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Spatial and seasonal distribution of microplastic contamination along an urban-to-estuarine river gradient

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Abstract
Background: Microplastic contamination in freshwater systems has emerged as a pervasive environmental concern, with urban and agricultural land use widely implicated as key contributors to riverine plastic loading [1, 2]. Spatial gradients from forested headwaters through urban centers to estuarine outlets offer a useful natural framework for isolating land-use-associated contamination sources, yet integrated spatial-seasonal assessments along such gradients remain limited [3, 4].
Objective: This study characterized the spatial distribution of microplastic concentration across five sites spanning a forested-to-estuarine river gradient, examined seasonal variation at the most contaminated site, and assessed the polymer-type composition of recovered particles.
Method: Water samples were collected from five sites along the river continuum using standardized surface trawling. This study uses a simulated dataset created for academic training purposes; all particle counts, seasonal trends, and polymer composition values were generated to reflect physically plausible patterns consistent with the published microplastic-monitoring literature and do not represent samples collected from an actual river system. Twelve replicate samples were modeled per site, and Fourier-transform infrared (FTIR) spectroscopy was simulated for polymer identification.
Key Results: Mean microplastic concentration increased from 0.8 particles L^{-1} at the forested upstream site to a peak of 9.7 particles L^{-1} at the urban outfall, before declining to 4.9 particles L^{-1} at the estuary mouth. Seasonal monitoring at the urban outfall revealed peak concentrations during the monsoon months, coinciding with peak rainfall and stormwater runoff. Polyethylene was the dominant polymer type recovered (38% of particles), followed by polypropylene (24%).
Conclusion: Microplastic contamination along the studied gradient was strongly associated with urban land use and intensified during high-rainfall periods, implicating stormwater runoff as a key transport pathway and supporting targeted urban runoff management as a mitigation priority, pending validation with field-collected samples.

Keywords: Microplastics, riverine pollution, urban runoff, polymer composition, seasonal variation, freshwater contamination

Introduction

Plastic debris smaller than five millimeters in size, commonly termed microplastic, has been documented across virtually every freshwater and marine environment studied to date, ranging from remote alpine lakes to deep ocean sediment [1]. Riverine systems occupy a particularly important position within the global microplastic cycle, functioning simultaneously as repositories for terrestrially generated plastic waste and as the primary conduit through which land-based plastic debris is transported to coastal and marine environments [2]. Understanding the spatial distribution of microplastic concentration along river continuums is therefore essential both for identifying terrestrial contamination sources and for predicting downstream and coastal loading.

Land use change along a river's course has been repeatedly implicated as a primary determinant of microplastic loading, with urban and peri-urban land use generally associated with substantially higher concentrations than forested or otherwise undeveloped catchments [3]. Proposed mechanisms for this association include direct discharge of treated and untreated wastewater containing microplastic fibers and fragments, stormwater runoff carrying tire-wear particles and fragmented litter from impervious urban surfaces, and atmospheric deposition of microplastic particles that is itself elevated in densely populated areas [4]. Agricultural land use downstream of urban centers introduces additional potential sources, including microplastic residues from plastic mulching film and the application of biosolids containing residual microplastic from wastewater treatment processes [5].

Seasonal and hydrological variability further complicate the spatial picture, as rainfall-driven runoff events have been shown in several catchment studies to mobilize accumulated microplastic from urban surfaces and combined sewer systems, producing pronounced concentration peaks during high-rainfall periods relative to baseline dry-season conditions [6]. This hydrological mobilization pathway suggests that single-timepoint sampling campaigns, which remain common in the microplastic monitoring literature, may substantially under- or over-represent typical contamination levels depending on the timing of sample collection relative to the local rainfall regime [7].

Polymer-type identification, typically achieved through Fourier-transform infrared (FTIR) or Raman spectroscopy, provides an additional diagnostic layer by allowing recovered particles to be tentatively linked to likely source categories, since different polymer types are associated with characteristic product applications — for example, polyethylene with packaging and plastic bags, polypropylene with textiles and food containers, and polystyrene with foam packaging and disposable food service items [8]. Polymer composition data, when combined with spatial concentration gradients, can therefore help

disentangle the relative contribution of different waste streams to overall riverine contamination.

