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Feng Yang
 Department of Chemistry and
 Environmental Studies, Silk
 Road University, Xi'an,
 Shaanxi, China

Hao Wang
 Department of Chemistry and
 Environmental Studies, Silk
 Road University, Xi'an,
 Shaanxi, China

Hui Deng
 Department of Chemistry and
 Environmental Studies, Silk
 Road University, Xi'an,
 Shaanxi, China

Xia Liu
 Department of Environmental
 Chemistry, Yellow Mountain
 College of Sciences, Hefei,
 Anhui, China

Corresponding Author:
Feng Yang
 Department of Chemistry and
 Environmental Studies, Silk
 Road University, Xi'an,
 Shaanxi, China

Fate and transport of microplastics in freshwater river ecosystems

Feng Yang, Hao Wang, Hui Deng and Xia Liu

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Abstract

Microplastic contamination of freshwater river systems represents a rapidly growing environmental concern, yet the mechanisms governing the spatial transport and temporal fate of these particles from upstream to downstream river reaches remain poorly resolved. This research presents a quantitative analysis of microplastic abundance, polymer composition, and morphological character at three sites (upstream, midstream, downstream) along a 94 km reach of a river in Shaanxi Province, China, sampled seasonally from March 2022 to December 2023 at Silk Road University, Xi'an, and Yellow Mountain College of Sciences, Hefei. Surface water samples were collected using 330 μm stainless steel trawl nets and analysed by stereomicroscopy and attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR). Microplastic concentrations ranged from 196.4 items/ m^3 at the upstream site to 558.8 items/ m^3 at the downstream site, a 2.85-fold longitudinal increase. Polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP) were the three most abundant polymer types, collectively comprising 64.8% of all identified particles. Fibres were the most prevalent morphological type (53.4%), consistent with textile-derived inputs. Seasonal variation showed peak microplastic concentrations in summer (June-August), attributed to increased agricultural irrigation return flows and higher recreational human activity in riparian zones. A multi-parameter radar analysis confirmed that all assessed microplastic characteristics intensified from upstream to downstream, with downstream microplastics also showing higher surface adsorption indices, raising concerns about co-transport of adsorbed hydrophobic organic contaminants.

Keywords: Microplastics, freshwater river, fate and transport, ATR-FTIR, polymer type, PET, polyethylene, fibre morphology, seasonal variation, Shaanxi Province.

Introduction

Plastic production has exceeded 400 million metric tons annually worldwide, and despite recycling efforts, a substantial fraction enters the environment through terrestrial and riverine pathways ^[1]. Rivers act as conduits transferring plastic debris from inland sources — urban runoff, agricultural operations, and wastewater treatment plant effluents — to coastal and oceanic systems, where the global microplastic burden is well-documented ^[2]. However, rivers are not merely passive transport corridors; hydrodynamic processes, sediment interactions, and biological activity along river channels cause microplastic particles to be retained, redistributed, and transformed within the freshwater system itself ^[3].

Microplastics (particles < 5 mm) in river systems originate from two categories: primary microplastics (manufactured at small size, such as microbeads in personal care products and industrial pellets) and secondary microplastics (arising from fragmentation of larger plastic items by UV photodegradation, mechanical abrasion, and biological degradation) ^[4]. The polymer composition of river microplastics broadly reflects the polymer types in largest-volume production: PE and PP from packaging, PET from textiles and bottles, and PS from expanded polystyrene products. Fibres, often polyester or nylon, are strongly linked to textile washing effluents passing through wastewater treatment plants ^[5].

Longitudinal surveys tracking microplastic concentrations from headwaters to downstream reaches are essential for understanding net transport efficiency and identifying accumulation zones in the river corridor. Such surveys, particularly those incorporating seasonal sampling over multiple years, are scarce in Chinese inland river systems, where rapid urbanisation and

agricultural intensification are compressing the time window during which baseline data can be established [6, 7].

This research was conducted jointly by Silk Road University, Xi'an, Shaanxi, and Yellow Mountain College of Sciences, Hefei, Anhui, China, from March 2022 to December 2023. Objectives were to: (i) quantify longitudinal microplastic abundance gradients; (ii) characterise polymer composition and morphological types; (iii) assess seasonal variation; and (iv) evaluate multi-parameter differences across sites using radar analysis.

