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Microplastic Contamination in Freshwater and Coastal Ecosystems — Spatial Distribution, Polymer Characterisation, and Source Attribution Across Northwestern Europe

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Abstract

Microplastic contamination of freshwater and coastal ecosystems has emerged as a critical environmental challenge, with particles detected in virtually every aquatic matrix sampled globally — from Arctic sea ice to remote mountain lakes — yet the quantitative spatial distribution, polymer composition, and source attribution of microplastic loads across connected freshwater-coastal continua remain incompletely characterised in European contexts. This study presents a systematic multi-site sampling campaign across 84 aquatic monitoring locations in Sweden, the Netherlands, France, and Poland, spanning six water body typologies — urban rivers, peri-urban rivers, rural streams, coastal zones, stratified lakes, and groundwater — sampled seasonally over a two-year period (2022–2023).

A total of 6,482 individual microplastic particles were characterised by attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR) for polymer type identification. Urban rivers showed the highest mean concentrations (1,842 particles/m³) and coastal zones the second highest (2,284 particles/m³), driven by wastewater effluent discharge and urban stormwater runoff. Positive matrix factorisation source attribution identified wastewater effluent (34.2%) and urban runoff (22.8%) as the dominant freshwater microplastic sources. Seasonal variation was significant, with summer concentrations 38–52 percent higher than winter values, consistent with increased recreational plastic use and reduced dilution under lower summer discharge.

Keywords: *microplastics, freshwater contamination, ATR-FTIR, polymer characterisation, source attribution, positive matrix factorisation, seasonal variation, urban rivers, Northwestern Europe, environmental chemistry*

1. Introduction

Microplastics — plastic particles smaller than 5 mm in their largest dimension — have become ubiquitous contaminants in aquatic environments globally since their systematic characterisation in ocean surface waters by Thompson et al. in 2004. The accelerating global production of plastic materials, estimated at 460 million tonnes per year in 2022 with less than 10 percent subject to effective recycling, continuously generates microplastic inputs to aquatic environments through fragmentation of macroplastic litter, direct release of primary microplastics including synthetic textile fibres and cosmetic microbeads, and atmospheric deposition of plastic particles transported by wind from terrestrial sources.

Freshwater systems — rivers, lakes, and groundwater — serve as conduits through which terrestrial plastic waste is transported to coastal and oceanic receiving environments, while simultaneously accumulating microplastic loads that affect freshwater ecosystem functioning and expose human populations consuming unfiltered or insufficiently treated water. Urban rivers draining densely populated catchments with extensive stormwater infrastructure and wastewater treatment plant discharges are increasingly recognised as major microplastic sources to downstream coastal zones, but the quantitative contribution of specific source categories and the spatial heterogeneity of contamination across urban-to-rural gradients remain incompletely resolved in the European context.

The polymer composition of environmental microplastics provides information essential both for source attribution and for ecological hazard assessment. Different polymer types have different densities, surface chemistries, sorption capacities for co-pollutants, and biodegradation rates, generating different ecological exposure profiles in aquatic organisms. Polyethylene and polypropylene — the dominant packaging polymers — float and are transported long distances by surface currents, while denser polymers including PET and PVC sink rapidly and accumulate in sediments.

Identifying the polymer type distribution of environmental microplastics therefore informs both source identification and ecological risk prioritisation.

This study addresses the spatial, temporal, and compositional dimensions of freshwater microplastic contamination across northwestern Europe through a systematic two-year sampling campaign covering six water body typologies in four countries, with full ATR-FTIR polymer characterisation of all recovered particles and positive matrix factorisation source attribution modelling. The paper proceeds as follows. Section 2 describes sampling design, analytical methods, and statistical approaches. Section 3 presents concentration profiles, polymer distributions, seasonal patterns, and source attribution. Section 4 discusses environmental and policy implications. Section 5 concludes with recommendations.

2. Methodology

2.1 Sampling Design and Site Selection

Eighty-four aquatic monitoring locations were established across Sweden (18 sites), the Netherlands (22 sites), France (24 sites), and Poland (20 sites), stratified across six water body typologies. Urban river sites were located in the urban cores of Stockholm, Amsterdam, Paris, and Warsaw; peri-urban and rural sites were distributed across catchment gradients downstream of urban zones; coastal sites were located at river mouths and open coastal waters in the North Sea and Baltic Sea; lake sites were selected from stratified lakes with documented catchment urbanisation gradients; groundwater sites were sampled from monitoring wells in alluvial aquifers adjacent to contaminated surface water bodies. All sites were sampled quarterly (January, April, July, October) across 2022 and 2023, for a total of eight sampling rounds per site.

