurrence and potential ecological and human health impacts (Thompson *et al.* 2004; Hartmann *et al.* 2019). They originate either as primary microplastics, intentionally manufactured at microscopic sizes for industrial and commercial applications, or as secondary microplastics formed through the degradation of larger debris. Their small size and diverse physicochemical properties allow ready transport by rivers, ocean currents, wind, wastewater and biological organisms across terrestrial, freshwater, marine and atmospheric environments (Akdogan and Guven, 2019; Windsor *et al*. 2019).

Over the past decade, microplastics have been documented in oceans, rivers, lakes, soils, sediments, glaciers, polar ice, atmospheric dust and remote mountain ecosystems, demonstrating their global distribution (Akdogan and Guven 2019). They have also been identified in drinking water, bottled water, seafood, table salt, fruits, vegetables and honey, indicating multiple pathways for human exposure (Smith *et al.* 2018; Cox *et al*. 2019). More recently, their detection in human blood, lung tissue, placental tissue, breast milk and faeces has intensified scientific interest in their health implications (Schwabl *et al.* 2019; Ragusa *et al.* 2021; Jenner *et al.* 2022; Leslie *et al.* 2022). Although these findings confirm widespread exposure, important uncertainties remain regarding mechanisms of toxicity, dose-response relationships and the consequences of chronic exposure, particularly to nanoplastics.

The environmental significance of microplastics extends beyond persistence and distribution. They interact with living organisms through ingestion, inhalation and physical contact, potentially causing physiological stress, inflammatory responses, reduced growth, impaired reproduction and altered ecosystem functioning (Wright *et al.* 2013; de Souza Machado *et al.* 2018). They also adsorb and transport heavy metals, persistent organic pollutants, pesticides, pharmaceuticals and plastic additives, while serving as substrates for the diverse microbial communities collectively known as the plastisphere (Rochman *et al.* 2013; Zettler *et al.* 2013). Microplastics therefore act both as physical pollutants and as vectors of chemical and biological contaminants.

Accurate assessment of microplastic contamination depends on reliable sampling, extraction, identification and quantification. Significant advances in Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy and pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) have improved characterization of polymer composition and particle morphology, yet methodological inconsistencies among studies continue to limit data comparability and complicate risk assessment. Standardized analytical protocols and harmonized quality assurance procedures have consequently become a major priority (Cowger *et al.* 2020; Primpke *et al.* 2020).

This review critically examines the current state of knowledge on microplastics by synthesizing published research on their definition, classification, sources, environmental distribution, analytical methods, and ecological and human health impacts, and by identifying key knowledge gaps and future research priorities. Fig. 1 presents this this framework as a flow chart of the microplastic life cycle (Bank and Hanson 2019). Plastics produced and used in industrial and consumer products (stage 1) give rise to primary and secondary microplastics (stage 2), which are released

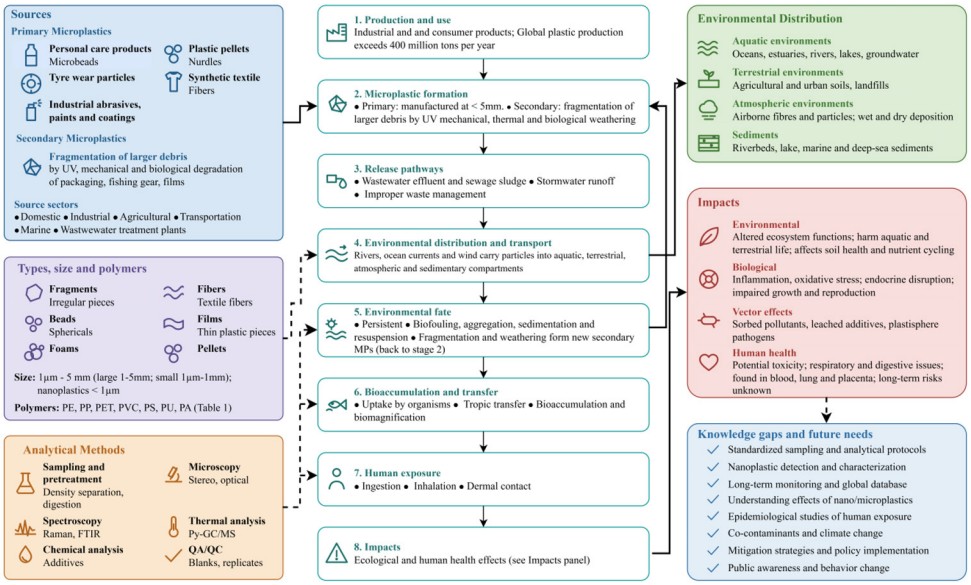


Fig. 1. Life cycle of microplastics in the environment, showing sources, release, distribution, fate, biological transfer, human exposure, impacts, analytical methods and knowledge gaps.

through wastewater, stormwater runoff and improper waste management (stage 3) and distributed among aquatic, terrestrial, atmospheric and sedimentary compartments (stage 4). There they persist, age and continue to fragment, forming new secondary particles (stage 5), before biological uptake and trophic transfer (stage 6) lead to human exposure through ingestion, inhalation and dermal contact (stage 7) and to ecological and human health impacts (stage 8). Side panels link each stage to the relevant sources, particle type, analytical methods and knowledge gaps discussed further this review.

Definition of Microplastics

Microplastics (MPs) are widely recognized as synthetic solid polymer particles measuring less than 5 mm in their longest dimension and insoluble in water (Hartmann *et al.* 2019). Although the 5 mm threshold is broadly accepted, refined definitions have been proposed that also consider particle morphology, polymer composition and environmental behavior. Hartmann *et al.* (2019) recommended a harmonized definition describing microplastics as solid polymer-containing particles, either intentionally manufactured or formed through fragmentation, excluding materials that are soluble or biodegradable under natural conditions. Such standardization improves consistency among studies and the comparability of monitoring data and risk assessments.

Microplastics are commonly classified by size into large microplastics (1-5 mm) and small microplastics (1 µm-1 mm). Particles smaller than 1 µm are generally referred to as nanoplastics, although an internationally accepted size threshold remains under discussion (Gigault *et al.* 2018). Compared with microplastics, nanoplastics possess much higher surface-area-to-volume ratios, greater mobility and enhanced biological availability, allowing them to penetrate cellular membranes and biological barriers more readily. They are therefore considered to present potentially greater ecological and toxicological risks, although their occurrence, behavior and health implications remain insufficiently understood because of analytical limitations (Gigault *et al.* 2018; Prüst *et al.* 2020).

