

REVIEW ARTICLE

Microplastics, much more than water
contaminants: Environmental trajectory and the
state of particles at exposureChristine Gaylarde^{1*}, Estefan Monteiro da Fonseca², Guy Gaylarde³, and
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Abstract

Microplastics were initially recognized and investigated primarily as aquatic contaminants, but they are now known to circulate among atmospheric, terrestrial, freshwater, and marine environments. Their significance therefore extends beyond their occurrence in individual environmental compartments. During transport, particles may undergo fragmentation, ultraviolet weathering, oxidation, contaminant sorption, and biological colonization, progressively modifying the physicochemical and biological characteristics of the material eventually encountered by organisms. This review examines microplastic pollution from a trajectory-aware perspective, in which environmental trajectory refers to the sequence of environmental compartments and transformation processes experienced by a particle between its source and the point of sampling or biological exposure. We propose that environmental risk should therefore be interpreted not only from polymer identity, particle size, or sampling compartment, but also from the “state of the particle at the point of exposure”. We synthesize evidence on microplastic sources, inter-compartment transport, environmental transformation, exposure pathways, and biological effects, with particular attention to the substantial variability reported among toxicological studies. Differences in particle properties, weathering history, associated contaminants, biological colonization, dose, exposure duration, analytical methods, and organismal characteristics may together explain why apparently similar studies produce divergent outcomes. This framework also highlights an important distinction between experimental reproducibility and environmental representativeness, since pristine commercial particles commonly used in laboratory studies may differ substantially from environmentally transformed microplastics. Airborne microplastics, ingestion and inhalation pathways, nanoplastics, and comparisons with historical particulate pollutants are considered within this broader context. We argue that future microplastic research should move beyond documenting where particles occur and increasingly determine how environmental trajectories shape particle state at exposure and, consequently, biological response.

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(cgaylarde@gmail.com)**Citation:** Gaylarde C, da Fonseca EM, Gaylarde G, Gaylarde K. Microplastics, much more than water contaminants: Environmental trajectory and the state of particles at exposure. *Explora Environ Resour*. doi: 10.36922/EER026320036**Received:** August 6, 2026**Revised:** August 27, 2026**Accepted:** September 2, 2026**Published online:** September 10, 2026**Copyright:** © 2026 Author(s). This is an Open-Access article distributed under the terms of the Creative Commons Attribution License, permitting distribution, and reproduction in any medium, provided the original work is properly cited.**Publisher's Note:** AccScience Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Microplastics were initially investigated mainly as marine and freshwater contaminants, but they are now recognized throughout atmospheric, terrestrial, freshwater, marine, and biological systems. This expanded distribution exposes a conceptual limitation in treating each environmental compartment as an isolated endpoint. Because particles can move repeatedly among air, soil, water, sediment, and organisms, the compartment in which a particle is detected represents only one stage of a broader environmental history. Understanding microplastic exposure therefore requires a framework that connects movement among compartments with the transformations undergone before sampling or biological contact.

Historical experience with other particulate pollutants provides useful context for this transition in perception. During the Victorian era, coal-fired industrialization generated pervasive soot pollution across Britain, contributing to widespread building discoloration and respiratory morbidity. The 1952 London smog resulted in approximately 4,000 deaths within a single week¹, illustrating the acute health consequences of severe particulate pollution^{2,3}. Despite these effects, however, coal contributed substantially to industrial development and improvements in living conditions.^{4,5} Asbestos followed a comparable historical trajectory: valued for insulation and fireproofing⁶, it was extensively used before the health consequences of fiber inhalation led to restrictions or bans in many countries.^{7–11} These examples are not intended to imply toxicological equivalence between soot, asbestos, and microplastics. Rather, they illustrate how materials that provide major societal benefits can later become sources of persistent particulate contamination whose environmental and health significance was not fully appreciated during their early use.