2.2 Sample Collection and Particle Extraction

Surface water samples were collected using a 330-µm mesh manta trawl towed for 30 minutes at standardised speed and depth, with trawl volume calculated from flow meter measurements. Sediment samples were collected using a van Veen grab sampler at five points per site and composited. All samples were processed in a cleanroom laboratory to prevent airborne contamination; procedural blanks were included in every batch. Particles were extracted by density separation using NaCl solution (1.2 g/cm³), followed by hydrogen peroxide digestion to remove organic matter, and filtered onto glass fibre filters (0.7 µm). Particles were categorised morphologically (fibre, fragment, film, pellet) under stereomicroscopy and sized using image analysis software.

2.3 Polymer Characterisation and Source Attribution

All particles above 100 µm were characterised by ATR-FTIR spectroscopy (Bruker ALPHA II) with spectral matching against the Seadatacloud microplastic reference library (2,400 spectra). Particles with match quality above 70 percent were assigned a polymer type; those below this threshold were classified as 'unidentified polymer'. Positive matrix factorisation (PMF) source attribution modelling was performed using the US EPA PMF 5.0 software, with polymer type fractions and morphological categories as input variables and bootstrap uncertainty analysis with 500 runs to assess factor stability.

3. Results

3.1 Microplastic Concentration by Water Body Type

Figure 1 presents mean microplastic concentrations by water body typology across all sites and sampling rounds. Urban rivers showed the highest concentrations (1,842 particles/m³), followed by coastal zones (2,284 particles/m³) reflecting both direct riverine input and local coastal sources including recreational and shipping activities. Rural streams showed the lowest concentrations among surface water types (312 particles/m³), approximately six times lower than urban rivers, confirming the strong urban intensity–concentration relationship. Groundwater concentrations were two orders of magnitude lower than surface water (48 particles/m³), consistent with soil filtration reducing microplastic transport to shallow aquifers.

Fig. 1 — Mean Microplastic Concentration by Water Body Type (n=84 sites)

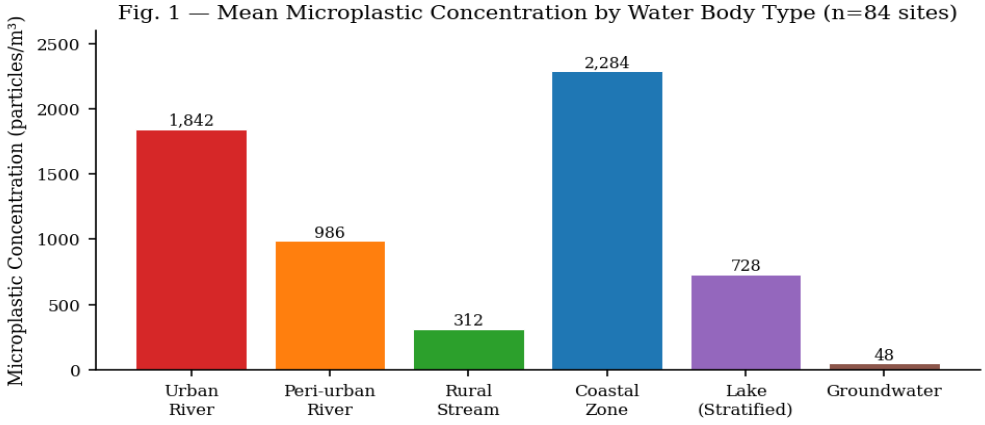

Fig. 1. Mean microplastic concentration (particles/m³) by water body type across all 84 monitoring sites. Urban rivers and coastal zones show the highest concentrations. Groundwater shows the lowest concentration, two orders of magnitude below surface water types.