Classification of Microplastics

Microplastics are broadly classified as primary or secondary according to their origin (Hartmann *et*

al. 2019).

Primary Microplastics

Primary microplastics are intentionally manufactured at microscopic sizes for commercial, industrial and research applications, and are released during production, transportation, use or disposal. Common examples include cosmetic microbeads formerly used in facial cleansers, toothpastes and exfoliating products; industrial abrasive media used in surface cleaning and polishing; pre-production resin pellets (nurdles); and polymer particles incorporated into paints, coatings, detergents, fertilizers and personal care products. Legislative restrictions on cosmetic microbeads have been introduced in several countries (Rochman *et al.* 2015), although many intentionally added microplastics remain in widespread industrial use (Cole *et al.* 2011).

Secondary Microplastics

Secondary microplastics form through the fragmentation and degradation of larger plastic products after prolonged environmental exposure, and represent the dominant source worldwide. Fragmentation proceeds through ultraviolet radiation, thermal weathering, mechanical abrasion by waves or wind, chemical oxidation and microbial degradation. Common parent materials include packaging, bottles, bags, fishing gear, agricultural films, construction materials and household products. Weathering progressively weakens polymer structures, producing successively smaller fragments that enter terrestrial, freshwater, marine and atmospheric environments. Because plastic production and consumption continue to increase, secondary microplastics are expected to remain the largest contributor to future contamination (Andrady 2017; Borrelle *et al.* 2020).

Polymer Types and Characteristics

Microplastics comprise numerous synthetic polymers whose physicochemical properties strongly influence their transport, persistence and biological interactions. The most frequently reported polymers, together with their resin identification codes, densities, characteristic properties and principal applications, are summarized in Table 1.

Polyethylene (PE) and polypropylene (PP) are the most abundant polymers reported in environmental samples because of their extensive use in packaging, consumer products and disposable items. Their low densities allow many particles to remain buoyant, facilitating long-distance transport by rivers and ocean currents. Denser polymers such as polyethylene terephthalate (PET) and polyvinyl chloride (PVC) are more likely to sink and accumulate in sediments unless biofouling alters the density of lighter particles. Polystyrene (PS) is widely used in food packaging and insulation, polyurethane (PU) in foams, coatings, adhesives and construction materials, and polyamide (nylon) in synthetic textiles, fishing nets and ropes, making the latter an important source of microfiber pollution (Browne *et al.* 2011).

Environmental behavior is determined not only by polymer type but also by physical and chemical characteristics. Density influences buoyancy and vertical transport; morphology, including fibers, fragments, films, foams, pellets and beads, affects settling velocity, ingestion by organisms and persistence; color may influence selective ingestion; and crystallinity governs resistance to degradation and weathering. Many plastics additionally contain plasticizers, flame retardants, pigments, antioxidants, ultraviolet stabilizers and fillers that improve performance but may subsequently leach into the environment. Together these properties control transport, degradation, contaminant adsorption and ecological impact across environmental compartments (Rochman *et al.* 2013; Andrady 2017).

Sources of Microplastics

Microplastics originate from a wide variety of anthropogenic activities and are continuously introduced into terrestrial, freshwater, marine and atmospheric environments. Their sources are broadly categorized as domestic, industrial, agricultural, transportation, marine and wastewater related.

Domestic Sources

Households are a significant source of microplastic

Table 1. Principal plastic polymers, resin identification codes (RIC), densities, characteristics and uses (modified from ASTM International 2021).

RIC	Polymer (abbreviation)	Formula	Density (g cm^{-3})	Key properties	Main applications	Recyclability
1	Polyethylene terephthalate (PET/PETE)	$(C_{10}H_8O_4)n$	1.38-1.41	Transparent, lightweight, impact-, crease- and water-resistant	Beverage bottles, jars, textiles, packaging, medical equipment	Easy
2	High-density polyethylene (HDPE)	$(C_2H_4)n$	0.94-0.96	Chemically and impact resistant, ductile, waxy, water-resistant	Milk jugs, shampoo bottles, grocery bags, pipes, fuel tanks	Recyclable but uneconomic
3	Polyvinyl chloride (PVC)	$(C_2H_3Cl)n$	1.16-1.45	Robust, insulating, fire and chemical-resistant; stabilizer-dependent	Plumbing pipes, cables, flooring, credit cards, medical tubing	Not viable
4	Low-density polyethylene (LDPE)	$(C_2H_4)n$	0.88-0.93	Highly ductile, low rigidity, chemical and water-resistant	Bread and trash bags, plastic wraps, films, cables, packaging	Recyclable but uneconomic
5	Polypropylene (PP)	$(C_3H_6)n$	0.85-0.95	Translucent, flexible, chemical and heat-resistant	Bottle caps, straws, yoghurt tubs, furniture, automotive parts	Recyclable but uneconomic
6	Polystyrene (PS)	$(C_8H_8)n$	0.96-1.05	Solid or foamed, transparent, hard, brittle, UV-degradable, flammable	Takeaway containers, cups, trays, CD cases, thermal insulation	Limited
7	Polyurethane (PU)	$C_3H_8N_2O$	1.00-1.20	Soft or rigid foam, high load-bearing, abrasion- and tear-resistant	Foams, coatings, adhesives, furniture, footwear, construction	Difficult; toxic emissions
-	Polycarbonate (PC)	$C_{15}H_{16}O_2$	1.20-1.22	Colorless, shatterproof, high transmittance, low chemical resistance	Eyeglass lenses, safety helmets, food storage, electronics	Recyclable; BPA concern
-	Polyamide, nylon (PA)	$(C_{12}H_{22}N_2O_2)n$	1.13-1.16	High strength and stiffness, abrasion-resistant, absorbs water	Synthetic textiles, fishing nets, ropes, automotive components	Not viable
-	Polymethyl methacrylate (PMMA)	$(C_5O_2H_8)n$	1.16-1.20	Colorless, rigid, excellent optical clarity, weather-resistant	Shatterproof windows, lenses, signage, medical devices	Easy
-	Polytetrafluoroethylene (PTFE)	$(C_2F_4)n$	2.10-2.30	Very low friction, high chemical, UV and weathering resistance	Non-stick coatings, seals, gaskets, engineering and medical parts	Recyclable

emissions. Washing synthetic textiles releases large quantities of polyester, nylon and acrylic fibers into domestic wastewater. Personal care products, cosmetics, cleaning agents and the degradation of plastic consumer goods contribute further primary and secondary particles, while indoor activities and household dust release airborne fibers that may be transported outdoors through ventilation (Browne *et al.* 2011; Dris *et al.* 2017).