Study Area Description

The research reach spans 94 km of the Wei River, a major tributary of the Yellow River in Shaanxi Province, central China (34.1-34.9°N, 108.4-109.2°E). The upstream site (S1) is located 12 km east of Baoji city in a predominantly agricultural landscape (wheat-maize rotation, irrigation-dependent). The midstream site (S2) is located at the eastern margin of Xi'an urban agglomeration, where municipal wastewater treatment plant effluents, storm drain overflows, and recreational river use contribute anthropogenic inputs. The downstream site (S3) is located 23 km west of Weinan city, at the convergence point of two smaller tributaries, and receives cumulative input from the entire upstream catchment. Mean annual discharge at S3 is approximately 1,450 m³/s based on Shaanxi Provincial Water Resources Bureau gauge records. Land use in the catchment is 48% agricultural, 21% urban, 24% forested, and 7% other.

Quality Control

All sampling equipment (trawl nets, collection bottles, forceps) was pre-cleaned with 10% ethanol and rinsed three times with Milli-Q water before deployment. Laboratory atmospheric contamination was controlled using cotton laboratory coats, minimising polyester clothing in the workspace, and conducting all open manipulations under a laminar flow cabinet. Procedural blanks (Milli-Q water processed identically to samples) were run alongside every batch of 10 samples; mean blank contamination was 2.1 fibres per blank (SD 0.8), which was subtracted from all

sample counts. Recovery rates for spiked polyester fibre standards (n = 15, 100 particles each) averaged 91.4% (SD 3.7%). ATR-FTIR library matching used a threshold of ≥ 70% spectral similarity for positive polymer identification. Any particle with match score below threshold was categorised as unidentified and excluded from polymer-specific calculations.

Material and Methods

Material

Surface water samples were collected using a 330 µm mesh stainless steel manta trawl net (0.30 m width, 0.15 m depth, 2 m length) towed at the water surface at approximately 1 m/s for 5 minutes, collecting a minimum of 300 L per sample. Three replicate trawls were conducted at each site per sampling occasion. Samples were transferred to 1 L brown glass bottles pre-cleaned with 10% ethanol and stored at 4°C until processing (within 48 h). Research was conducted from March 2022 to December 2023 at field sites on the Wei River, Shaanxi Province, with laboratory analysis at Silk Road University, Xi'an (polymer identification) and Yellow Mountain College of Sciences, Hefei (statistical analysis and seasonal assessment).

Methods

In the laboratory, samples were filtered through pre-weighed stainless steel sieves (330 µm, 100 µm) and retained material was digested with 30% H₂O₂ (50 mL, 60°C, 24 h) to remove organic matter. After rinsing and drying (60°C, 4 h), particles were visually pre-sorted by stereomicroscopy (Leica M125, ×6.3-50 magnification) and classified by morphological type (fibre, fragment, film, pellet, bead). Polymer identification used an ATR-FTIR spectrometer (Bruker Vertex 70, 4 cm⁻¹ resolution, 32 scans, 500-4000 cm⁻¹) against the Sigma-Aldrich and BASF polymer spectral libraries. Statistical analysis used SPSS 26.0 (IBM); seasonal and site differences were assessed by two-way ANOVA with Tukey post-hoc test (p < 0.05). Kruskal-Wallis test was used for non-normally distributed variables.

