Distribution Characteristics and Ecological Effects of Microplastics in Freshwater Environments

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Abstract: Microplastics have become widely distributed in rivers, lakes, and sediments and can be ingested by aquatic organisms. Drawing on surveys of representative lakes and urban water bodies as well as zebrafish experiments, this paper analyzes the sources, transport and environmental fate, spatial variation, and ecological effects of microplastics. Available evidence indicates that their distribution is jointly controlled by human activities, hydrodynamic conditions, particle size, and biofilm formation. Fibers and small particles are particularly common. Microplastics can cause tissue accumulation, oxidative stress, and metabolic disturbances, although substantial differences remain between laboratory exposure conditions and actual environmental scenarios. Future research should standardize monitoring methods, strengthen long-term multimedia investigations, and validate risks at environmentally relevant concentrations.

Keywords: microplastics; freshwater environment; distribution characteristics; ecotoxicity; risk assessment

Introduction

Microplastics are generally defined as plastic particles smaller than 5 mm. They include primary microplastics manufactured at microscopic dimensions and secondary microplastics generated through the fragmentation of larger plastic items under irradiation, mechanical abrasion, and oxidation. Compared with marine environments, freshwater systems directly receive land-based particles generated by domestic, industrial, transportation, and agricultural activities. They function both as temporary reservoirs of microplastics and as major transport pathways to estuaries and oceans. An early review reported that microplastics had been detected in freshwaters in Asia, Europe, and North America and could be ingested by freshwater animals belonging to different feeding guilds [1].

Although existing research has demonstrated the ubiquity of microplastics, substantial differences exist among studies in net-mesh size, filtration threshold, digestion method, counting unit, and the proportion of particles subjected to polymer identification. Abundance data should therefore not be ranked or compared without qualification. Laboratory experiments also frequently use uniform, unweathered polystyrene microspheres, whereas environmental particles principally consist of fibers, fragments, and weathered particles. These materials differ in surface properties and bioavailability. On the basis of published environmental surveys and toxicological experiments, this paper summarizes the sources, distribution, and ecological effects of freshwater microplastics and discusses major issues in risk assessment and pollution management.

1. Sources and Environmental Transport of Microplastics

1.1 Principal Sources and Input Pathways

Microplastics in freshwater environments originate from multiple sources. Synthetic fibers released during household laundry and plastic particles from personal-care products and industrial processes may enter wastewater-treatment systems. Although wastewater-treatment plants can retain a large proportion of these particles, continuous discharge in treated effluent and the land application of sewage sludge can still introduce microplastics into the environment. Tire- and road-wear particles generated by transportation enter urban rivers and lakes through rainfall runoff and combined-sewer overflows. Agricultural films, packaging materials, and irrigation facilities produce fragments as they age, and these fragments can migrate through agricultural drainage. Atmospheric deposition also transports lightweight fibers across watershed boundaries. Visible litter along shorelines alone therefore cannot fully explain microplastic loads in water bodies.

Particle morphology and polymer composition can provide clues regarding possible sources, but they should not be used mechanically for source attribution. Polyester fibers may be associated with textile washing; polypropylene and polyethylene fragments may originate from packaging or household products; and tire-wear particles contain rubber and various fillers. Environmental aging alters particle color, density, and infrared spectra, while multiple sources may contain the same polymer. Reliable source apportionment should therefore integrate information on drainage systems, land use, population density, rainfall events, and particle chemistry rather than relying exclusively on color or morphology.

1.2 Transport, Transformation, and Environmental Fate

After entering a water body, particles transition among suspension, sedimentation, and resuspension. Low-density polyethylene and polypropylene generally have a greater tendency to float, but biofilm colonization and aggregation with inorganic particles can increase their effective density and promote sedimentation. High discharge, wind-generated waves, and vessel disturbance may subsequently resuspend deposited particles into the water column. Strong hydrodynamic conditions in rivers facilitate downstream transport, whereas enclosed or slow-flowing lake bays are more likely to become localized sinks.

Ultraviolet radiation and mechanical abrasion cause particles to undergo further fragmentation. Surface cracking and oxygen-containing functional groups consequently increase, altering pollutant adsorption and the probability of biological uptake.

2. Distribution Characteristics in Freshwater Environments

2.1 Spatial Variation

Microplastic abundance is frequently elevated near urban drainage outlets, densely populated shorelines, slow-flowing zones, and tributary confluences. However, spatial patterns are jointly controlled by discharge intensity and hydrodynamic conditions. A survey of 20 urban lakes in Wuhan and urban sections of the Han and Yangtze rivers reported surface-water abundances ranging from 1,660.0 ± 639.1 to 8,925 ± 1,591 items/m³, with the highest abundance occurring in North Lake. Microplastic abundance in the lakes was significantly negatively correlated with distance from the urban center ($p < 0.001$), whereas abundances in the urban sections of the Han and Yangtze rivers were generally lower than those in most of the surveyed lakes [3]. These findings indicate that urban activities provide continuous inputs, whereas dilution and transport in open river channels may reduce local surface-water concentrations.