Plastics transformed modern society through their durability, low cost, versatility, and widespread use across healthcare, transportation, construction, packaging, textiles, and other sectors.¹² Those same properties also favor persistence after release. Weathering, abrasion, fragmentation, and direct release generate particles that can circulate among environmental compartments and undergo further physical, chemical, and biological modification, including changes in size, morphology, surface chemistry, and interactions with additives, contaminants, and biological systems.^{13–16} The resulting mobility and transformation are central to understanding microplastic exposure and risk.

Against this background, we use environmental trajectory to mean the sequence of environmental compartments and physical, chemical, and biological

transformation processes experienced by a microplastic particle between its source and the point at which it is sampled or encountered by an organism. The trajectory-aware framework developed here links inter-compartment transport and particle transformation to particle state at exposure and biological response, shifting the emphasis from where particles are detected to how their prior environmental history may have shaped the material ultimately encountered by organisms. We synthesize evidence on sources, distribution, transport, transformation, exposure pathways, and biological effects, with particular attention to airborne microplastics, nanoplastics, and factors contributing to variability among toxicological studies. By integrating these components, the review aims to clarify why experimental reproducibility does not necessarily ensure environmental representativeness and how trajectory information may improve the interpretation of environmental and human-health risk. Historical particulate pollutants are considered as contextual analogues within this broader framework.

2. From plastic production to environmental microplastics

The development of synthetic polymers during the 19th and 20th centuries transformed modern society. Their durability, low cost, light weight, and adaptability enabled plastics to replace many natural materials and become integrated into virtually every sector of human activity.^{17,18} Global production subsequently increased from approximately 2 million tonnes in 1950 to hundreds of millions of tonnes annually, and further substantial growth is projected over coming decades.^{15,19} This rapid expansion has created an equally persistent environmental legacy because many of the characteristics that make plastics technologically valuable also favor their accumulation and long-term persistence after disposal.

Plastics have provided substantial societal benefits. They are essential in healthcare, food preservation, transportation, construction, water distribution, and textile production, where they have improved safety, reduced material and transportation costs, facilitated sterile medical procedures, and enabled numerous technological advances.^{20–35} The environmental problem associated with plastics therefore does not arise simply from their use, but from the scale of production, patterns of disposal, environmental persistence, and progressive fragmentation of plastic materials. In this respect, the benefits of plastics and their environmental consequences are intrinsically connected: durability is simultaneously one of their most useful properties and one of the principal reasons for their persistence in natural systems.

The environmental significance of plastics is further complicated by their chemical diversity. Commercial polymers commonly contain plasticizers, stabilizers, flame retardants, antioxidants, pigments, biocides, fillers, and other additives designed to modify their physical or chemical properties.^{36,37} Thousands of plastic-associated chemicals have been identified, including substances of environmental and toxicological concern.^{38–42} Consequently, environmental plastic particles cannot necessarily be regarded as chemically inert polymer fragments. Their composition, additive content, and subsequent interactions with surrounding contaminants may influence their environmental behavior and biological effects.

Microplastics arise both through the direct release of intentionally manufactured small particles and through the progressive fragmentation of larger plastic products. Weathering processes, including ultraviolet radiation, thermal stress, mechanical abrasion, oxidation, and biological activity, progressively alter plastic surfaces and promote fragmentation.⁴³ Important sources include synthetic textiles, tire wear, packaging, industrial materials,

coatings, urban runoff, wastewater effluents, landfill-associated releases, and the degradation of discarded plastic debris. Once released, these particles are no longer restricted to the compartment in which they originated (Figure 1).

Once generated, microplastics may move through runoff, rivers, wastewater, ocean circulation, wind, atmospheric deposition, sedimentation, and resuspension. Transport can modify size, morphology, density, surface chemistry, contaminant load, and biological associations. Their environmental identity therefore reflects both polymer origin and the sequence of environments encountered after release, providing the basis for the trajectory-aware framework developed below.