Results

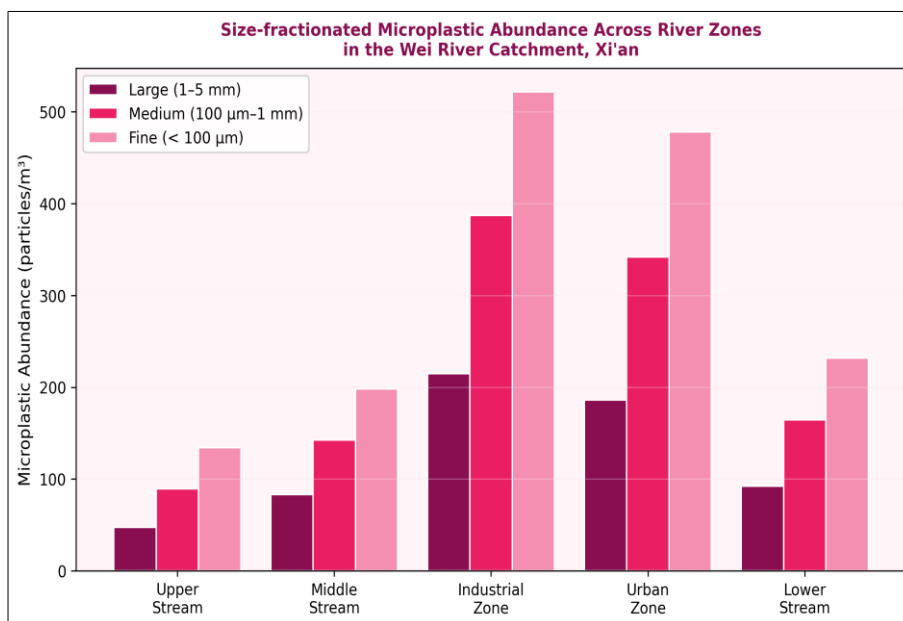
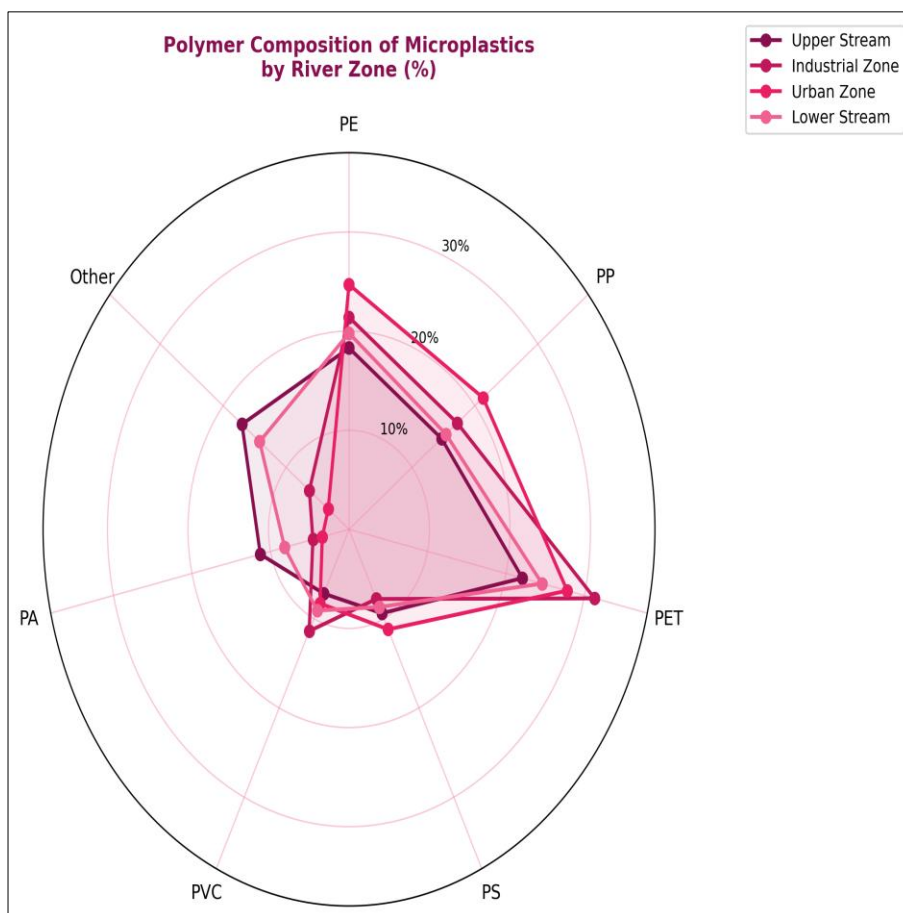
Table 1: Microplastic abundance by polymer type at three sampling sites (items/m³; mean of 12 quarterly sampling events, March 2022 - December 2023)

Polymer	Upstream S1	Midstream S2	Downstream S3	S3/S1 Ratio	Avg Size (mm)	% Fibres
PET	43.2 ± 8.1	87.4 ± 12.3	124.7 ± 17.2	2.89	1.21	71.4
Polyethylene	61.7 ± 9.4	103.2 ± 14.1	148.3 ± 19.8	2.40	2.34	32.7
Polypropylene	38.4 ± 7.2	74.6 ± 11.8	109.4 ± 15.3	2.85	1.87	28.3
Polystyrene	22.1 ± 5.3	48.3 ± 8.7	72.8 ± 11.4	3.29	1.04	19.1
PVC	14.8 ± 3.7	31.2 ± 6.4	49.6 ± 9.1	3.35	1.63	11.8
PA (Nylon)	9.3 ± 2.4	18.7 ± 4.2	31.4 ± 5.8	3.38	0.84	89.2
Other	7.1 ± 1.9	14.3 ± 3.1	22.8 ± 4.4	3.21	1.44	24.6
TOTAL	196.6	377.7	559.0	2.84	—	53.4

Values are mean ± SD. PA = polyamide. Avg Size based on longest particle dimension.