Industrial Sources

Industrial activities contribute microplastics through plastic manufacturing, processing, transportation and

recycling. Losses of resin pellets during production and transport are an important source of primary microplastics. Paint manufacturing, coating industries, construction materials, abrasive blasting and plastic processing facilities also release polymer particles through wastewater discharges and atmospheric emissions (Cole *et al.* 2011).

Agricultural Sources

Plastic mulch films, greenhouse coverings, irrigation pipes, silage wraps and controlled-release fertilizer coatings degrade under field conditions to generate secondary microplastics. Sewage sludge and compost applied as soil amendments frequently contain substantial quantities of particles retained from municipal wastewater treatment, and irrigation with reclaimed wastewater introduces further particles into agricultural soils, where they accumulate over time (Rillig *et al.* 2019; Xu *et al.* 2020).

Transportation Sources

Road transport is recognized as one of the largest sources of primary microplastic emissions. Tyre wear particles generated by friction between tyres and road surfaces are continuously released and transported by stormwater runoff and atmospheric dispersion. Abrasion of road markings, brake linings and other vehicle components adds to environmental loads, particularly in urban areas with high traffic density (Xu *et al.* 2020).

Marine Sources

Lost or discarded fishing nets, ropes, traps, aquaculture equipment and shipping materials fragment into secondary microplastics under sunlight, wave action and mechanical abrasion. Recreational boating, maritime transport and offshore industrial activities contribute additional debris to marine ecosystems, where long residence times sustain continued fragmentation (Andrady 2017; Law 2017).

Wastewater Treatment Plants

Wastewater treatment plants (WWTPs) link domestic, industrial and urban sources with receiving waters. Conventional treatment removes a substantial proportion of particles through sedimentation, filtration and biological treatment, yet millions of particles may still be discharged daily in treated effluents because of the volumes processed (Mintenig *et al.* 2017; Lares *et al.* 2018). Most retained particles accumulate in sewage sludge, which is frequently applied to agricultural land, thereby transferring microplastics from aquatic to terrestrial systems (Xu *et al.* 2020). WWTPs therefore function both as removal systems and as redistribution pathways.

Overall, the diversity of sources and transport pathways underscores the complexity of microplastic pollution and highlights the importance of integrated source control, standardized monitoring and life-cycle management practices for reducing future contamination (Lebreton and Andrady 2019; Borrelle *et al.* 2020).

Environmental Distribution and Transport

Following release, microplastics are transported through interconnected terrestrial, freshwater, marine, atmospheric and sedimentary environments by physical, chemical and biological processes. Distribution is governed by both intrinsic particle properties and external environmental conditions, producing heterogeneous spatial and temporal contamination patterns (Windsor *et al.* 2019). Rivers act as major conduits between land and sea, atmospheric transport disperses particles across continents into remote regions, and sedimentation, resuspension, biofouling and biological interactions continuously redistribute particles among compartments (Akdogan and Guven 2019).

Factors Affecting Transport

Particle size is among the most influential factors because it determines buoyancy, settling velocity, atmospheric suspension and biological uptake; smaller particles travel further by water and air, whereas larger particles settle more rapidly into sediments and soils (Akdogan and Guven 2019). Polymer density is equally important: low-density PE and PP typically float and are carried by rivers, ocean currents and wind-driven surface circulation, whereas denser PET and PVC tend to sink and accumulate in ben-

thic environments, although these behaviors change following weathering or microbial colonization (Andrady 2017).

Morphology further influences transport dynamics. Fibers settle slowly and are easily carried by atmospheric currents and wastewater, whereas fragments, pellets, films and foams differ in hydrodynamic behavior according to shape and surface area (Akdogan and Guven 2019); morphology also affects ingestion by organisms and retention within sediments (Wright *et al.* 2013). Environmental processes continuously modify particle behavior: biofouling by microorganisms, algae and other organisms increases density and frequently causes buoyant plastics to sink, while ultraviolet, thermal and mechanical degradation fragments particles and alters their transport properties. Aggregation with suspended sediments and natural organic matter increases settling rates, whereas turbulent flow disrupts aggregates and enhances redistribution (Koelmans *et al.* 2019).

Meteorological and hydrological conditions are also decisive. Wind transports lightweight fibers and fragments over regional and continental scales; rainfall mobilizes particles from land surfaces and drives wet deposition; and river discharge, tidal currents, wave action and ocean circulation determine dispersion and accumulation in aquatic systems. Sedimentation followed by resuspension during storms, floods or strong currents continuously redistributes deposited particles (Windsor *et al.* 2019).

Marine Ecosystems

Marine ecosystems represent the ultimate sink for much of the world's plastic waste. Rivers deliver large quantities of land-based plastics to coastal waters, after which ocean currents redistribute particles regionally and globally; subtropical gyres concentrate floating debris into extensive convergence zones (Akdogan and Guven 2019). Substantial accumulations also occur in estuaries, mangroves, coral reefs, beaches, continental shelves and deep-sea sediments (Law 2017).

Microplastics have been detected throughout marine food webs, including plankton, bivalves, crustaceans, fish, seabirds, turtles and marine mammals, with fibers and irregular fragments generally dominant because of the degradation of textiles, fishing gear and consumer plastics (Cole *et al.* 2011; Andrady 2017). Ingestion occurs directly through filter feeding or indirectly through trophic transfer, raising concerns regarding bioaccumulation, ecological disruption and seafood safety (Smith *et al.* 2018; Provencher *et al.* 2019). Deep-sea sediments have emerged as important long-term repositories because biofouling and aggregation promote vertical transport from surface waters, and they act both as sinks and as secondary sources when resuspension occurs (Jambeck *et al.* 2015; Law 2017).