3. Microplastics across interconnected environmental compartments

The term “microplastics” was introduced in 2004 to describe plastic particles smaller than 5 mm.⁴⁴ They include primary microplastics, intentionally produced at microscopic dimensions, and secondary microplastics

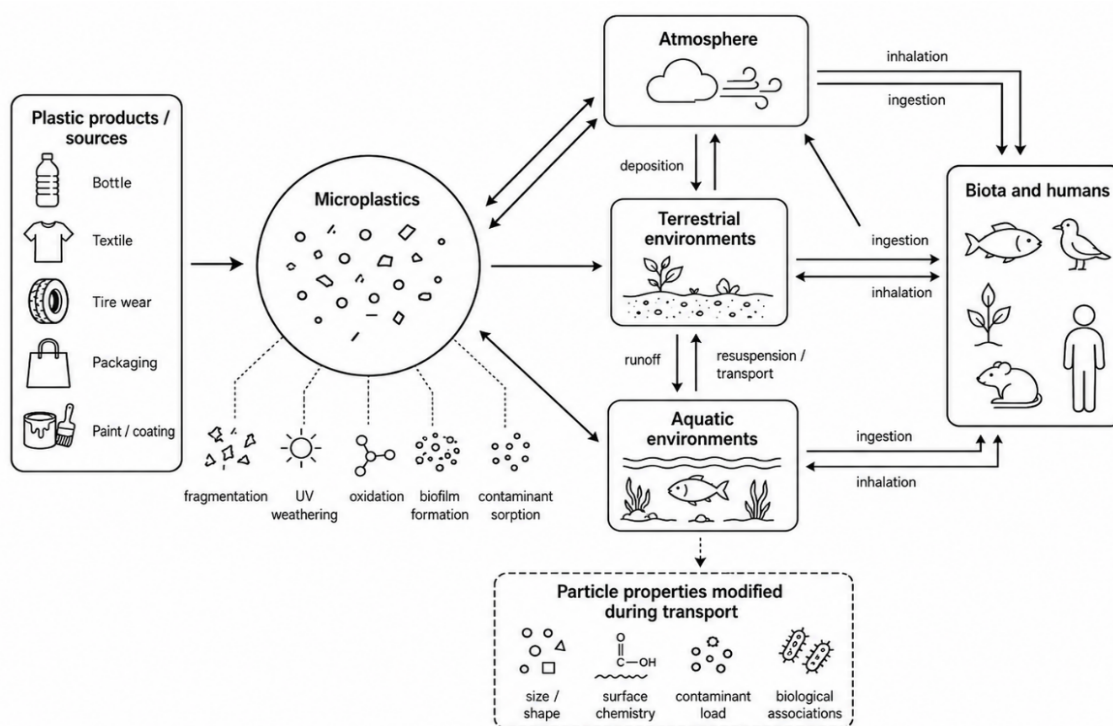


Figure 1. Conceptual representation of microplastic sources, transport among atmospheric, terrestrial, and aquatic environments, and transformations occurring during environmental circulation that may modify particle properties and exposure pathways

generated through the fragmentation and weathering of larger plastic materials. Nanoplastics, generally defined as particles smaller than 1 μm , represent the lower end of this continuum and present additional analytical and biological challenges because of their small size.⁴⁵ Environmental microplastics occur as fibers, fragments, films, spheres, foams, and other irregular forms, with fibers among the most frequently reported morphologies.^{46–48}

Early observations of plastic contamination were predominantly marine^{49–51}, contributing to the historical perception of microplastics as aquatic pollutants. It is now evident, however, that microplastics occur throughout atmospheric, terrestrial, freshwater, marine, cryospheric, and biological systems.^{52–65} Their occurrence in remote mountains, polar environments, deep-sea sediments, and high-altitude lakes demonstrates that proximity to plastic production or disposal is not required for contamination.^{53,54,62–69} Rather than representing isolated reservoirs, these environments form interconnected components of a broader microplastic cycle (Figure 1).