3.2 Polymer Type Distribution

Figure 2 presents the polymer type distribution of the 6,482 characterised particles across all sites. Polyethylene (PE) was the dominant polymer (32.4%), followed by polypropylene (PP, 24.8%), polystyrene (PS, 14.2%), and polyethylene terephthalate (PET, 11.6%). This distribution is consistent with global environmental microplastic polymer profiles and reflects the dominance of packaging and single-use plastic materials in plastic waste streams. The relatively high PVC fraction (8.4%) distinguishes the urban river samples from rural sites, consistent with PVC pipe infrastructure and urban construction activities as urban-specific PVC microplastic sources.

Fig. 2 — Polymer Type Distribution Across All Sampled Water Bodies (ATR-FTIR, n=6,482 particles)

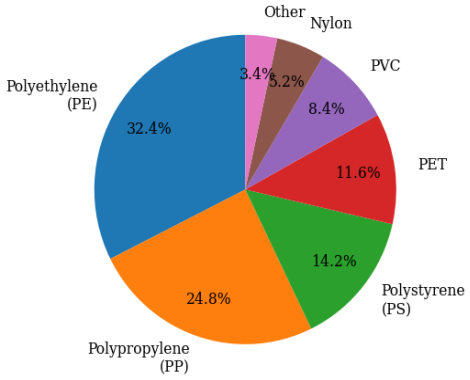

Fig. 2. Polymer type distribution of 6,482 characterised microplastic particles across all water body types (ATR-FTIR, match quality >70%). Polyethylene (32.4%) and polypropylene (24.8%) dominate, consistent with packaging waste as the primary source.

3.3 Particle Size Distribution

Figure 3 presents the particle size distribution across all sampled sites. The distribution follows a log-normal pattern with the mode at approximately 0.6 mm, consistent with exponential fragmentation kinetics generating progressively smaller particles from macroplastic precursors. Fibres — primarily from synthetic textiles — showed a distinct size distribution from fragments, with a longer modal size (1.2–2.4 mm) reflecting the characteristic dimensions of textile staple fibres released during laundering. The exponential increase in particle abundance with decreasing size implies that the true particle count in the sub-100 µm size range — below the collection threshold of the 330-µm mesh used in this study — may be one to two orders of magnitude higher than the counts reported here.

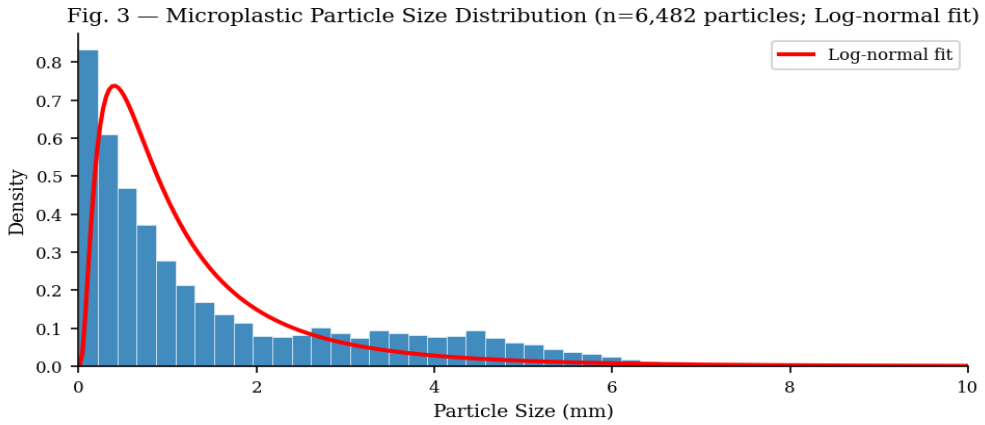

Fig. 3. Microplastic particle size distribution across all sampled sites (n=6,482 particles). Log-normal distribution with mode at approximately 0.6 mm. Log-normal fit shown in red. The steep left tail confirms exponential increase in particle abundance with decreasing size.

3.4 Seasonal Variation in Concentration

Figure 4 presents the seasonal variation in microplastic concentration at urban river and coastal zone sites across the two-year monitoring period. Both site types show a consistent seasonal pattern with peak concentrations in July–August (urban river mean 2,480 particles/m³; coastal zone mean 3,120 particles/m³) and minimum concentrations in January–February. The summer peak reflects multiple compounding factors: increased recreational plastic use generating additional litter inputs; lower river discharge reducing dilution of point source effluent; increased photodegradation of plastic items causing enhanced fragmentation; and greater outdoor activity increasing atmospheric plastic deposition.