Freshwater Ecosystems

Freshwater environments serve as both transport pathways and temporary storage reservoirs before eventual transfer to marine systems. Rivers, lakes, reservoirs, wetlands and streams receive particles from wastewater effluents, urban stormwater, agricultural drainage, industrial discharges and atmospheric deposition (Koelmans *et al.* 2019). Urban rivers generally exhibit higher concentrations than rural systems owing to population density, industrial activity and wastewater inputs, whereas lakes and reservoirs act as accumulation zones where reduced velocities promote sedimentation, and wetlands temporarily retain particles through interactions with vegetation and sediments. Seasonal rainfall, flooding and sediment resuspension during high flows repeatedly remobilize and redistribute deposited particles (Windsor *et al.* 2019).

Terrestrial Ecosystems

Terrestrial environments are increasingly recognized as major reservoirs of microplastics. Agricultural soils receive particles through degradation of mulch films, greenhouse coverings and irrigation infrastructure, sewage sludge and compost application, reclaimed wastewater irrigation and atmospheric deposition (Rillig *et al.* 2019; Xu *et al.* 2020). Urban soils accumulate particles from tyre wear, road dust, construction and litter fragmentation, whereas forest soils receive them mainly through atmospheric deposition and runoff (Allen *et al.* 2019).

Once deposited, microplastics may persist for extended periods. Soil structure, texture, biological activity and precipitation control vertical movement: smaller particles migrate downward through pores or with infiltrating water, while larger particles remain concentrated in surface horizons, and earthworm burrowing and root growth redistribute particles within the profile (Huerta Lwanga *et al.* 2016). Terrestrial ecosystems therefore act not only as long-term sinks but also as secondary sources that release microplastics to freshwater systems through erosion and runoff (de Souza Machado *et al.* 2018; Windsor *et al.* 2019).

Atmospheric Transport

Atmospheric transport is a major pathway for global dispersal. Airborne particles originate primarily from synthetic textile fibers, tyre wear, road dust, construction, industrial emissions and the resuspension of deposited plastics, with indoor environments representing significant additional sources because of synthetic fabrics, carpets and furnishings (Dris *et al.* 2016, 2017; Allen *et al.* 2019). Lightweight fibers and fragments may remain airborne for prolonged periods and travel considerable distances, explaining detections in remote mountain ranges, glaciers and polar regions (Allen *et al.* 2019). Particles return to terrestrial and aquatic surfaces through dry gravitational settling or wet deposition with rainfall and snowfall. Atmospheric microplastics are of growing concern because inhalation is an important human exposure route, with smaller particles able to penetrate deep into the respiratory tract (Prata 2018).

Environmental Fate of Microplastics

After release, microplastics undergo continuous physical, chemical and biological transformation. Fragmentation driven by ultraviolet radiation, mechanical abrasion and thermal weathering progressively reduces particle size while increasing abundance. Ageing alters surface chemistry, increasing roughness and introducing oxygen-containing functional groups that enhance adsorption of metals, organic pollutants and other contaminants (Rochman *et al.* 2013; Andrady 2017).

Biofouling is central to environmental fate: colonization by microorganisms, algae, fungi and small invertebrates increases particle density and frequently causes buoyant plastics to sink into deeper waters and sediments, whereas biofilm decomposition or turbulence may restore buoyancy and promote resuspension (Zettler *et al.* 2013). Aggregation with suspended sediments, clay minerals and natural organic matter further increases settling rates and alters particle stability. Deposited particles may remain buried for prolonged periods, although storms, floods, dredging and bioturbation remobilise them and redistribute them among compartments (Hurley *et al.* 2018).

The environmental fate of microplastics is therefore governed by an interplay of fragmentation, ageing, biofouling, aggregation, sedimentation and resuspension, which together determine long-term persistence and bioavailability. Although transport pathways are increasingly well described, important uncertainties remain regarding the fate of weathered microplastics and nanoplastics, their interactions with natural organic matter and contaminants, and their responses to changing climatic conditions; addressing these gaps is essential for improving ecological risk assessment (Koelmans *et al.* 2022).

Analytical Approaches for Microplastic Detection, Identification and Quantification

Accurate detection, identification and quantification of microplastics are essential for understanding their environmental distribution, transport, ecological consequences and implications for human health. Reliable analytical approaches underpin the evaluation of contamination levels, identification of sources, assessment of exposure pathways and development of mitigation strategies. Microplastic analysis nevertheless remains one of the most challenging aspects of plastic pollution research because of the complex physicochemical characteristics of the particles and the diversity of matrices in which they occur (Hidalgo-Ruz *et al*. 2012; Cowger *et al.* 2020).

Microplastics are highly heterogeneous, varying in size, shape, color, polymer composition, density, surface characteristics and degree of weathering, and they occur in marine and freshwater systems, sediments, soils, atmospheric deposition, wastewa-

ter, food products and biological tissues (Prata *et al.* 2019; Koelmans *et al.* 2022). No single method provides complete information on abundance, morphology, polymer identity, chemical composition and associated contaminants simultaneously (Primpke *et al.* 2020). A further difficulty is the absence of universally standardized protocols: differences in sampling strategies, sample volumes, extraction and digestion procedures, instrumentation, detection limits, size classification criteria and reporting units have produced considerable variation among published studies. For example, studies using coarse sampling nets report substantially lower concentrations because smaller particles remain undetected (Cowger *et al.* 2020; Koelmans *et al.* 2019).

The analytical workflow generally comprises sample collection, pretreatment and extraction, microscopic examination, polymer identification, chemical characterization, and quality assurance and quality control (QA/QC). Method selection depends on the environmental matrix, research objectives, required detection limits, available instrumentation and the target size range (Hidalgo-Ruz *et al.* 2012; Prata *et al.* 2019). Visual microscopy remains widely applied because it is inexpensive and allows rapid assessment of abundance and morphology, but it is insufficient for reliable polymer confirmation because organic debris, mineral fragments and biological materials may resemble microplastics; spectroscopic confirmation by FTIR or Raman spectroscopy is therefore considered essential (Hidalgo-Ruz *et al*., 2012; Käppler *et al*., 2016; Araujo *et al*., 2018).