3.1. Atmospheric environments

The recognition of airborne microplastics substantially expanded the environmental framework within which

microplastic pollution is understood. Early studies in Paris demonstrated microplastic deposition from the atmosphere and subsequently showed that indoor concentrations could exceed those measured outdoors.^{70,71} Similar observations have since been reported in multiple regions and indoor environments.^{72–78} Synthetic fibers from textiles, tire and road wear, degradation of plastic materials, industrial activities, and resuspension of previously deposited particles all contribute to the atmospheric burden.

Atmospheric transport also provides an efficient mechanism for redistribution over large spatial scales. Microplastics can be transported far from their original sources and have been detected in remote mountainous regions, polar areas, and other locations with limited local plastic emissions.^{53,54,62,63,65,79–81} Their atmospheric residence and transport depend on particle size, shape, density, meteorological conditions, and aerodynamic behavior. Fibers may be particularly relevant because their morphology influences suspension and deposition processes^{46,47} (Table 1). The atmosphere therefore functions both as an environmental compartment and as a transport pathway. Deposition followed by resuspension enables repeated redistribution between air and terrestrial or aquatic surfaces, including over long distances.

Table 1. Major sources and pathways contributing to airborne microplastics

Source or pathway	Predominant particle types	Main emission or mobilization process	Environmental relevance	Ref.
Synthetic textiles	Fibers	Fiber shedding during wearing, handling, washing, drying, and degradation of textiles	Important source of indoor and outdoor airborne fibers	46,48,72,73,75,77
Tire and road wear	Fragments and irregular particles	Mechanical abrasion during vehicle use followed by atmospheric suspension or resuspension	Major urban source with potential transfer between road surfaces, soil, runoff, and air	52,78
Indoor furnishings and plastic materials	Fibers and fragments	Abrasion, aging, human activity, and resuspension of settled dust	Contributes to higher microplastic concentrations frequently reported in indoor environments	72,73,75–77
Plastic waste and exposed plastic surfaces	Fragments and fibers	Weathering, fragmentation, mechanical abrasion, and wind mobilization	Provides secondary microplastics capable of entering atmospheric transport	52,78
Industrial and urban activities	Fibers, fragments, and particles	Material handling, abrasion, processing, construction activities, and urban dust resuspension	Generates locally elevated atmospheric inputs in densely populated and industrialized areas	52,78
Resuspension from terrestrial surfaces	Fibers and fragments	Wind and mechanical disturbance of previously deposited particles	Allows repeated exchange between terrestrial and atmospheric compartments	62,65,78
Aquatic and marine surfaces	Mainly small fragments and fibers	Aerosolization, sea spray, and re-emission of particles previously present in water	Provides a pathway for return of aquatic microplastics to the atmosphere and further long-range transport	78

3.2. Terrestrial environments

Terrestrial systems are both recipients and sources of microplastics. Particles reach soils through atmospheric deposition, fragmentation of discarded plastic materials, tire wear, urban runoff, agricultural practices, wastewater-derived materials, and other anthropogenic inputs.⁵² Once incorporated into soils, their mobility is influenced by particle size and density as well as soil texture, aggregation, water movement, biological activity, and land use. Importantly, terrestrial deposition does not necessarily represent a permanent environmental sink. Surface particles can be transported by wind, while rainfall and surface runoff can mobilize particles toward drainage systems, rivers, lakes, and coastal environments. Soil erosion and mechanical disturbance may further promote redistribution. Thus, particles that initially enter terrestrial environments may subsequently become atmospheric or aquatic contaminants.

Terrestrial systems illustrate why environmental identity is not fixed: a tire-wear particle may move from a road surface to freshwater or sediment and later be resuspended. Its classification therefore depends partly on when and where it is sampled.

