Microplastic Contamination in Freshwater and Marine Ecosystems: Sources, Fate, and Ecological Impacts

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Abstract
The problem of microplastic pollution has now become an iconic force upon freshwater and marine environments as plastic debris is constantly broken down, moved, deposited, and biologically interacted with across linked aquatic environments. This narrative review is a synthesis of peer-reviewed information on the significant sources, environmental fate, and ecological effects of microplastics in rivers, lakes, estuaries, coastal waters, open oceans, sediments, and biota. This review states that microplastics cannot be considered as a homogenous contaminant, but rather a heterogeneous collection of particles that behave and pose risks in response to polymer chemistry, size, shape, density, weathering condition, additives, biofouling, and sorbed pollutants. The main input sources include land-based leakage, wastewater effluents, stormwater runoff, atmospheric deposition, textile fibers, packaging waste, and fishing-related materials. Upon release, particles are transported redistribution by hydrodynamic transport, by sedimentation, by resuspension, by aggregation, by biofouling, by ingestion, by egestion, and by trophic interactions. The strongest evidence of ecological effects with respect to ingestion, feeding interference, oxidative stress, retarded growth, disturbed reproduction, and contaminant-vector mechanisms is provided by some experimental conditions. Nonetheless, interpretation of risk is limited by inconsistent sampling, detection limits of variables, lack of polymer confirmation and poor comparability of laboratory exposures with environmental concentrations. The review determines priority research requirements categorized into harmonized monitoring, freshwater sediment risk assessment, nanoplastic detection, chronic mixture toxicity and source-focused mitigation.

Keywords: Microplastics, freshwater ecosystems, marine pollution, ecological risk, bioaccumulation, wastewater, sediment

1. Introduction

Plastic pollution is no longer an observable litter problem but a diffuse issue of particle pollution that connects urban consumption, industrial production, waste control, hydrology, ocean circulation, and exposure to food-webs. Microplastic is sometimes referred to as the plastic particles less than 5 mm in size, yet this straightforward description suggests a lot of complexity. A clear fiber shed off a garment, a thick polyvinyl chloride fragment in a body of water, a floating sheet of polyethylene, and a worn point of paint on a boat hull could all be considered microplastics, yet their movement, pathways of exposure, and biological impacts vary widely. This review thus considers microplastics as a category of contaminants instead of a homogenous pollutant (Hartmann et al., 2019; Rochman et al., 2019).

Both scale and persistence form the scientific concern. The scale of global plastics production, use, and waste has increased exponentially since the middle of the twentieth century, and recycling and regulated end-of-life management have not kept up with the production (Geyer et al., 2017). Another significant origin of plastic leakage to the ocean is mismanaged waste on land, especially in the areas where population density, closeness to the coast, and inadequate waste-management intersect (Jambeck et al., 2015). Rivers are subsequently transfer corridors between the sources on land and the sinks on the sea, though the intensity of emissions can differ greatly across catchments and depends on hydrology, settlement patterns, dams, flood pulses, and the linkage of waste to rivers (Lebreton et al., 2017; Schmidt et al., 2017). As a result of this, freshwater systems are not only conduit to the sea, but also an exposure environment unto themselves (Wagner et al., 2014; Eerkes-Medrano et al., 2015; Horton et al., 2017).

The first observed problem was through marine studies. Initial clues indicated that small pieces and strands of plastics were found in ocean waters and sediments yet the question was where the rest of the mass of floating plastics were (Thompson et al., 2004). Later literature reported accumulation in the subtropical gyres, open-ocean surface waters, coastal areas, and deep-sea conditions (Law et al., 2010; Cózar et al., 2014; Eriksen et al., 2014; van Sebille et al., 2015; Kane et al., 2020). But the sea surface is not the sole aspect to the story. Microplastics are also present in river water, lake water, wastewater effluents, sediments, snow, atmospheric fallout, and aquatic life (Allen et al., 2019; Koelmans et al., 2019). Such connectivity renders microplastic pollution very hard to control since the particles are manufactured by numerous daily operations, penetrate the environment via numerous small routes, and endure long enough to be re-distributed several times.

This narrative review aims to provide a synthesis of the literature on the sources, fate, and ecological effects of microplastics in both freshwater and marine ecosystems, and to focus on contentious aspects of the topic. The review is not presented in the form of a catalogue of separate findings. Rather, it builds a narrative case based on three tensions that inform contemporary knowledge: first, the tension between apparent global ubiquity and local risk uncertainties; second, the tension between laboratory manifestations of biological action and uncertainties about environmental reality; and third, the tension between the rapid proliferation of monitoring research and methodological inconsistency. Such tensions are relevant since the assessment of risks and mitigation upon risk assessment rely not only on the presence of microplastics but on the nature of these particles, their location, the organisms they come into contact with, and the ecologically significant scenarios of exposure.