Recent advances have improved sensitivity, automation and throughput. Automated micro-FTIR imaging, Raman mapping, laser direct infrared spectroscopy, hyperspectral imaging and artificial intelligence-assisted image recognition allow analysis of large particle numbers while reducing operator bias, and thermal methods such as Py-GC/MS and thermal extraction desorption-GC/MS provide quantitative information on polymer mass and additives (Käppler *et al.* 2016; Dümichen *et al.* 2015; Primpke *et al.* 2020). Detection of nanoplastics below 1 µm nevertheless remains limited, and electron microscopy, atomic force microscopy, nanoparticle tracking analysis and advanced spectroscopy have yet to be translated into standardized routine monitoring methods (Gigault *et al.* 2018; Koelmans *et al.* 2022). International bodies including ISO, NOAA and GESAMP have accordingly emphasized harmonized sampling protocols, validation procedures and reporting frameworks (Cowger *et al.* 2020; Primpke *et al.* 2020).

Sampling Strategies

Sampling is the first and one of the most critical stages of microplastic analysis because errors introduced during collection propagate directly into estimates of abundance, distribution and composition. An appropriate strategy must account for matrix characteristics, expected concentration, particle size distribution, spatial variability, temporal fluctuation and analytical objectives (Hidalgo-Ruz *et al.* 2012; Cowger *et al.* 2020).

Aquatic Sampling

Aquatic environments are the most extensively investigated compartments. Common approaches include manta trawls, neuston nets, plankton nets and bulk water collection (Hidalgo-Ruz *et al.* 2012). Surface trawling suits large-scale monitoring, but mesh sizes of 300-500 µm recover few small particles and may underestimate contamination (Koelmans *et al.* 2019). Bulk water sampling with filtration detects smaller particles, reduces size-selective bias and is more compatible with spectroscopic analysis, though it is more labour-intensive (Prata *et al.* 2019). Sampling depth matters because buoyant PE and PP are enriched at the surface, whereas denser PET and PVC accumulate in deeper water and sediments (Andrady 2017).

Sediment and Soil Sampling

Sediments are important long-term sinks. Marine and freshwater samples are collected using grab samplers, box corers, Van Veen grabs and sediment corers; surface sampling is common because particles concentrate in upper layers, whereas deeper cores reveal historical accumulation (Hurley *et al.* 2018). Soil sampling typically employs quadrat-based designs, composite sampling and systematic collection across land-use categories (Rillig *et al.* 2019). Because soil

texture, vegetation cover, agricultural practice, rainfall and land management all influence accumulation, replicate samples and standardized sampling depths are recommended to improve representativeness (de Souza Machado *et al*. 2018; Rillig *et al.* 2019).

Atmospheric Sampling

Atmospheric sampling employs passive deposition collectors, which characterize fallout over extended periods, and active high-volume samplers, which quantify airborne concentrations (Allen *et al.* 2019). Synthetic textile fibers, tyre wear particles, household dust, industrial emissions and resuspended plastics are the major sources (Prata 2018). Indoor concentrations often exceed outdoor levels because of abundant synthetic materials and reduced air exchange (Dris *et al.* 2017), and strict contamination control is essential because airborne laboratory fibers readily introduce artefacts.

Biological and Food Sample Collection

Biological sampling requires careful consideration of tissue type, digestion procedure, contamination prevention and ethical requirements (Rochman *et al.* 2019). The gastrointestinal tract is most commonly analyzed as the primary accumulation site, although investigations have expanded to blood, placenta, lung and other tissues following evidence of particle translocation (Leslie *et al.* 2022).

Mesh size, sample volume, sampling frequency, geographical coverage and seasonal timing strongly influence reported concentrations (Cowger *et al.* 2020). Single sampling events may fail to capture temporal variability associated with seasonal change, rainfall, tourism and industrial discharge. Future monitoring programmes should therefore adopt harmonized sampling frameworks that account for environmental variability and permit reliable comparison across regions.

Sample Pretreatment and Extraction

Environmental samples contain complex mixtures of organic matter, minerals and microorganisms that interfere with identification, so pretreatment and extraction are required to isolate plastic particles before microscopic, spectroscopic or thermal analysis (Prata *et al.* 2019). Method selection depends on sample characteristics, polymer composition and analytical objectives; an ideal procedure maximizes recovery while minimizing polymer degradation, contamination and chemical alteration. The principal steps are density separation, organic matter digestion, and filtration and concentration.

Density Separation

Density separation exploits differences between polymer density and that of surrounding mineral particles, enabling preferential flotation or sedimentation relative to the separation medium (Prata *et al.* 2019). Efficiency depends on polymer density, solution density, particle characteristics and the degree of weathering or biofouling. Low-density polymers such as PE (0.9–0.96 g cm^{-3}) and PP (0.90-0.92 g cm^{-3}) are effectively separated using saturated sodium chloride, but NaCl performs poorly for denser polymers including PET (approximately 1.38 g cm^{-3}), PS (1.04 –1.10 g cm^{-3}) and PVC (1.16–1.58 g cm^{-3}), causing incomplete recovery of environmentally relevant polymers (Hidalgo-Ruz *et al.* 2012; Claessens *et al*. 2013).

High-density media such as zinc chloride, sodium iodide, sodium polytungstate and sodium tungstate (1.5-1.8 g cm-3) recover a broader range of polymers. Sodium iodide is favored for its high density, relatively low toxicity and suitability for recycling after purification, although cost and disposal requirements limit routine application (Claessens *et al.* 2013; Prata *et al.* 2019). Recovery may also be reduced when weathering, microbial colonization, mineral attachment or biofilm formation raise the apparent density of particles, or when very small particles remain trapped within organic or mineral aggregates; density separation is therefore commonly combined with digestion (Andrady 2017). Protocols should be optimized to the matrix rather than applied universally, and recovery rates should be validated using reference particles (Lusher *et al.* 2017; Cowger *et al.* 2020).

Organic Matter Digestion

Digestion removes plant residues, algae, microorgan-

isms and animal tissues that obscure identification and interfere with spectroscopic measurement, and should do so while preserving polymer structure (Hurley *et al.* 2018).