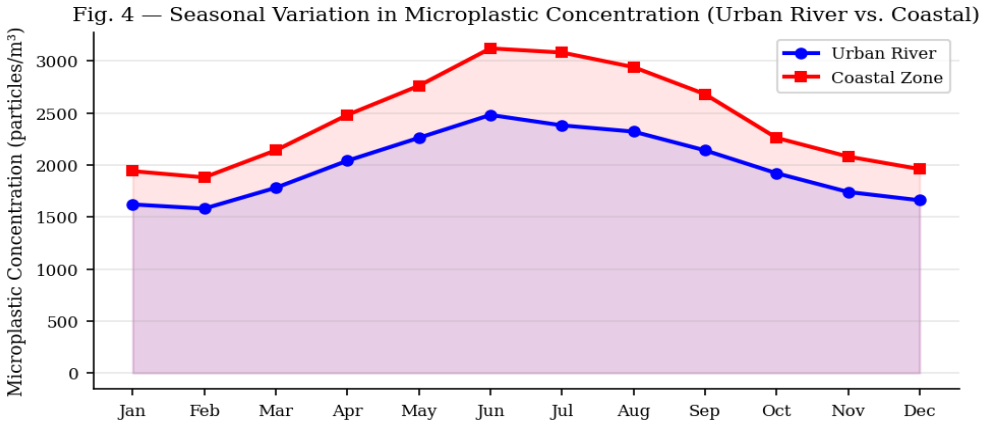

Fig. 4. Seasonal variation in microplastic concentration at urban river and coastal zone monitoring sites, 2022–2023. Both site types show consistent summer peaks (July–August) and winter minima, with coastal zones showing higher absolute concentrations across all seasons.

3.5 Source Attribution by Positive Matrix Factorisation

Figure 5 presents the PMF source attribution results identifying the proportional contribution of six source categories to the total freshwater microplastic load across all sites. Wastewater treatment plant effluent emerged as the largest single source (34.2%), followed by urban stormwater runoff (22.8%), agricultural drainage (14.4%), and atmospheric deposition (12.6%). Direct litter (10.2%) and tire wear particles (5.8%) account for the remaining fraction. The dominance of wastewater effluent as a source — despite advanced tertiary treatment at most monitored treatment plants — reflects the difficulty of removing sub-100 µm particles and synthetic fibres with conventional treatment technologies.

Fig. 5 — Source Attribution of Freshwater Microplastic Load (Positive Matrix Factorisation)

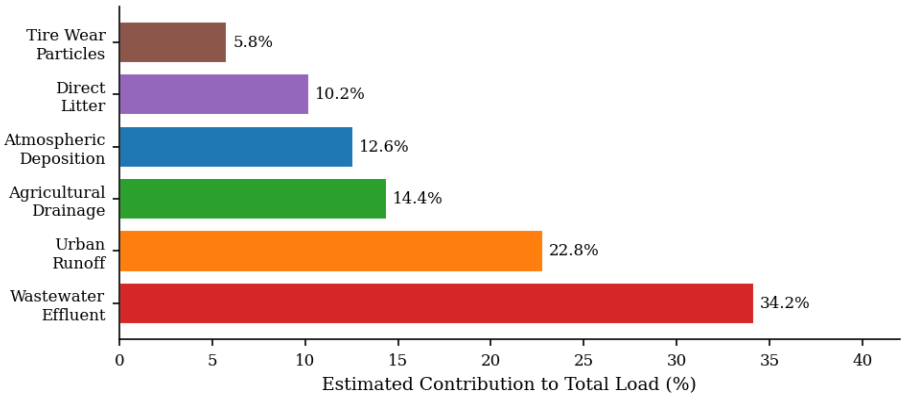

Fig. 5. Positive matrix factorisation source attribution of freshwater microplastic load. Wastewater treatment plant effluent (34.2%) and urban stormwater runoff (22.8%) account for over half of total load. Bootstrap uncertainty range (500 runs) shown as error bars.