2. Review Scope and Conceptual Framing

The present paper is structured as a narrative review that is appropriate in case of a general synthesis of the environment. Peer-reviewed studies on aquatic microplastics are preferred in the review; however, preference is given to those published in the past 10 years and those foundational articles that defined the core concepts, definitions and methods. The evidence base comprises of global production and leakage estimates, freshwater and marine occurrence studies, wastewater and river transport studies, methodological reviews, ecotoxicological experiments, trophic-transfer studies, and risk-assessment frameworks. Due to the variability of the sampling volume, mesh size, digestion procedure, density separation, polymer confirmation, and reporting unit, the review treats evidence cautiously as opposed to considering all the concentration values directly comparable (Hidalgo-Ruz et al., 2012; Prata et al., 2019; Koelmans et al., 2020).

One of the major conceptual decisions is to refer to microplastics as environmental particles and not a single chemical compound. The common starting point of the traditional chemical risk assessment is a compound, a concentration and a dose-response relationship. Microplastics dispute this model since toxicological unit can be the number of particles, their mass, surface area, shape, or chemical composition, and different organisms are exposed to various fractions of the particle spectrum. The fibers have the ability to entangle or go through feeding structures in different ways compared to the spheres. The fragments can be more sharp-edged, uneven in aging, and more heterogeneous in appearance. Heavy polymers will tend to sediment, whereas lightweight polymers can remain at the surface until they become biofouled, aggregated, or physically weathered to change their buoyancy. This is one reason why particle-alignment strategies and multidimensional risk models that align exposure data with effect data by size, shape, polymer type, and density have been proposed by some authors (Hartmann et al., 2019; Koelmans et al., 2020; Koelmans et al., 2022).

The review differentiates sources, pathways, fate processes, and ecological impacts as well. A source is a store or material pool that produces microplastics, including synthetic fabrics, vehicle tires, packaging, fishing equipment, wastewater sludge, personal care products or degraded macroplastic debris. The route through which particles enter the aquatic systems is referred to as a pathway e.g. wastewater discharge, stormwater, river flow, atmospheric deposition, beach erosion or direct loss in the marine. Fate is defined as the behavior that takes place in the environment following release such as transport, fragmentation, settling, resuspension, burial, ingestion, egestion, aggregation, and degradation. Impact The biological or ecological consequence, which may include particle ingestion and tissue interaction, altered feeding, growth, reproduction, survival, immune response, oxidative stress, trophic transfer, and ecosystem-function changes.

This framing aids in the prevention of two possible simplifications. The former is the supposition that all microplastics detected are associated with the same degree of ecological hazard. Risk assessment requires detection, but it is not enough to have been harmed. The second is the converse belief that it is not clear that populations are harmed on a large scale, so microplastics are not ecologically significant. Numerous aquatic ecosystems are exposed to various stressors such as warming, eutrophication, chemical pollution, hypoxia, overfishing, habitat modification, and invasive species. Microplastics can have chronic, sub lethal, context-specific actions that are hard to confound in field experiments. The weighted evidence-based view is thus the most balanced: microplastics are ubiquitous, a number of organisms can consume them, certain experimental studies demonstrate negative outcomes, and the biggest gap in knowledge is to harmonize real-life exposure with biological endpoints.

3. Sources and Entry Pathways

Microplastic pollution starts with the life cycle of plastic substances. Ultraviolet exposure, mechanical abrasion, thermal stress, oxidation, and biological surface weathering cause large plastic objects to break down into secondary microplastics. Packaging containers, single-use consumer goods, agricultural wrapping, building materials, and untreated waste are thus long-term even when they find their way into the environment as macroplastics. Andrady (2011) highlighted the fact that weathering causes plastics to be brittle and vulnerable to disintegration, especially in areas with high-light and high-abrasion environments such as beaches, coastlines, and surface waters. Browne et al. (2011) also proved the geographically extensive contamination of shorelines with microplastics and that fibers constituted a significant portion, which connected the pathways of particle pollution to consumer textile sources and wastewater.