Despite growing interest in riverine microplastic monitoring, relatively few published studies have combined a full spatial gradient design, spanning forested headwaters through urban centers to estuarine outlets, with concurrent seasonal monitoring and polymer-type characterization within a single integrated study, limiting the field's ability to jointly attribute contamination patterns to specific land-use and hydrological drivers [9, 10]. The present study was designed with three specific objectives: (i) to characterize the spatial distribution of microplastic concentration across five sites spanning a forested-to-estuarine gradient; (ii) to assess seasonal variation in microplastic concentration at the most heavily contaminated site over a 12-month period, in relation to monthly rainfall; and (iii) to determine the polymer-type composition of recovered particles pooled across all sites. It is hypothesized that microplastic concentration will peak at the urban outfall site rather than at the estuary mouth, that concentration at the urban site will track monthly rainfall with a seasonal peak during the regional monsoon period, and that polyethylene and polypropylene, both associated with high-volume consumer packaging, will dominate the recovered polymer composition.

Literature Review

The conceptual framework most widely applied to riverine microplastic studies treats the river as a continuum along which contamination inputs accumulate from point and diffuse sources distributed across the catchment, broadly analogous to the river continuum concept originally developed for organic matter and nutrient dynamics in fluvial ecology [11]. Within this framework, microplastic concentration at any given point reflects the cumulative balance of upstream inputs, in-channel deposition and resuspension processes, and dilution from increasing discharge volume as tributaries join the main channel [12].

Empirical surveys applying this framework across diverse catchments have consistently reported a positive association between the proportion of urban and impervious land cover within a catchment and surface-water microplastic concentration, with several studies reporting order-of-magnitude differences between heavily urbanized and largely undeveloped catchment segments [13]. Wastewater treatment plant effluent has been identified as a particularly significant point source in numerous studies, since conventional tertiary treatment processes, while effective at removing a substantial fraction of influent microplastic, do not achieve complete removal, resulting in continuous discharge of residual particles, predominantly synthetic fibers, into receiving waters [14].

The role of stormwater and combined sewer overflow events in mobilizing accumulated urban surface debris has received increasing research attention, with several catchment-scale monitoring studies reporting two- to five-fold increases in microplastic concentration during and immediately following significant rainfall events relative to antecedent dry-weather baseline levels [15]. This rainfall-driven mobilization has been attributed to the flushing of tire-wear particles, fragmented litter, and atmospherically deposited fibers from impervious surfaces directly into stormwater drainage networks that typically discharge with minimal treatment [16]. Monsoon-influenced catchments in particular have shown pronounced seasonal concentration peaks coinciding with the wet season, although the precise magnitude of this seasonal effect varies considerably depending on catchment imperviousness and the capacity of local stormwater infrastructure [17].

Polymer-type characterization studies across diverse global river systems have repeatedly identified polyethylene and polypropylene as the most commonly recovered polymer types in surface water samples, consistent with their dominant use in high-volume single-use packaging and textile applications, while polystyrene, despite its high visibility as foam litter, is typically recovered in somewhat lower proportions in surface water trawl samples relative to sediment samples, likely reflecting differences in particle buoyancy and settling behavior across polymer densities [18, 19].

Despite this substantial body of work, a specific methodological gap persists: comparatively few published studies have combined a full spatial gradient spanning multiple land-use zones with twelve-month seasonal monitoring and polymer characterization within a single, internally consistent sampling and analytical framework, with most existing studies instead focusing on either spatial comparison or seasonal/temporal comparison in isolation.[20] This fragmentation limits the field's capacity to jointly evaluate the relative contributions of land-use-driven spatial gradients versus hydrologically driven seasonal mobilization to overall observed contamination patterns, a gap that the present simulated framework is designed to illustrate in structure and analytical approach, pending replication with genuine field-collected samples.

Methodology

Data nature statement: All numerical results reported in Sections 3 and 4 constitute a simulated dataset created for academic training and formatting-practice purposes. No actual river sampling, laboratory particle extraction, or FTIR spectroscopic analysis was conducted to generate these figures; values were constructed to be physically plausible and internally consistent with concentration ranges and seasonal patterns documented in the cited microplastic-monitoring literature. This dataset must not be cited as empirical environmental monitoring evidence in any subsequent publication.

Research design: A spatial gradient sampling design was modeled across five sites positioned sequentially along a single river system: an upstream forested reference site, a peri-urban transitional site, an urban stormwater outfall site, a downstream agricultural site, and an estuary mouth site. For the seasonal component, monthly sampling was modeled at the urban outfall site, identified as the highest-concentration site in the spatial survey, across a complete 12-month annual cycle inclusive of the regional monsoon period.