3.3. Aquatic environments

Aquatic environments remain among the best studied reservoirs of microplastic pollution. Microplastics occur in freshwater, groundwater, estuarine, coastal, and marine systems, as well as in sediments and drinking-water sources.^{82–86} Inputs include wastewater effluents, urban runoff, synthetic textiles, tire wear, road markings, industrial pellets, marine coatings, discarded plastic materials, and atmospheric deposition.^{52,87–89} Distribution within aquatic systems is heterogeneous.⁹⁰ Although low-density polymers may initially remain near the water surface, aggregation with suspended particles, biological colonization, incorporation into organic matter, and other environmental processes can modify their effective density and favor downward transport. Consequently, sediments frequently represent important accumulation zones for microplastics.^{83–85,91} Sedimentation, however, should not necessarily be interpreted as permanent removal from environmental circulation. Hydrodynamic disturbance, biological activity, storms, dredging, and other processes can remobilize previously deposited particles.

The recent detection of substantial quantities of nanoplastics in the North Atlantic further illustrates the potential importance of particle fractions that remain difficult to quantify using conventional analytical approaches.⁵⁵ Because analytical recovery decreases with particle size, present estimates of environmental

microplastic abundance may disproportionately represent larger and more readily detectable particles. Comparisons among environmental compartments must therefore account for methodological differences as well as genuine differences in particle abundance.

3.4. Inter-compartment transport and transformation

The occurrence of microplastics in air, soil, water, sediment, and remote environments is often described separately. However, this compartment-based approach can obscure an important characteristic of microplastic pollution: environmental compartments are connected by continuous particle exchange. Atmospheric deposition transfers particles to terrestrial and aquatic surfaces; runoff transfers terrestrial particles to freshwater and marine systems; sedimentation moves particles from the water column to benthic environments; and resuspension, erosion, spray generation, and wind transport may return previously deposited particles to the water column or atmosphere (Figure 1).

Transport between compartments is accompanied by transformation. Ultraviolet (UV) exposure, oxidation, mechanical abrasion, biological colonization, and interactions with dissolved or particulate substances can modify particle size and shape, surface chemistry, density, sorption behavior, contaminant load, and biological associations.^{92–95} Consequently, particle state at exposure may reflect environmental history as well as polymer identity, size, and source. This distinction matters for toxicology because particles defined only by polymer type, size, and concentration may not reproduce the state of environmentally transformed particles.

4. Biological effects and exposure pathways

Microplastic distribution across environmental compartments creates multiple exposure pathways, including ingestion, inhalation, contact with contaminated matrices, and food-web transfer. Which pathway dominates depends on the organism, habitat, particle properties, and environmental conditions. Biological response, however, is not determined by exposure pathway alone; it reflects particle state at exposure together with associated chemicals and microorganisms, exposure route and dose, and organismal characteristics. This relationship provides the bridge between environmental trajectory and the variability among studies examined in the Discussion section.

4.1. Wildlife exposure and ecological effects

Ingestion represents one of the best documented routes of microplastic exposure in aquatic organisms. Microplastics

can be taken up directly from the surrounding environment or indirectly through contaminated prey, and transfer between trophic levels has been demonstrated in aquatic food webs.^{96–99} Such transfer, however, should not be interpreted as evidence that biomagnification occurs universally, since retention, elimination, particle size, feeding strategy, and organism physiology may substantially influence particle burdens. Biological effects reported following ingestion include reduced feeding efficiency, impaired nutrient assimilation, altered energy allocation, gastrointestinal damage, changes in growth and reproduction, oxidative stress, immune responses, and behavioral alterations.^{98,100–106} Microplastics have also been detected in terrestrial wildlife, domestic animals, and predatory birds, demonstrating that exposure is not restricted to aquatic food webs.^{107–112}

The mechanisms underlying the effects of microplastics are diverse. Larger particles may exert physical effects within digestive systems, while smaller microplastics and nanoplastics may interact more extensively with biological barriers and tissues. Particle exposure has been associated with oxidative stress, inflammation, endocrine-related effects, immune modulation, and neurobehavioral responses in experimental systems.^{101,102,105,113–119} However, the occurrence and magnitude of these effects vary substantially among studies, reflecting differences in particle characteristics, dose, exposure duration, organism, and experimental design.