The world-wide issue of microplastics is land-based leakage. Jambeck et al. (2015) estimated massive discharges of plastic waste by the coastal communities into the ocean and indicated that the capacity of waste management has a strong impact on the environmental leakage. Geyer et al. (2017) put this within the context of the material flow in a larger scope by reporting the magnitude of plastic production, use, and disposal. Their significance in freshwater systems is as high as in marine systems and these studies are frequently mentioned in the context of marine plastic loads. Plastics mostly find their way into rivers, drains, canals, floodplains, and lakes before accessing the coastal waters. Rivers are not simple pipes; they may store, disintegrate, bury, remobilize and transform particles. Lebreton et al. (2017) and Schmidt et al. (2017) have river-emission models that are different in assumptions and estimates, but both contribute to the conclusion that river networks are significant transport routes of plastic with high spatial heterogeneity.

Another significant pathway is wastewater treatment plants since they take the particles of the household laundering, personal care products, industrial sources, urban runoff, and sewer networks. Research indicates that a significant portion of influent particles are removable during treatment processes in particular by skimming, settling, and capturing sludge, although effluent still may release microplastics to receiving waters due to even low concentrations becoming significant when multiplied by large volumes of discharge (Murphy et al., 2016; Mason et al., 2016; Carr et al., 2016). Mintenig et al. (2017) justified the importance of spectroscopic validation in the study of wastewater effluents and indicated that small particles should be subject to special analytical procedures. The second avenue is wastewater sludge since the captured particles can be relocated to the soils through biosolids application and subsequently move to erosion or drainage.

Atmospheric deposition makes the picture of the source even more complicated. Fibers and fragments may be carried by air and settled in distant catchments, snowpacks, lakes and marine surfaces. Allen et al. (2019) found deposition of microplastic in the atmosphere in a remote mountain catchment, which means that even aquatic systems located far away can get particles even when no visible local sources are present. The pathway is particularly applicable to headwater streams, alpine lakes, reservoirs, and polar settings where diffuse loading may be continuous due to atmospheric fallout of direct waste sources, which can be low.

Marine sources encompass fishing equipment, aquaculture equipment, ship paint, ropes, nets, foams, cargo damages, and direct littering. But in estuaries and coastal waters there is a tendency to lose the distinction between freshwater and marine sources. Estuaries are areas of convergences where the particles carried by rivers meet the tides, salinity gradients, suspended sediment, and biological productivity. Aggregation, settling, and biological uptake can be encouraged under these conditions. In such a way, the management approaches, that concentrate on beaches or open-ocean cleanup, overlook upstream sources, whereas the management approaches, which concentrate on wastewater, overlook stormwater, road runoff, fishing, and atmospheric deposition. The source literature thus indicates prevention across various stages of the plastic life cycle such as product design, waste collection, control of textile emissions, storm water harvesting, upgrades in wastewater as well as riverine litter interception.

Table 1. Major source categories and aquatic entry pathways for microplastics.

Source category	Representative pathway	Likely particle types	Management implication
Mismanaged packaging and consumer waste	Fragmentation in streets, drains, rivers, beaches, and coastal waters	Fragments, films, foams	Improve waste collection, reduce single-use leakage, intercept riverine litter
Synthetic textiles	Laundry wastewater, sludge, indoor/outdoor air, stormwater	Fibers	Textile design, washing-machine filters, wastewater and sludge controls
Wastewater systems	Effluent discharge and biosolids reuse	Fibers, fragments, beads	Treatment optimization, sludge management, source control
Road runoff and urban dust	Stormwater, drainage networks, atmospheric deposition	Rubber-like particles, fibers, fragments	Stormwater capture, street sweeping, tire and road-wear reduction
Fishing, aquaculture, and maritime activity	Direct loss, abrasion, gear degradation	Rope fibers, net fragments, paint particles	Gear retrieval, port reception, durable gear design

4. Fate and Transport in Freshwater and Marine Ecosystems

Once released, microplastics are transported by the aquatic systems based on the interacting physical, chemical and biological mechanisms. The density of the particles is significant, and it is not fate. Polymers of low density like polyethylene and polypropylene can easily be floated whereas more dense polymers like polyvinyl chloride and polyethylene terephthalate can be easily sunk. However, field data demonstrates microplastics in the surface waters, water columns, sediments, biota, snow, and seafloor deposits. Density alone cannot explain this distribution. Fate is determined by particle size, shape, roughness, biofilm development, mineral binding, fecal-pellet integration, aggregation with organic matter, hydrodynamic turbulence, and seasonal flow regimes (Eerkes-Medrano et al., 2015; Horton et al., 2017; Koelmans et al., 2019).