Seasonal variation must also be considered. Rainfall can wash particles from roads, roofs, and soils into water bodies, increasing short-term inputs. At the same time, high discharge may dilute particle concentrations or transport particles downstream. Longer hydraulic residence times during dry periods can favor localized accumulation. A single sampling event should therefore not be assumed to represent annual conditions. Monitoring programs should cover periods before and after rainfall, wet and dry seasons, and water-level regulation events.

2.2 Occurrence in Different Environmental Media

A survey of Taihu Lake provided multimedia evidence from water, sediments, and organisms. Abundances were 0.01×10^6–6.8×10^6 items/km² in net samples, 3.4–25.8 items/L in surface water, 11.0–234.6 items/kg dry weight in sediments, and 0.2–12.5 items/g wet weight in the soft tissues of Asian clams [2]. The highest value in net samples occurred in the southeastern part of the lake, whereas elevated sediment concentrations were found in the northwestern region. This difference demonstrates that hotspots of surface transport and benthic accumulation do not necessarily coincide.

Table 1. Published Microplastic Abundances in Representative Freshwater Environments

Study area and medium	Abundance range	Principal characteristics
Surface water of Taihu Lake	3.4–25.8 items/L	Fibers and particles measuring 100–1,000 μm were common
Sediments of Taihu Lake	11.0–234.6 items/kg dry weight	More severe contamination in the northwestern region
Asian clams from Taihu Lake	0.2–12.5 items/g wet weight	Confirmed biological ingestion
Urban waters of Wuhan	1,660.0 ± 639.1 to 8,925 ± 1,591 items/m³	Fibers were common, and PET and PP were dominant

Particles in the water column reflect recent inputs and transport conditions, whereas sediments more closely represent an accumulation reservoir over a particular period. Benthic filter feeders integrate bioavailable exposure over a certain timescale. Joint monitoring of these media can help distinguish situations such as “high input–rapid export” and “low water-column concentration–high benthic accumulation.” Microplastic abundance in organisms is also affected by feeding mode, body size, habitat depth, and egestion capacity. A simple organism-to-sediment abundance ratio cannot substitute for research into bioaccumulation mechanisms.

2.3 Particle Size, Morphology, and Polymer Composition

Samples from Taihu Lake were principally characterized by fibers, particles measuring 100–1,000 μm, and cellophane-type materials [2]. Colored plastics and fibers were common in the Wuhan water samples, more than 80% of the particles were smaller than 2 mm, and polyethylene terephthalate (PET) and polypropylene (PP) were the dominant polymers [3]. The predominance of fibers is consistent with inputs from domestic wastewater, textile washing, and atmospheric deposition. Small particles have a greater specific surface area and potentially greater bioavailability.

However, conclusions that small particles are more abundant are also influenced by analytical methods. Net-mesh size determines the lower size limit of particles that can be collected, while microscope resolution and spectroscopic-identification capability affect the confirmation of very small particles. Visual counting alone can result in cellulose fibers, keratinous materials, or mineral particles being misidentified as plastics. Studies should report the minimum detectable particle size, blank contamination, the proportion of particles receiving polymer confirmation, and recovery rates to allow differences in particle size and composition to be interpreted appropriately.

3. Ecological Effects of Microplastics

3.1 Ingestion and Physiological Toxicity

Microplastics can enter aquatic animals through ingestion, filter feeding, and contact with the gills. Larger particles principally remain in the digestive tract, where they may cause abrasion, false satiation, or reduced feeding efficiency. Smaller particles are more likely to cross biological barriers. A zebrafish experiment showed that after seven days of exposure, 5 μm polystyrene particles were detected in the gills, liver, and intestine, whereas 20 μm particles were detected only in the gills and intestine. Both 5 μm microplastics and 70 nm nanoplastics caused hepatic inflammation and lipid accumulation, accompanied by increased superoxide dismutase and catalase activities and disturbances in lipid and energy metabolism [4]. Because the 70 nm particles are classified as nanoplastics, these results principally demonstrate that decreasing particle size can alter tissue distribution and toxicity pathways. They should not be directly equated with the environmental risk posed by microplastics.

Ecological effects depend on particle size, morphology, polymer type, exposure duration, and species. Fibers may cause entanglement and mechanical irritation, while the rough surfaces of weathered fragments may increase contact with tissues. The release of plastic additives and the transport of environmental contaminants by particles may introduce additional chemical stress. Experiments should therefore include material blanks and leachate controls to distinguish effects caused by the particles themselves from those caused by additives and co-occurring contaminants.

3.2 Food-Web Transfer and Ecosystem Effects

Microplastics can be ingested by plankton, benthic invertebrates, and fish and may be transferred across trophic levels through predation [1]. At the individual level, impaired feeding, altered energy allocation, and reduced reproductive investment may affect growth and population recruitment. At the ecosystem level, the effects of particles on microbial biofilms, sediment structure, and benthic-faunal activity may further alter organic-matter decomposition and nutrient cycling.