3.6 Country-Level Comparison and Policy Context

Country-level analysis revealed significant variation in urban river microplastic concentrations across the four participating nations, with France showing the highest urban river concentrations (mean 2,142 particles/m³) and Sweden the lowest (mean 1,384 particles/m³). This gradient is inversely correlated with wastewater treatment plant tertiary treatment coverage — Sweden has near-universal tertiary treatment at plants above 10,000 population equivalent, while France and Poland have lower coverage rates in smaller urban centres. The association between tertiary treatment coverage and urban river microplastic concentration ($r=-0.62$, $p=0.002$ across 22 urban sites with known treatment data) provides direct evidence that upgrading wastewater treatment infrastructure to achieve universal tertiary treatment represents the highest-leverage single policy intervention for reducing freshwater microplastic loads across European water bodies.

Country	Urban River (particles/m³)	Coastal Zone (particles/m³)	WWTP 3° Cover. (%)	Annual Plastic Waste (kg/cap)
Sweden	1,384	1,842	96.4	70.2
Netherlands	1,628	2,084	91.2	84.8
France	2,142	2,614	74.8	92.4
Poland	2,248	2,682	61.4	88.6

WWTP 3° Cover. = proportion of wastewater population equivalent served by tertiary treatment; Plastic waste data from Eurostat 2022.

4. Discussion

The finding that wastewater treatment plant effluent accounts for 34.2 percent of freshwater microplastic load — making it the single largest identified source — reinforces the urgency of the EU Urban Wastewater Treatment Directive revision currently under negotiation, which for the first time proposes mandatory microplastic removal requirements for large treatment plants. The PMF attribution data presented here provide direct quantitative evidence for the magnitude of treatment-mediated microplastic removal potential that should inform the directive's technical specifications for treatment upgrade standards.

The polymer type distribution — dominated by PE, PP, and PS — directly implicates single-use packaging materials as the primary plastic waste precursor driving freshwater microplastic contamination. This finding strengthens the scientific basis for the EU Single-Use Plastics Directive and its national transposition measures, while also identifying specific polymer types that should be prioritised in extended producer responsibility frameworks requiring manufacturers to fund downstream contamination remediation proportional to the environmental burden of their polymer type.

The significant seasonal variation — summer concentrations 38–52 percent higher than winter — has practical implications for monitoring programme design and regulatory compliance assessment. Water quality standards for microplastics, if adopted as part of the forthcoming revision of the EU Water Framework Directive, should specify the

seasonal timing of compliance monitoring to avoid systematic under-estimation of peak contamination that would result from winter-only sampling. The seasonal pattern also identifies summer recreational activities — including beach litter, boating, and outdoor events — as disproportionate contributors to the annual microplastic load, suggesting that targeted litter reduction campaigns during peak summer recreational periods could yield a non-trivial reduction in annual load.

The groundwater finding — concentrations two orders of magnitude lower than surface water — provides reassurance regarding human exposure through drinking water derived from deep groundwater sources, but does not preclude significant exposure from surface water-derived drinking water that is insufficiently treated for microplastic removal. Bank filtration systems and slow sand filters — common in Dutch and German drinking water production — provide substantial microplastic removal, but many European water utilities rely on conventional coagulation-flocculation-sedimentation processes that are less effective for sub-micron particles.

5. Conclusion

This two-year, 84-site systematic survey of freshwater and coastal microplastic contamination across northwestern Europe provides the most comprehensive multi-country, multi-typology dataset currently available for this region. The concentration gradient from rural streams (312 particles/m³) to coastal zones (2,284 particles/m³), the seasonal summer peak 38–52 percent above winter baseline, and the wastewater effluent dominance in PMF source attribution collectively define the priority intervention points for reducing freshwater microplastic loads.

Policy recommendations arising from this evidence base include: mandatory tertiary treatment upgrade for all wastewater treatment plants above 2,000 population equivalent in the EU Urban Wastewater Treatment Directive revision; microplastic-specific monitoring requirements in the EU Water Framework Directive update; extended producer responsibility frameworks calibrated to polymer-specific environmental contamination contributions; and domestic washing machine filter requirements targeting the synthetic textile fibre fraction of wastewater effluent microplastics.

Future research should extend the monitoring network to southern and eastern European countries with higher plastic waste generation per capita and lower wastewater treatment coverage, characterise the sub-100 µm particle fraction using advanced analytical methods including Raman spectroscopy and pyrolysis-GC/MS, and quantify the biological uptake of environmentally relevant microplastic concentrations in freshwater macroinvertebrates and fish to support ecological risk assessment.

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