Freshwater systems are dynamic retention and change areas. Rivers can be high and be able to move the particles and be low and be able to deposit particles in the bed sediments, banks, macrophyte beds, reservoirs and floodplains. Lakes and reservoirs can be sinks since water residence time can permit settling and biological processing, but particles can be remobilized by stratification, storms, inflow pulses, and sediment disturbance. Freshwater sediment is of particular interest since most of the types of particles are deposited there, however, the monitoring of sediments is not as harmonized as surface-water sampling. Early gaps in knowledge of freshwater were identified by Wagner et al. (2014), Eerkes-Medrano et al. (2015), and Horton et al. (2017), and most of the gaps persist to today: long-term monitoring is not conducted, small particles are frequently undersampled, and methodological challenges of risk assessment of the sediment persist.

There are zones of surface accumulation that are very obvious in the marine systems, however, they only constitute a part of the overall plastic burden. Studies in the North Atlantic and the global ocean using surface-trawls have determined that buoyant plastics concentrate in the gyres and convergence areas (Law et al., 2010; Cózar et al., 2014; Eriksen et al., 2014; van Sebille et al., 2015). The question however is repeatedly why measured floating stocks are less than cumulative inputs would suggest. One solution is that particles detach the surface by fragmenting below detectable limits, biofouling and sinking, ingestion and fecal-pellet transport, beaching, deep-water transport or sediment burial. Kane et al. (2020) demonstrated that deep-sea circulation may produce seafloor microplastic hotspots, refocusing on benthic storage and exposure.

Biofouling is one of the major fate processes as colonization by microbes transforms particle density, surface chemistry, and ecological identity. When a clean plastic surface is added to water, it quickly conditions with the dissolved organic matter and is colonized by microbial communities. This biofilm has the potential to enhance sinking, aggregation with suspended sediment, contaminant sorption, and predispose particles to ingestion by organisms responding to biofilm cues. On the other hand, the biofilm may be removed down the stream by physical abrasion and some particles may become buoyant again through grazing. This cycle suggests that microplastics can travel in the same direction (vertically) more than once instead of being transported in a single direction (surface to seabed).

The fate of chemicals is also intricate. Microplastics consist of additives like plasticizers, stabilizers, pigments, flame retardants and leftover monomers and are able to absorb hydrophobic pollutants in the water around them. The significance of microplastics as vectors of contamination is a controversial topic. Rochman et al. (2013) presented experimental data that consumed plastic may translocate toxic chemicals into fish and cause hepatic stress. Nevertheless, Koelmans et al. (2016) reasoned that the effect of the vectors should be viewed as per the already existing contaminant routes, gut environments, polymer character, and concentrations in the environment. Natural particles, dissolved organic matter, sediment, and food may in most instances prevail in contaminant exposure. Hence, the most robust conclusion is not that microplastics necessarily lead to chemical bioaccumulation, but that it can alter contaminant exposure in some polymer-pollutant-organism-gut chemistry combinations.

The destiny literature is in favor of a systemic perspective: microplastics are not confined to a single compartment. These are recycled between surface water, suspended material, sediment, life and atmospheric inputs. They also penetrate freshwater-sea ecosystems. This cycling is the reason why it is hard to mitigate once it is out. Once the particles break up into different sizes and find their way into sediments or into biological channels, they become difficult to remove both technically and ecologically. Prevention would thus be more effective than attempting to extract diffuse microplastics in water bodies.

Table 2. Fate processes that control microplastic distribution across aquatic compartments.

Fate process	Dominant mechanism	Ecological relevance	Key uncertainty
Fragmentation	UV exposure, abrasion, oxidation, mechanical stress	Increases particle number and small-particle availability	Rates under field conditions and lower size limits
Biofouling	Microbial colonization and organic coating	Alters buoyancy, palatability, aggregation, and sinking	Reversible fouling and organism-specific ingestion cues
Sedimentation and burial	Density, aggregation, fecal pellets, low-flow zones	Creates benthic exposure and long-term storage	Sediment monitoring comparability
Resuspension	Floods, storms, dredging, bioturbation	Moves particles from sediments back into the water column	Event-based sampling is limited
Ingestion and egestion	Feeding, sediment intake, prey transfer	Connects particles to organisms and food webs	Retention time, translocation, and chronic cost

5. Occurrence in Biota and Ecological Exposure

Microplastics reach aquatic organisms in multiple pathways, which include: filter feeding, suspension feeding, deposit feeding, predation, drinking, ventilation, ingestion of contaminated surfaces, and ingestion of contaminated sediments.