Microplastics may also influence biological systems through their chemical composition and interactions with other contaminants. Plastic additives can be released from polymer matrices, while environmental particles can sorb hydrocarbons, persistent organic pollutants, metals, and other chemicals.^{120–122} Desorption may subsequently occur under changing environmental or gastrointestinal conditions.^{123,124} The resulting biological response may therefore derive from the particle itself, polymer-associated chemicals, environmentally acquired contaminants, or combinations of these factors. The relative contribution of microplastics as vectors of chemical exposure remains context-dependent and should not be assumed to be equivalent for all polymers, contaminants, or environmental conditions.^{122,125}

Biological colonization introduces another level of complexity. Environmental microplastics commonly acquire microbial biofilms, and interactions between particle-associated microorganisms and host organisms may influence immune responses and host–microbe interactions.^{93,126} Thus, environmentally aged particles can differ substantially from pristine particles not only in surface chemistry but also in their biological associations.

4.2. Human exposure and potential health effects

Human exposure occurs principally through ingestion and inhalation. Microplastics have been reported in drinking water and food-associated pathways, while contamination of fish and other edible organisms provides an additional route of dietary exposure.^{58,59,100,127} The presence of microplastics in food or drinking water demonstrates exposure potential, but does not by itself establish a corresponding health effect; dose, particle characteristics, retention, translocation, and biological persistence remain critical considerations.

Inhalation has gained particular attention following the recognition that indoor and outdoor air contain microplastic particles and fibers.^{70–78} Microplastics have been isolated from human lower airways and bronchoalveolar lavage fluid^{128,129}, providing direct evidence that inhaled environmental particles can reach the respiratory system. Indoor environments may be especially relevant because synthetic textiles, furnishings, household materials, and human activity continuously generate and resuspend fibers and fragments^{72,73,75–78}. Evidence of deposition in the human respiratory tract should nevertheless be distinguished from evidence of disease causation. Experimental and mechanistic studies indicate that micro- and nanoplastic exposure can induce inflammatory responses, epithelial dysfunction, oxidative stress, and immune activation under certain conditions.^{114,117,118,130–132} However, unlike asbestos and combustion-derived particulate pollution, for which causal relationships with specific human diseases are well established, current evidence does not yet permit comparable conclusions for environmentally realistic microplastic exposure. This distinction is particularly important when historical comparisons among particulate pollutants are made.

4.3. Nanoplastic exposure and tissue-level interactions

Particle size is likely to be a major determinant of biological interaction. Nanoplastics occupy a different biological scale from larger microplastics and may cross biological barriers and interact with cells and intracellular structures more readily. Their small dimensions also increase surface area relative to mass and may alter sorption, chemical reactivity, and biological availability. Recent evidence suggesting large environmental reservoirs of nanoplastics emphasizes the potential importance of this poorly quantified particle fraction.⁵⁵

Experimental research has raised concerns regarding inflammatory, cardiovascular, neurological, endocrine, and immune-related effects of micro-

and nanoplastics.^{56,57,113,114,116–118,133,134} Nevertheless, extrapolation from experimental systems to environmental human exposure remains difficult. Many studies employ specific polymers, relatively uniform particles, or exposure concentrations that do not necessarily reproduce the complexity of environmentally transformed particles or realistic long-term exposure scenarios.

5. Discussion: Why do microplastic effects differ across studies?

Apparently inconsistent findings on microplastic behavior, contaminant sorption, and biological effects do not necessarily represent contradictory evidence. They may instead reflect the heterogeneity of microplastics as particulate contaminants and the changes they undergo during environmental transport and exposure.¹²² The **Discussion** section therefore focuses on the variables most directly relevant to the trajectory-aware framework.

5.1. Particle heterogeneity and environmental transformation

Microplastics differ in polymer composition, size, shape, density, surface area, additive content, and degree of degradation, all of which can influence transport, uptake, chemical interactions, and toxicity.^{42,113,120} Particle size and morphology are especially important because they affect aerodynamic behavior, retention, surface area, and interaction with biological barriers. Studies using nominally different particle types therefore cannot be expected to produce equivalent biological responses.