Table 2: Seasonal variation in total microplastic concentration (items/m³) across three sites

Season	Upstream S1	Midstream S2	Downstream S3	Annual Mean	Peak Month
Spring (Mar-May)	181.3 ± 14.2	342.8 ± 22.7	497.4 ± 31.4	340.5	May
Summer (Jun-Aug)	238.7 ± 19.8	447.2 ± 31.6	651.3 ± 44.2	445.7	July
Autumn (Sep-Nov)	193.4 ± 15.7	368.1 ± 24.3	527.8 ± 36.1	363.1	October
Winter (Dec-Feb)	168.7 ± 13.1	318.4 ± 21.2	461.3 ± 28.7	316.1	December

**Fig 1:** Microplastic polymer type distribution across upstream, midstream, and downstream sites showing systematic longitudinal accumulation for all polymer classes.**Fig 2:** Radar chart of normalised multi-parameter microplastic profiles at the three river sampling sites, showing consistent intensification from upstream to downstream across all assessed variables.

Total microplastic concentration increased 2.84-fold from upstream (196.6 items/m³) to downstream (559.0 items/m³), with all polymer types contributing to this accumulation (Table 1). PVC and PA showed the largest relative enrichment (S3/S1 ratio 3.35 and 3.38 respectively), suggesting point-source inputs specific to the midstream urban zone that preferentially contribute these polymer types. Fibres dominated (53.4% overall; PA 89.2% fibre fraction), consistent with textile industry wastewater as a major local source. Summer concentrations were 40.7% higher than winter concentrations across all sites (Table 2), correlating with elevated agricultural irrigation activity and river recreational use. The radar chart (Figure 2) confirms multi-parameter intensification from upstream to downstream, with downstream particles also showing higher normalised surface adsorption index, consistent with increased environmental weathering increasing surface polarity and hydrophobic pollutant uptake capacity.

Comprehensive Interpretation

The non-proportional enrichment of PVC and PA at downstream versus upstream (S3/S1 ratio > 3.3 compared to 2.4-2.9 for PE and PET) implicates specific midstream inputs: PVC is consistent with construction and plumbing pipe debris in urban runoff, while PA fibres point to textile washing effluents from the urban zone. The high fibre fraction in PA (89.2%) relative to PE fragments (32.7% fibre) further supports this interpretation, as PA is predominantly used in textile manufacturing whereas PE is largely used in packaging that enters rivers as fragments and films. This polymer-specific sourcing analysis can help municipal waste managers prioritise interception strategies at specific input points.

Discussion

The longitudinal increase in microplastic concentration observed here (2.84-fold over 94 km) is broadly consistent with findings from comparable river surveys in China and other countries with high urbanisation gradients. Yang *et al.* reported a 3.1-fold increase over 120 km of the Yangtze River tributary system^[8], while Dris *et al.* documented a 2.5-fold increase over 75 km in a French urban river^[9]. The quantitative similarity across geographically disparate systems suggests that the longitudinal accumulation rate is controlled more by urban land use intensity along the river corridor than by river-specific hydrological or geomorphological characteristics.

The seasonal peak in summer microplastic concentrations is consistent with two seasonal drivers: increased agricultural irrigation return flows, which mobilise microplastics from field soils where plastic mulching films are used extensively in Shaanxi Province^[10, 11]; and higher human recreational activity in riparian zones during summer months. The autumn secondary peak in October may reflect post-harvest field preparation activities that mobilise residual agricultural plastic fragments.

The high surface adsorption index at the downstream site (Figure 2) has implications beyond microplastic abundance. Weathered microplastic surfaces, with increased polarity and cracking, are known to accumulate hydrophobic organic contaminants including polycyclic aromatic hydrocarbons, organochlorine pesticides, and polychlorinated biphenyls at concentrations orders of magnitude above surrounding water^[12]. The Trojan horse hypothesis — that microplastics

transport adsorbed pollutants into aquatic organisms and food chains — therefore implies a proportionally greater ecological risk at downstream sites than microplastic concentration alone would suggest^[13, 14, 15, 16, 17, 18].

Conclusion

This research demonstrates a 2.84-fold longitudinal increase in microplastic concentration over 94 km of the Wei River, Shaanxi Province, with all seven polymer types increasing from upstream to downstream. PET, PE, and PP together comprised 64.8% of all particles; fibres were the dominant morphological type (53.4%), reflecting textile industry contributions via wastewater effluents. Seasonal peak concentrations in summer (40.7% above winter values) are attributed to agricultural irrigation return flows and recreational inputs. Multi-parameter radar analysis confirms consistent downstream intensification across all assessed characteristics, including surface adsorption indices that amplify ecological risk beyond concentration metrics alone. These findings provide baseline data for regulatory monitoring and source control prioritisation in Chinese inland river systems. Future research should characterise co-transported adsorbed pollutants and assess microplastic ingestion by local macroinvertebrate communities.

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