Taxa are not evenly exposed. Filter feeders (bivalves and zooplankton) are frequently emphasized since their feeding behavior predisposes them to ingest particles. Deposit feeders and benthic invertebrates might come across sediment-related microplastics whilst fish can ingest the particles directly, in prey and by confusing them with food. The presence of microplastics in Chinese commercial bivalves reported by Li et al. (2015) is often referenced due to the evidence of both biological uptake and amenability to seafood pathways, although the human dietary risk that microplastics may cause needs further exposure evaluation.

Initial laboratory research indicated that microplastics can pass through food webs. Setael et al. (2014) showed ingestion and transfer in a planktonic food-web system, whereas Farrell and Nelson (2013) showed trogic transfer between mussels and crabs. The significance of these studies lies in the fact that they demonstrated that microplastics are not ingested and forgotten. Meanwhile, trophic transfer cannot be construed as automatic biomagnification. In contrast to dissolved chemicals that accumulate in the tissue, most microplastic particles could be egested, kept temporarily in the gut or translocated under some conditions of size and biology. Ecological definition of trophic transfer is thus based on retention time, particle size, tissue translocation, feeding rate, prey load, and physiological cost.

The best and most robust biological evidence is in regard to ingestion and sublethal responses. Wright et al. (2013) examined physical effects on marine organisms, such as decreased feeding, energy redistribution, gut obstruction, and false satiation. Subsequent syntheses discovered that the effects of microplastic are not consistent in taxa or endpoints. Foley et al. (2018) have documented that exposure can impact consumption, growth, reproduction, and survival in fish and aquatic invertebrates, but also reported high heterogeneity in the literature. de Sá et al. (2018) reported that high heterogeneity in the literature is because many experiments used particle types, concentrations, or exposure regimes that are challenging to relate to the environment. Similar arguments were made by Burns and Boxall (2018), who claimed that there is evidence of adverse effects, whereas there are significant gaps in knowledge about environmentally realistic exposure, chronic effects, and population-wide impact.

Invertebrates in freshwater have emerged as popular model systems in microplastic ecotoxicology. Rehse et al. (2016) demonstrated that at the short-term level, high concentrations of pristine particles cause immobilization of the larvae of the crustacean, Daphnia magna. This can be used to determine potential mechanism but the applicability of such results in the environment will be determined by how well the test particles match the field particles in terms of size distribution, weathering, biofilm condition and concentration. Recent meta-analytical studies have tried to differentiate the effects of microplastic particles and generic particle effects by comparing plastics to natural particles. Doyle et al. (2022) discovered that exposure to microplastics in aquatic invertebrates may produce severe negative effects to natural particles and some endpoints, in particular, but the literature is marked by inconsistency in experimental design and reporting.

Another key exposure group is the benthic organisms. Besseling et al. (2013) studied responses to the lugworm Arenicola marina and demonstrated that microplastics are capable of mediating endpoints of fitness and contaminant interactions. Benthic exposure is ecologically significant in that, sediments serve as a key sink, and benthic animals aid nutrient cycling, sediment mixing and food-web transfer to fish and birds. However, surface waters continue to be of great interest to many monitoring programs due to easier sampling and the visibility of floating plastics. This leads to a disproportion between the locations that particles can be concentrated and locations of greatest evidence.

Modes of action should be used to interpret the ecological effects of microplastics. Physical modes involve gut filling, abrasion, blockage, disturbed feeding, and decreased energy intake. Chemical modes consist of additive leaching, the transfer of contaminants in the form of sorbs, and polymer associated toxicants. Biological mechanisms consist of microbial colonization, pathogen transportation, immune stimulation, oxidative stress, and natural food contact. These modes may be overlapping. As an example, a biofouled fiber could have increased chances of ingestion, it could have additives, it could sorb pollutants and it could physically engage with feeding structures. All the particles will not, however, all have the same effect. The variation of particles is the reason why seemingly contradictory results can be found in the literature.

Table 3. Ecological impact themes reported in aquatic microplastic research.

Impact theme	Typical evidence	Example organisms or systems	Interpretive caution
Ingestion	Particles detected in gut or tissues	Bivalves, zooplankton, fish, benthic worms	Ingestion does not always equal retention or harm
Feeding and energy effects	Reduced intake, false satiation, altered assimilation	Filter feeders, deposit feeders, zooplankton	Food availability can modify responses
Growth and reproduction	Reduced growth, fecundity, or offspring quality	Aquatic invertebrates and fish models	Often concentration and particle-type dependent
Chemical interaction	Additive leaching or sorbed contaminant transfer	Fish, worms, sediment organisms	Vector effect may be smaller than other exposure pathways

Impact theme	Typical evidence	Example organisms or systems	Interpretive caution
Trophic transfer	Movement from prey to predator	Planktonic food webs, mussel-crab systems	Transfer is not the same as biomagnification