Hydrogen Peroxide Oxidation

Hydrogen peroxide (15–35%) is the most widely used agent because it oxidizes organic material while generally maintaining the integrity of common polymers, though temperature, reaction time and concentration must be controlled to limit alteration of susceptible additives and weathered surfaces (Hurley *et al*. 2018).

Fenton's Reagent Digestion

Fenton oxidation, in which hydrogen peroxide reacts with iron catalysts to generate hydroxyl radicals, digests high organic loads more rapidly, but requires careful control of reaction conditions and additional washing to remove residual iron before spectroscopic analysis (Tagg *et al.* 2017).

Alkaline and Acid Digestion

Alkaline digestion with potassium or sodium hydroxide effectively dissolves proteins and tissues and is particularly useful for fish gastrointestinal samples, although it may damage polyamide and certain polyesters (Lusher *et al.* 2017). Acidic digestion using nitric or hydrochloric acid removes organic matter efficiently but risks polymer degradation, surface modification and additive loss, and is generally avoided when detailed polymer characterization is required.

Enzymatic Digestion

Enzymatic digestion using proteinase-K, lipase, cellulase, chitinase or amylase selectively removes biological material with minimal polymer damage, making it well suited to spectroscopic work, though cost, processing time and the need for optimized enzyme combinations remain limitations (Cole *et al.* 2014). No single technique suits all matrices; matrix-specific protocols combined with recovery experiments are recommended (Cowger *et al.* 2020).

Filtration and Concentration

Extracted particles are concentrated by filtration, which both removes residual impurities and collects particles within a controlled analytical area. Glass fiber, aluminium oxide, polycarbonate, cellulose nitrate and stainless-steel filters are all used; membranes producing minimal spectral interference are preferred for FTIR and Raman analysis (Prata *et al.* 2019). Pore size governs recovery, with smaller pores retaining fine particles at the cost of longer filtration times and clogging, and larger pores allowing small microplastics to pass and contamination to be underestimated. Contamination control is essential and typically includes filtered reagents, covered filtration systems, procedural blanks, cotton laboratory coats, glass equipment and clean-air environments (Cowger *et al.* 2020). Automated filtration combined with micro-FTIR imaging and Raman mapping now permits rapid analysis of thousands of particles, although filtration remains poorly suited to nanoplastics, for which field-flow fractionation, thermal analysis and advanced spectroscopy are being explored (Primpke *et al.* 2020).

Microscopic Identification and Morphological Characterisation

Microscopic examination provides information on particle abundance, morphology, size distribution and color before chemical confirmation, and optical microscopy, stereomicroscopy and digital imaging remain widely used because they are inexpensive, rapid and broadly accessible (Hidalgo-Ruz *et al.* 2012). Particles are commonly categorized as fibres, fragments, films, foams, pellets and spheres. Fibers dominate in aquatic and atmospheric environments and are associated with synthetic textiles, fishing activities and wastewater discharge (Dris *et al*. 2017); fragments derive from the breakdown of larger items; and films are linked to packaging and agricultural plastics.

Morphology also indicates likely sources and transport histories, with weathered irregular fragments suggesting secondary degradation and industrial pellets and spheres indicating primary sources. Visual identification is nevertheless limited: cellulose fibers, mineral fragments and biological debris can resemble synthetic polymers, and visual classification alone produces substantial false identification rates, particularly below 500 µm (Käppler

et al. 2016). Combining microscopy with FTIR or Raman spectroscopy links morphological observation to polymer-specific chemical information (Araujo *et al.* 2018). Automated microscopy and machine learning-based image recognition have improved throughput and reduced operator bias, although chemical confirmation remains necessary because morphology alone cannot determine polymer identity (Primpke *et al*. 2020).

Thermal and Chemical Characterization

Thermal analytical techniques provide quantitative information on polymer composition. Pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) thermally decomposes polymers into characteristic fragments that are then separated and identified, providing accurate polymer identification and quantification even in complex environmental samples. Thermal extraction desorption-GC/MS enables polymer characterization and additive analysis without extensive particle isolation and is particularly useful for determining polymer-specific contamination profiles (Dümichen *et al.* 2015). Because microplastics frequently contain plasticizers, flame retardants, antioxidants, pigments and stabilizers, many of which are persistent and potentially toxic, chemical characterization of additives is an important component of ecological and human health risk assessment (Rochman *et al.* 2013).

Quality Assurance and Quality Control

Airborne fibers and laboratory contamination can substantially influence results, so QA/QC procedures are essential. Common measures include procedural blanks, filtered reagents, glass laboratory equipment, contamination-free working environments and replicate analyses (Cowger *et al.* 2020). Standardized QA/QC protocols are increasingly recognized as a prerequisite for reliable and reproducible microplastic research.

Analytical Limitations and Future Directions

Airborne fibers and laboratory contamination can substantially influence results, so QA/QC procedures are essential. Common measures include procedural blanks, filtered reagents, glass laboratory equipment, contamination-free working environments and replicate analyses (Cowger *et al.* 2020). Future work should develop automated, high-throughput and standardized analytical frameworks capable of simultaneously quantifying microplastics, nanoplastics and associated contaminants across diverse environmental matrices.

Ecological Impacts of Microplastics

Microplastics interact with organisms across aquatic, terrestrial and atmospheric ecosystems, causing physical damage, altering physiological processes, affecting reproductive success and disrupting ecosystem functioning. Their capacity to adsorb and transport chemical contaminants and microbial pathogens further increases their ecological significance (Wright *et al.* 2013; de Souza Machado *et al.* 2018).

Effects on Marine Organisms

Microplastics have been reported in zooplankton, bivalves, crustaceans, fish, seabirds, turtles and marine mammals, entering organisms directly through feeding or indirectly through trophic transfer (Cole *et al.* 2011). Physical effects include gastrointestinal blockage, reduced feeding efficiency, false satiation, tissue abrasion and impaired nutrient assimilation (Wright *et al.* 2013). Experimental exposure has reduced growth, reproductive output and survival in several species: polystyrene microspheres decreased feeding rates and reproductive success in zooplankton (Cole *et al.* 2015), and exposed bivalves showed reduced filtration efficiency and altered immune responses (Browne *et al.* 2008). At the cellular level, microplastics may induce oxidative stress, inflammation, DNA damage and metabolic disturbance, and nanoplastics can penetrate biological membranes and accumulate within tissues (Gigault *et al*. 2018; Prüst *et al.* 2020).