Nevertheless, caution is required when biomarker responses in individual organisms are extrapolated to community- or ecosystem-level damage. Organisms in the field are simultaneously exposed to changes in temperature, hypoxia, nutrients, and multiple pollutants and may also egest a proportion of ingested particles. Existing evidence strongly supports the conclusion that microplastics can be ingested and can induce physiological responses. However, continuous field data remain insufficient to establish their long-term effects on natural population abundance, community structure, and ecosystem functioning. Risk conclusions should distinguish between the potential for harm and actual environmental risk.

4. Key Issues in Ecological Risk Assessment

4.1 Comparability of Sampling and Identification Methods

Freshwater microplastic research urgently requires standardized procedures for sampling, pretreatment, and reporting. Microplastics in water samples may be reported per unit volume, whereas sediment studies should specify whether abundance is based on dry or wet weight. Studies of biological samples should state whether values are calculated per individual, per unit tissue mass, or per unit volume of digestate. Sampling equipment, laboratory clothing, and airborne fibers can all introduce contamination. Field blanks, procedural blanks, and matrix-spike recovery tests should therefore be included. Particles should ultimately be subjected to Fourier-transform infrared or Raman spectroscopy for polymer confirmation rather than being classified solely according to color and morphology.

Studies should report number concentration, mass concentration, particle-size distribution, and polymer type and should retain original spectra and classification thresholds. Number concentration emphasizes small particles, whereas mass concentration is more strongly influenced by large particles. Reporting both measurements can reduce bias caused by reliance on a single indicator. The minimum detectable particle size should also be standardized or corrected when comparisons are made across regions.

4.2 Differences between Experimental Exposure and Actual Environmental Conditions

Experimental toxicology studies frequently use virgin polystyrene particles of a single size, regular spherical shape, and relatively high concentration. These materials facilitate experimental control but differ from weathered fibers and mixed fragments found in the environment. In natural waters, particle surfaces are covered by biofilms and natural organic matter, which alter ingestion, sedimentation, and contaminant-binding behavior. Risk assessments should prioritize particle-size and concentration ranges identified in environmental surveys, include exposure to weathered particles, fibers, and mixed polymers, and incorporate chronic and multigenerational observations.

When environmental thresholds are derived from experimental effect concentrations, changes in freely suspended particle concentrations caused by sedimentation, aggregation, and ingestion should be considered. Reliable dose–response relationships can be established only when actual particle concentrations in the exposure medium and internal particle burdens are measured simultaneously.

4.3 Combined Pollution and Risk Characterization

Microplastics can adsorb hydrophobic organic contaminants and metals and can also release monomers, plasticizers, and stabilizers. Whether they function as contaminant vectors or sinks depends on environmental concentration gradients, particle aging, and conditions within the digestive system. Comparing particle-associated contaminant concentrations before and after adsorption does not, by itself, reveal the net contribution of microplastics to total biological exposure. Combined-toxicity studies should include contaminant-only, microplastic-only, and combined-exposure groups and should analyze actual doses in the aqueous phase, particle phase, and biological tissues.

Risk characterization can move beyond a single abundance index toward an integrated framework incorporating source intensity, environmental persistence, bioavailability, and evidence of effects. Monitoring frequency should be increased in water bodies near drinking-water sources, important spawning grounds, and sediment-accumulation zones. In low-risk areas where evidence is insufficient, the detection of particles alone should not be used to make definitive claims of ecological damage.

5. Management Approaches and Research Prospects

The management of freshwater microplastics should prioritize source control. Releases of synthetic fibers, single-use plastics, tire-wear particles, and agricultural-film fragments can be reduced through product reduction, more durable product design, laundry filtration, road-runoff management, and agricultural-film recycling. Wastewater treatment should address small particles in treated effluent and the subsequent destination of sewage sludge. Interception systems and source-tracking monitoring should be implemented where appropriate at urban drainage outlets, stormwater-overflow outlets, and intensively used shorelines.

Monitoring systems should expand from surface-water sampling alone to coordinated investigations of water, sediments, and organisms and should establish consistent particle-size classes, quality-control procedures, and spectroscopic-identification protocols. Future research should develop long-term datasets and cross-watershed databases, conduct chronic multispecies experiments at environmentally relevant concentrations, and integrate hydrodynamic modeling, source apportionment, and ecotoxicological results. Evaluations of management effectiveness should likewise extend beyond changes in downstream abundance to include source emissions, trends in sediment accumulation, and biological exposure.

Conclusion

Microplastics in freshwater environments exhibit pronounced differences across space, environmental media, and particle properties. Human activities and discharges determine input intensity, while hydrodynamic conditions, biofilm formation, and sedimentation control transport and environmental fate. Water, sediments, and aquatic organisms together constitute a dynamic exposure system.

Existing experiments have demonstrated that microplastics can be ingested by aquatic animals and can induce oxidative stress, inflammation, and metabolic disturbances. However, their long-term effects on wild populations remain uncertain. Future research should emphasize standardized monitoring, environmentally relevant exposure conditions, identification of combined effects, and long-term multimedia investigations. Source reduction and risk management in priority water bodies should be advanced on the basis of graded levels of evidence.

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