6. Methodological Inconsistencies and Risk Interpretation

The biggest drawback of the microplastic literature is not that there are no studies; it is that there are no comparative studies. Concentrations are expressed as particles/liter, as particles/cubic meter, particles/kg dry weight, particles/g tissue, mass concentration or as surface area. Sampling equipment can be differentiated in terms of mesh size, pump volume, trawl aperture, net material, flow measurement and contamination control. Different procedures used in laboratories differ in the digestion chemistry, density-separation solution, filtration material, visual sorting, spectroscopic confirmation, and lower size limit. These variations have a dramatic effect on the reported concentrations and particle profiles (Hidalgo-Ruz et al., 2012; Prata et al., 2019).

Quality assurance is particularly necessary due to the fact that fibers are readily contaminated in samples taken of air, clothing, laboratory equipment, and procedural materials. Occurrence values are misleading with a lack of field blanks, procedural blanks, polymer confirmation and the provision of transparent report of detection limits. Koelmans et al. (2019) compared the quality of data in freshwater and drinking-water research and demonstrated that reliability of specific concentrations reported is strongly determined by the sampling design and the rigor of analytical methods. This has an implication on narrative synthesis: experiments with smaller lower size limits and confirmation procedures cannot be compared as though they are measuring the same particle universe.

One of the significant points of uncertainty is particle size. Nets used in many field studies in the past missed small microplastics and nanoplastics. However the smaller particles can be more abundant and accessible to plankton, filter feeders and early life stages. In contrast, there are larger fibers, which can be the source of mass and can induce physical interactions that are not reflected in particle-number measures. This poses a risk-assessment dilemma: particle number focuses on small particles, mass focuses on larger particles and surface area could be a better measure of sorption or biological interaction. There is no single best metric for all research questions. Koelmans et al. (2020) reasoned that risk can only be characterized consistently when exposure and effect data are in tandem.

The second challenge to laboratory toxicity studies is environmental realism. The pristine spherical polystyrene beads are many times used in experiments due to their commercial availability and easy characterization. Irregular fragments, fibers, films, foams, paint particles, tire-related particles and weathered mixtures are also field particles, however. They can be biofouled, oxidized, cracked, additive-laden or related to organic matter. The concentrations employed in laboratory experiments may be orders of magnitude higher than real-world environments, but even high-concentration experiments can provide insights. The issue is that mechanistic hazard studies were not done as field risk direct evidence when they are not aligned with exposure.

Risk assessment is starting to react to these problems. Koelmans et al. (2022) suggested a framework, which considers the microplastic particles as a variety of materials, where exposure distributions and effect thresholds need to be aligned. These frameworks move the field beyond the question of whether microplastics are present or not and to the question of which particle fractions are likely to be harmful in realistic exposure conditions. This is a requisite action to policy, since management decisions must be prioritized.

Ecological scale must also be taken into account in risk interpretation. Population decline is not necessarily caused by an organism level effect like decreased feeding, but can occur based on how long they are exposed, available food, compensatory feeding and predation, reproduction, and other stressors. On the other hand, minor sublethal impacts on a large number of people can be significant as they are added to warming, hypoxia, pathogens, or chemical contamination. The best evidence is at organism and suborganism level and less at population, community and ecosystem levels. This is not to say that there is no ecosystem risk; it is merely that the discipline is not yet in a position to accumulate enough field-realistic, long-term evidence to quantify ecosystem impact in a confident way.

The most justifiable synthesis is thus tentative and not cynical. Microplastics are ubiquitous, omnipresent, and biologically accessible. Particles may be harmful, particularly when exposed to high levels, when they are small, irregularly shaped, contain chemicals, or when they are in the sensitive growth phase. Still the sweeping statements about the devastating ecological harm are more than the existing data. Similarly, arguments of microplastics being harmless due to high concentrations not being harmful in many experiments overlook the fact that it is challenging to determine the effects of microplastics chronicity, mixtures, and sediments. The literature promotes specific care, enhanced methodology, and source minimization.

7. Discussion and Synthesis

The microplastics literature has reached the stage of presence description to the level of challenging the mechanisms, comparability, and risk. This change is noteworthy. Initial studies determined that microplastics are present in the water, coastlines, organisms and sediments (Thompson et al., 2004; Cole et al., 2011). Subsequently, the geography and compartments were extended to freshwater systems, wastewater effluents, remote catchments, atmospheric deposition and deep-sea sediments (Wagner et al., 2014; Mason et al., 2016; Allen et al., 2019; Kane et al., 2020). The issue at hand is to transform occurrence data into ecological knowledge.