Effects on Freshwater Biota

Freshwater organisms, including zooplankton, benthic invertebrates, molluscs, fish and amphibians, are exposed to particles delivered by wastewater effluents, agricultural runoff, industrial discharges and urban stormwater (Koelmans *et al.* 2019). Laboratory studies report reduced feeding activity,

impaired growth, behavioral alteration, oxidative stress and reproductive abnormalities, while exposed fish may show intestinal inflammation, altered energy metabolism and changes in gut microbiota (Scherer *et al.* 2017). Benthic organisms are particularly susceptible because particles accumulate in sediments, and chronic exposure may alter community structure, productivity and nutrient cycling. Freshwater impacts nevertheless remain less studied than marine ones (Windsor *et al.* 2019).

Impacts on Soil Ecosystems

Microplastics modify soil bulk density, porosity, aggregation, water-holding capacity and hydraulic conductivity, influencing aeration, water movement and root development (de Souza Machado *et al.* 2018). They also alter habitat conditions and microbial activity. Soil fauna including earthworms, nematodes, collembolans and arthropods ingest particles during feeding, and exposed earthworms show reduced growth, altered burrowing behavior, oxidative stress and reproductive impairment (Huerta Lwanga *et al*. 2016). Such effects may ultimately influence soil fertility, decomposition and nutrient cycling (Boots *et al.* 2019).

Plant-Microplastic Interactions

Microplastics influence plant growth directly and indirectly through changes in soil properties and microbial communities, and depending on polymer type, particle size, concentration and conditions may either inhibit or stimulate growth (Boots *et al.* 2019). Reported effects include altered seed germination, root elongation, nutrient uptake, photosynthesis and biomass production. Nanoplastics may penetrate root tissues and translocate to aboveground organs, raising concerns for food safety and human exposure through agricultural products (Li *et al.* 2020). Microplastics may also interfere with plant-microbe interactions such as mycorrhizal associations and nitrogen-fixing symbioses, although the governing mechanisms remain incompletely understood (Rillig *et al.* 2019).

Microplastics as Vectors of Pollutants and Pathogens

Because of their hydrophobic surfaces and high surface-area-to-volume ratios, microplastics readily adsorb persistent organic pollutants, polycyclic aromatic hydrocarbons, pesticides, pharmaceuticals and heavy metals (Rochman *et al.* 2013). Ingestion of contaminated particles may enhance the bioavailability of these pollutants, and particles may additionally transport manufacturing additives such as plasticisers, flame retardants, antioxidants and pigments. Plastic surfaces also support distinct microbial communities, the plastisphere, which may include opportunistic pathogens, antibiotic-resistant bacteria and harmful algal species, facilitating microbial dispersal across environmental compartments (Zettler *et al*. 2013; Rochman *et al.* 2019).

Bioaccumulation, Biomagnification and Trophic Transfer

Microplastics enter food webs through ingestion by plankton, benthic invertebrates and detritivores, and may then be transferred to predators, leading to accumulation across trophic levels (Setälä *et al.* 2014). Trophic transfer from zooplankton to fish and from prey to higher predators has been repeatedly demonstrated, and marine birds, mammals and commercially important fish have been reported to contain particles in their digestive systems (Provencher *et al.* 2019). Evidence for classical biomagnification remains limited and sometimes contradictory, but repeated trophic transfer increases exposure opportunities and may move associated contaminants through food webs, potentially altering predator-prey relationships and feeding behavior.

Ecosystem-Level Consequences

Reported ecosystem-level effects include altered species composition, biodiversity, nutrient cycling, decomposition rates, primary productivity and trophic interactions in both aquatic and terrestrial systems (de Souza Machado *et al*. 2018). In marine environments, effects on plankton communities may influence carbon cycling and productivity, while in terrestrial systems disruption of soil microbial communities and fauna may impair nutrient turnover and resilience. Microplastic contamination may further interact with climate change, habitat degradation, eutrophication and chemical pollution, amplifying ecological im-

pacts (Ford *et al*. 2022; Koelmans *et al.* 2022).

Human Health Implications of Microplastic Exposure

Microplastics have been detected in human blood, lung tissue, placental tissue, breast milk and faeces, indicating that exposure is widespread and continuous (Ragusa *et al.* 2021; Leslie *et al.* 2022). Although long-term consequences remain incompletely understood, increasing evidence suggests that microplastics may induce adverse biological responses through physical, chemical and toxicological mechanisms (Galloway & Lewis, 2016; Wright & Kelly, 2017). Exposure occurs primarily through ingestion and inhalation, with dermal contact considered a minor route.

Exposure Pathways

Ingestion is considered the primary route. Particles have been identified in bottled and tap water, seafood, table salt, honey, fruits, vegetables, dairy products and beverages (Cox *et al.* 2019), and marine fish, shellfish and crustaceans accumulate particles that may transfer to humans through seafood consumption (Smith *et al.* 2018). Agricultural products may be contaminated through sewage sludge application, wastewater irrigation, atmospheric deposition and mulch degradation (Li *et al.* 2020). Once ingested, particles interact with gastrointestinal tissues and may translocate into the circulation depending on size, shape and physicochemical properties (Yong *et al.* 2020).

Inhalation is an increasingly important pathway.

Airborne particles derive from synthetic textile fibres, tyre wear, household dust, industrial emissions and resuspension, and indoor concentrations often exceed outdoor levels (Allen *et al*. 2019). Deposition within the respiratory tract depends on size and aerodynamic characteristics: larger particles are trapped in the upper airways, whereas smaller particles may penetrate deep into the lungs and potentially enter systemic circulation (Prata 2018). Occupational exposure may be substantial among textile, plastic manufacturing and waste management workers.

Dermal exposure may occur through personal care products, synthetic textiles, contaminated water and household dust; intact skin is an effective barrier to most particles, although nanoplastics may show greater potential for transdermal absorption through damaged skin (Yee *et al.* 2021).