Environmental history adds further heterogeneity. Weathering can alter surface roughness, chemical functionality, density, fragmentation behavior, and interactions with chemicals and organisms; different aging strategies have produced distinct surface characteristics and adsorption behaviors in otherwise comparable microplastics.⁹⁴ Sorption and leaching are likewise context-dependent, varying with polymer characteristics, particle aging, contaminant chemistry, environmental conditions, and exposure time.^{120–122} Desorption can occur under gastrointestinal conditions^{123,124}, but sorption alone does not establish biologically meaningful transfer. Together, these processes help explain why particles with similar nominal polymer and size may behave differently at exposure.

5.2. Experimental representativeness and study comparability

Pristine commercial particles provide experimental control but may not represent the state of particles encountered in natural environments. Weathering can modify surface

chemistry and morphology⁹⁴, environmental contaminants can become associated with particle surfaces^{121,122}, and microbial colonization can generate biological interfaces.¹²⁶ Mechanistic results obtained with standardized particles should therefore not automatically be generalized to environmentally transformed particles.

Study outcomes also depend on dose, exposure duration, biological context, and analytical design. Concentrations and exposure periods vary widely, and acute high-dose responses cannot necessarily be extrapolated to chronic lower-dose exposure. Organismal traits influence uptake, retention, and elimination, contributing to differences in responses such as oxidative stress, inflammation, endocrine effects, immune modulation, and neurobehavioral effects.^{101,102,105,113–119}

Methodological differences further complicate comparison. Sampling, filtration, digestion, particle identification, contamination control, detection limits, and reporting units vary substantially among studies, while the smallest microplastics and nanoplastics remain especially difficult to quantify reliably.¹³⁵ These differences can make measured concentrations and apparent effects partly method-dependent rather than directly comparable.

5.3. Trajectory-aware risk interpretation

Taken together, these factors suggest that the environmental significance of microplastics cannot be determined solely from polymer identity or measured particle concentration. Risk emerges from an interaction among intrinsic particle characteristics, environmental transformations, exposure pathway, dose, and biological context. As summarized in [Figure 2](#), source and environmental trajectory influence particle transformation and state at exposure, which interact with exposure pathway and biological context to shape response. The compartment in which a particle is sampled is therefore a snapshot rather than necessarily its origin, and particle state at exposure should be treated as an interpretive variable alongside polymer, size, concentration, and dose.

6. Knowledge gaps and future research priorities

Future work should address four interrelated scientific questions that directly determine how environmental trajectory shapes particle state and risk interpretation.

6.1. How can environmental trajectories and particle transformations be quantified?

Quantitative transfer rates among environmental compartments remain poorly constrained. Future studies should measure fluxes associated with atmospheric

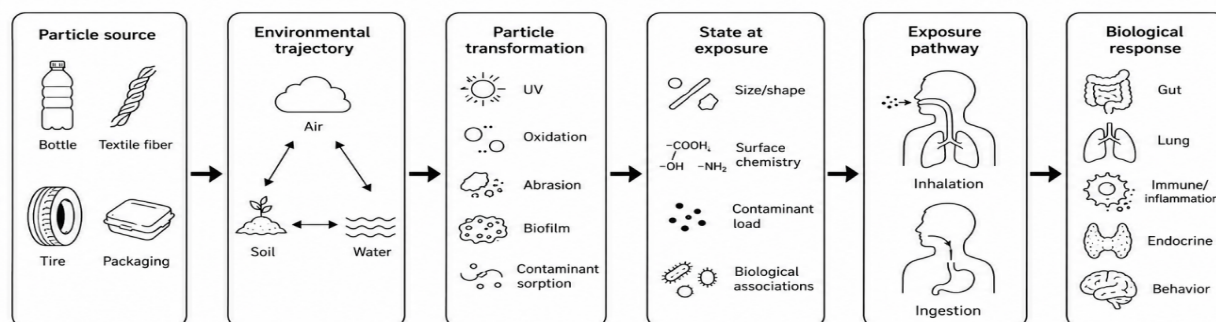


Figure 2. Conceptual framework linking microplastic source, environmental trajectory, particle transformation, state at exposure, exposure pathway, and biological response. The scheme emphasizes that biological effects may depend not only on intrinsic particle characteristics, but also on the environmental transformations experienced before exposure.