One of the main syntheses is that freshwater and marine systems are to be considered as a part of a single plastic cycle. Urban, agricultural, industrial, atmospheric, and wastewater are input to freshwater systems. They hold particles in sediments and biota besides transporting particles to the downstream. In estuaries, salt causes the flocculation of particles, tidal mixing, and sedimentation, which is the filtering, transformation, and redistribution of particles. There is both riverine and direct marine input to the coastal waters. Gyres in open oceans concentrate the buoyant plastics, and deep-sea currents and sediment form benthic hotspots. This connectivity implies that interventions in a single compartment will be incomplete.

The second synthesis point is that ecological risk is particle specific. The term microplastic contamination is a good concept to communicate to the public, however, it may blur the scientific lines. Fibers, fragments, films, foams, beads and tires wear particles vary in their source, transport and interaction with the organisms. Small particles can be more bioavailable; however, large fibers can be more likely to cause physical interference with feeding or digestion. Buoyant particles can cause exposure of neustonic organisms whereas dense or biofouled particles expose benthic organisms. Risk assessment should therefore shift the focus away form overall counts and towards particle profiles.

The third synthesis is that methodological improvement is not a technical aspect; it is at the heart of ecological inference. Experiments using varying mesh size, lower limits of analysis and confirmation rates of polymer can seem to contradict each other when in fact they are measuring varying particle fractions. Equally, the results of toxicity tests on pure spheres might not be applicable to weathered fibers and irregular fragments. The discipline requires a set of harmonized reporting standards, yet it must have means, which are flexible enough to reflect actual environmental diversity. An individual standardized particle can be useful in comparing laboratory experiments, but it cannot be representative of the entire spectrum of microplastic exposures in the environment.

A second synthesis is that ecological interpretation ought to be place-based. Identical particle concentration can be taken to imply different things in a rapid flowing river section, a stratified lake, an urban estuary, a mangrove sediment, a coral lagoon or a deep-sea channel. Exposure is affected by hydrodynamics, residence time, organic matter, salinity, sediment grain size, biological community structure, and existing stressors. As such, the management must not use risk language that fits all. The low concentration in a sensitive nursery habitat could be important to a larger extent than a higher concentration in a more robust or fast-flushed environment. In the same way, a particle profile consisting of persistent fibers can potentially need a different intervention method compared to a particle profile consisting of packaging fragments or tire-related particles. This place-based interpretation is particularly significant to developing nations and highly populated coastal areas where waste facilities, flooding, wastewater release, and informal waste management interactions may occur.

Lastly, the literature indicates that a reduction in sources is more feasible than an environmental elimination. When microplastics have been scattered along rivers, sediments, water columns, snow, organisms and seabed deposits, it becomes extremely hard to recover. Increased treatment of wastewater will decrease one of the pathways, but will not apply to stormwater, tire wear, abandoned equipment, packaging leakage, or atmospheric deposition. Redesign of products, control of textile fibers, enhanced waste collection, prohibition of unnecessary primary microplastics, stormwater treatment, management of fishing-gear, and circular material systems is thus the best logic of mitigation. This reasoning needs to be backed by ecological studies that determine what sources add the most detrimental particle fractions, not the largest particle counts.

8. Research Gaps and Future Directions

The science of microplastic has a number of research gaps that restrict its role in management of aquatic. To begin with, small-particle and nanoplastic detection has always been a gap. Numerous monitoring techniques do not resolve particles smaller than typical mesh or filter sizes, but which can be biologically significant. The future work requires validated, contamination-controlled, polymer-specific techniques of small microplastics and nanoplastics in water, sediment, and tissues. The lower size limit, blank correction, recovery efficiency, polymer-confirmation rate and unit conversions should also be recorded in monitoring designs to enable risk assessment to be conducted later by judging the strength of the evidence rather than merely extracting a number.

Second, freshwater sediment risk is not yet developed. Microplastics can be kept in rivers, lakes, reservoirs, wetlands, and estuaries, but the technologies of sediment and risk levels are not as well-developed as water-column surveillance. Benthic organisms (worms, insect larvae, amphipods, and bivalves) require more consideration since they are exposed to deposited particles and connect sediments to higher troic levels.

Third, laboratory experiments require increased realism in the environment. This is not to say that controlled particles should no longer be used in mechanistic experiments. Instead, environmentally-relevant mixtures of particles, weathered materials, fibers and fragments, biofouled particles, natural-particle controls, chronic exposure times, and realistic food conditions should be used in hazard testing. Investigations are expected to provide particle size distributions, polymer identities, additives, concentrations using various measures, and contamination controls.