Toxicological Effects and Mechanisms

Toxicological effects depend on particle size, shape, polymer type, surface chemistry, concentration, exposure duration and associated contaminants. Experimental studies report oxidative stress, inflammation, cytotoxicity, immune dysfunction and metabolic disturbance (Wright and Kelly 2017). Microplastics may also carry heavy metals, polycyclic aromatic hydrocarbons, persistent organic pollutants and additives such as bisphenol A and phthalates, which may desorb within tissues and increase internal chemical exposure (Rochman *et al.* 2013). Animal studies have linked exposure to reproductive toxicity, endocrine disruption, neurotoxicity, hepatic damage and altered gut microbiota, although extrapolation to humans remains uncertain because of differences in exposure levels and experimental conditions (Yong *et al.* 2020).

Cellular and Molecular Mechanisms

At the cellular level, the most frequently reported mechanism is oxidative stress arising from excessive production of reactive oxygen species, which damages proteins, lipids and nucleic acids (Jeong *et al.* 2016; Prokić *et al*. 2019). Microplastics may also activate inflammatory pathways through stimulation of immune cells and cytokine production, and chronic inflammation can contribute to tissue damage and disease susceptibility. DNA damage, mitochondrial dysfunction, apoptosis and altered gene expression have also been reported (Yong *et al.* 2020). Nanoplastics are of particular concern because they can cross intestinal epithelia, pulmonary tissues and possibly the blood-brain barrier, enhancing cellular uptake, intracellular accumulation and systemic distribution (Prüst *et al.* 2020).

Current Evidence from Human Studies

Direct evidence in humans is limited but expanding

rapidly. Ragusa *et al.* (2021) reported microplastic particles in human placentas, raising concerns about fetal exposure, and Leslie *et al.* (2022) detected particles in human blood, demonstrating the potential for systemic circulation. Causal relationships between exposure and specific diseases have not been established, and most available evidence originates from laboratory experiments, animal studies and observational investigations, leaving substantial uncertainty regarding exposure thresholds, dose-response relationships and long-term outcomes.

Risk Assessment Challenges

Risk assessment is complicated by variability in particle size, shape, polymer composition, weathering status and associated contaminants, by analytical limitations that restrict detection of smaller particles and nanoplastics, and by the absence of standardized monitoring protocols and toxicological benchmarks (Koelmans *et al.* 2022). Future assessments will require harmonized methodologies, long-term epidemiological studies and improved understanding of microplastic toxicokinetics and toxicodynamic.

Knowledge Gaps and Emerging Concerns

Although substantial progress has been made, several critical knowledge gaps remain, and addressing them is essential for improving risk assessment and developing effective mitigation.

Standardization of analytical methodologies is the most pressing requirement. Differences in sampling, extraction, identification and reporting protocols produce inconsistent datasets and hinder comparison among studies, so internationally harmonized methodologies and quality assurance frameworks should be prioritized (Cowger *et al.* 2020). Detection and characterization of nanoplastics is a second priority: current techniques are designed for microplastics and often fail to detect nanoplastics, whose greater mobility, bioavailability and toxicity potential make their environmental occurrence and biological impacts poorly understood (Gigault *et al.* 2018; Prüst *et al.* 2020).

Long-term ecological consequences also remain unclear because most studies use short-term laboratory exposures that poorly represent field conditions; long-term investigations are required to evaluate chronic effects on biodiversity, ecosystem functioning, nutrient cycling and resilience (de Souza Machado *et al.* 2018). Similarly, despite growing evidence of human exposure, large-scale epidemiological studies are needed to establish exposure pathways, dose-response relationships, vulnerable populations and potential disease associations (Leslie *et al.* 2022).

CONCLUSION

Microplastics have become one of the most widespread and persistent anthropogenic contaminants in the global environment. Continuous release from primary sources, including industrial pellets, cosmetic products and synthetic fibers, and from secondary sources generated by fragmentation of larger debris, has produced extensive distribution across marine, freshwater, terrestrial and atmospheric environments. Small particle size, chemical stability, resistance to degradation and susceptibility to long-range transport allow accumulation even in remote ecosystems, including polar regions and the deep sea, and their detection in food chains, drinking water and human biological matrices demonstrates the global scale of contamination.

Available evidence indicates that microplastics influence biological systems through interconnected physical, chemical and biological mechanisms. Across diverse taxa, exposure has been associated with reduced feeding efficiency, impaired growth, reproductive dysfunction, oxidative stress, inflammatory responses and cellular damage, and at the ecosystem level contamination may modify species interactions, nutrient cycling and ecological resilience. Microplastics additionally act as carriers of persistent organic pollutants, heavy metals, plastic additives and plastisphere-associated microorganisms. In humans, exposure occurs primarily through ingestion and inhalation, and particles have been reported in blood, lung, placental and other tissues; definitive causal relationships with specific diseases remain unconfirmed, and major uncertainties persist regarding environmentally relevant exposure concentrations, dose-response relationships and the

consequences of chronic exposure to nanoplastics.

Analytical capability has advanced considerably, with FTIR and Raman spectroscopy, Py-GC/MS, thermal extraction desorption methods and automated spectroscopic imaging substantially improving polymer characterization and throughput. Differences in sampling strategies, extraction procedures, detection limits, identification criteria, reporting units and quality assurance nevertheless continue to restrict comparison among studies, making internationally harmonized protocols and standardized monitoring frameworks a critical priority.

Future research works are needed to prioritize improved detection and characterization of nanoplastics, long-term ecological monitoring, environmentally realistic exposure experiments, mechanistic understanding of toxicity pathways, and evaluation of interactions between microplastics and other environmental stressors such as climate change and chemical pollution. Therefore, the human health risk assessment requires multidisciplinary collaboration integrating environmental science, toxicology, epidemiology and analytical chemistry, supported by long-term monitoring programmes based on standardized methodologies.

Future Prospects

Furthermore, the microplastic research is expected to move beyond documenting environmental occurrence toward understanding mechanisms of toxicity, ecosystem-level consequences, and the effectiveness of mitigation strategies. Advances in analytical technologies, environmental monitoring, risk assessment frameworks, and sustainable material innovation will improve our understanding of microplastic pollution and support the development of effective management approaches. Integrating scientific evidence with policy implementation and public engagement will be critical for reducing plastic emissions and safeguarding environmental and human health in the coming decades.

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