deposition, runoff, sedimentation, resuspension, erosion, and aerosolization, while also determining how these transport histories modify particle size, morphology, surface chemistry, density, sorption behavior, additive release, and biological associations under realistic conditions.⁹⁴ Linking fluxes to transformation would allow environmental trajectory to be evaluated as a process rather than inferred from occurrence alone.

6.2. How can environmental realism and study comparability be improved?

Trajectory-aware assessment requires comparable analytical and experimental approaches. Sampling, identification, detection limits, contamination control, and reporting should be harmonized, particularly for small microplastics and nanoplastics.¹³⁵ Toxicological studies should also compare pristine and environmentally transformed particles and use exposure conditions that better reflect environmental scenarios.^{136,137}

Studies should report the particle characteristics most relevant to state at exposure, including size distribution, morphology, polymer composition, weathering state, surface chemistry, associated contaminants, biological colonization, and sampling context. Where environmental history cannot be reconstructed, pristine experimental particles should be clearly distinguished from particles recovered from environmental matrices.

6.3. What remains unknown about nanoplastics and human exposure?

Nanoplastics remain a priority because their small size increases both analytical difficulty and potential biological interaction, while evidence of substantial marine reservoirs

suggests that conventional monitoring may underestimate this fraction.⁵⁵ For human exposure, research should establish realistic inhalation and ingestion ranges and relate external exposure to internal burden, persistence, tissue distribution, and biological response; this is particularly important given the detection of particles in the respiratory system.^{128,129}

6.4 How can airborne microplastics be incorporated into regulatory frameworks?

Airborne microplastics present a regulatory challenge because they comprise heterogeneous polymers, fibers, fragments, and particle states that cannot necessarily be represented by conventional particulate-matter mass metrics alone.¹³⁸ Particle number, size distribution, morphology, polymer composition, surface chemistry, and environmental transformation may all influence exposure relevance.

Broader international and national policy initiatives have similarly focused on product restrictions, waste reduction, and source control, while the incorporation of human-health evidence remains uneven.^{139–141} Current measures primarily control sources rather than airborne exposure. In the European Union, Commission Regulation (EU) 2023/2055 restricts intentionally added synthetic polymer microparticles, while Regulation (EU) 2025/2365 addresses plastic pellet losses.^{142,143} These measures may reduce emissions indirectly but do not establish specific ambient-air exposure limits for microplastics.

The absence of standardized sampling, identification, and exposure metrics remains a major barrier to health-based limits. In the short term, source reduction is therefore likely to be more practical than defining ambient-

air thresholds; longer-term regulation will depend on methods that connect atmospheric measurements to particle characteristics relevant to exposure and biological response.

Removal technologies, including advanced adsorption and separation approaches^{144,145}, may complement source reduction, although scalability, cost, sorbent recovery, and environmental safety remain important constraints.¹⁴⁶

7. Conclusions

Microplastics are not confined to aquatic systems but circulate among atmospheric, terrestrial, freshwater, marine, sedimentary, and biological compartments. Along these trajectories, transformation can alter the properties presented to organisms. The resulting state at exposure therefore provides a useful link between environmental history and variability in biological effects, while also highlighting the limits of extrapolating from pristine, standardized particles.

Future assessment should integrate transport, particle state, exposure pathway, and biological context rather than treating occurrence in individual compartments as the endpoint. This trajectory-aware view captures why microplastics are more than water contaminants and provides a more environmentally realistic basis for ecological and human-health risk interpretation.

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Conflict of interest

The authors declare no conflicts of interest.

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