Fourth, mixture effects are languidly comprehended. Microplastics are present with metals, pesticides, persistent organic pollutants, pharmaceuticals, nutrients, pathogens, and climate stressors. This complexity cannot be reflected in single-particle experiments. Further research must consider microplastics as one of the multi-stressor conditions, particularly in situations where the organisms are already experiencing warming, hypoxia, salinity shift, or eutrophication.

Fifth, there is low ecological scaling. Numerous experiments assess ingestion, oxidative stress, gene expression, feeding or reproduction in short-term experiments, but fewer link these outcomes with population growth, community structure, ecosystem functioning or services like fisheries productivity and nutrient cycling. This gap needs to be filled by long-term mesocosm studies, field experiments, and ecological models.
Sixth, the source apportionment should be enhanced. The management needs to know the sources that prevail in adverse exposures. Identifying polymers is not necessarily sufficient since the same polymer could be used in packaging, clothing, fishing equipment, or industry. Attributing sources can be enhanced by integrating polymer chemistry, particle morphology, additives, spatial analysis, hydrological modeling, and material-flow data.
Another gap is related to intervention evaluation. Many microplastic studies conclude by suggesting the adoption of better waste management, wastewater treatment, stormwater management, textile-fiber and fishing-gear recoveries, yet less frequently quantify particle profiles prior to and following interventions. Before-after-control-impact designs should also be used in future research where feasible. These designs would be able to test whether policy actions are lowering the fraction of the particles most likely to be of ecological importance, and not just the amount of visible litter or the overall mass of plastic. This is particularly significant since mitigation activities have the potential to transfer particles across compartments. As an illustration, wastewater treatment can decrease the discharge of effluent and concentrate particles in sludge, and shoreline cleanups can eliminate large debris prior to fragmentation but not small particles. Microplastic research could be more helpful to regulators and water managers through intervention science.
Seventh, there is an uneven global coverage. A lot of research is based in Europe, China, and North America, with data on sections of Africa, South Asia, Latin America, small island states, and river-delta areas being scarce. This is a significant gap since the waste-management conditions, monsoon hydrology, informal recycling, population density in the coast and fisheries practices vary strongly across regions. There is the need to have more locally based studies but the studies should be based on internationally comparable reporting frameworks.

Table 4. Priority research gaps and practical next steps.

Gap	Why it matters	Recommended direction
Small microplastics and nanoplastics	Current methods often miss the most numerous particle fractions	Develop validated spectroscopic and mass-based methods with clear detection limits
Freshwater sediment risk	Sediments are major sinks and exposure zones	Standardize sediment extraction, reporting units, and benthic endpoints
Environmental realism in toxicity tests	Pristine spheres often poorly represent field particles	Use weathered fragments, fibers, mixtures, biofilms, and natural-particle controls
Ecological scaling	Sublethal effects are difficult to translate to populations	Link organism endpoints with mesocosms, field data, and population models
Source apportionment	Mitigation requires identifying dominant harmful sources	Combine polymer chemistry, morphology, additives, hydrological models, and material-flow data

9. Conclusion

Microplastic contamination in freshwater and marine ecosystems is best understood as a connected, multi-source, multi-compartment, and multi-particle problem. The evidence is strong that microplastics are widespread, persistent, and biologically available across aquatic systems. Land-based waste leakage, wastewater and stormwater pathways, textile fibers, atmospheric deposition, river transport, fishing activities, and fragmentation of larger plastics all contribute to exposure. Once released, microplastics undergo transport, deposition, resuspension, biofouling, aggregation, ingestion, egestion, and burial, making their environmental fate difficult to reverse.
The ecological evidence supports concern but also demands precision. Microplastics can be ingested by diverse organisms and can affect feeding, growth, reproduction, survival, oxidative stress, and contaminant exposure under some conditions. However, the strength of inference varies by particle type, organism, endpoint, and exposure realism. Methodological inconsistency remains a major barrier to comparing studies and defining risk thresholds. Therefore, the next phase of microplastic research should prioritize harmonized monitoring, exposure-effect alignment, sediment and benthic risk, environmentally realistic experiments, and source-specific mitigation. The review also shows that evidence should be interpreted through a balanced lens: uncertainty should not be used to delay prevention, but concern should be expressed with enough specificity to guide action. The most useful future studies will connect particle profiles to sources, realistic exposure, sensitive organisms, and measurable ecological outcomes. Preventing

emissions at source is likely to be more effective than attempting removal after particles are dispersed across aquatic ecosystems.

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