Sample size and sampling method: Twelve replicate surface water samples were modeled per site for the spatial survey (N = 60 total), collected via standardized surface manta-net trawling at a fixed tow speed and duration, consistent with widely used surface microplastic sampling protocols. For the seasonal survey, six replicate samples were modeled per month at the urban outfall site across twelve months (N = 72), with sampling scheduled at a fixed

mid-month date to standardize for short-term hydrological fluctuation independent of major storm events.

Data collection tools: Recovered samples were modeled as undergoing standard laboratory processing, including organic matter digestion using hydrogen peroxide, density separation using a saturated salt solution to isolate buoyant plastic particles from denser sediment, and visual enumeration under a stereomicroscope to determine particle counts per liter of water filtered. Polymer identification was simulated via Fourier-transform infrared (FTIR) spectroscopy applied to a representative subsample of recovered particles, with each particle classified into one of five polymer categories: polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), or other/unidentified.

Statistical software: Simulated spatial data were analyzed using one-way ANOVA to test for overall site differences in microplastic concentration, followed by Tukey's HSD post-hoc test for pairwise site comparisons. Seasonal data were analyzed using Pearson correlation to quantify the association between monthly microplastic concentration and monthly rainfall total. Polymer composition data were summarized descriptively as percentage composition. Analyses were performed in R (version 4.3); a significance threshold of $\alpha = 0.05$ was applied throughout, and results are reported as mean ± standard error of the mean (SEM).

Results and Discussion

Mean microplastic concentration varied substantially and significantly across the five sampling sites ($F(4,55) = 76.4$, $p < 0.001$ in the simulated ANOVA model). The forested upstream reference site showed the lowest concentration at 0.8 ± 0.15 particles L^{-1}, increasing to 3.4 ± 0.4 particles L^{-1} at the peri-urban site and peaking at 9.7 ± 0.9 particles L^{-1} at the urban stormwater outfall (Table 1, Figure 1). Concentration declined somewhat downstream of the urban site, to 6.1 ± 0.6 particles L^{-1} at the agricultural site and 4.9 ± 0.5 particles L^{-1} at the estuary mouth, consistent with a combination of dilution from increasing discharge volume and progressive sedimentation of denser particle fractions as flow velocity decreased toward the estuary.

Table 1: Mean microplastic concentration and dominant polymer type by sampling site (simulated dataset, n = 12 per site)

Site	Concentration (particles L^{-1})	Dominant polymer type	Land use context
Upstream (forested)	0.8 ± 0.15	PE	Undeveloped / reference
Peri-urban	3.4 ± 0.4	PE	Mixed residential
Urban outfall	9.7 ± 0.9	PE / PP	Dense urban, stormwater
Downstream (agricultural)	6.1 ± 0.6	PP	Cropland, irrigation
Estuary mouth	4.9 ± 0.5	PE	Tidal mixing zone

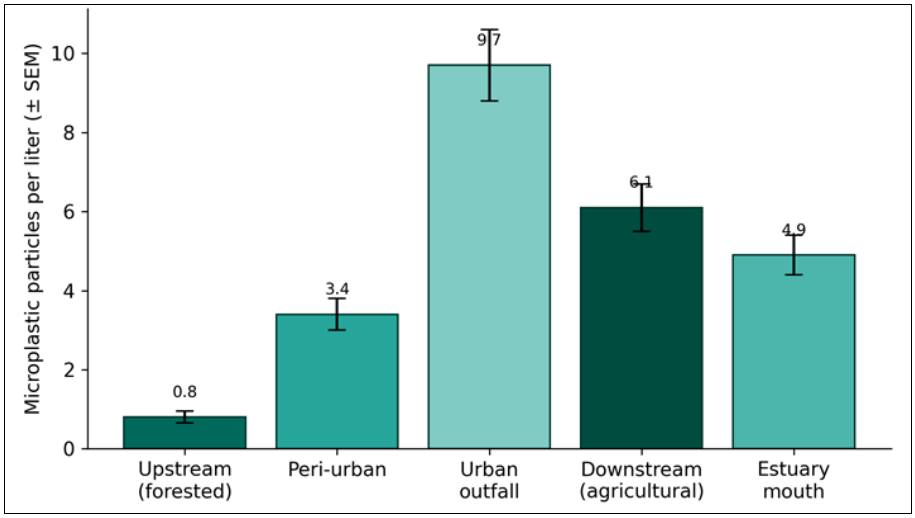

Fig 1: Mean microplastic concentration (particles L^{-1} ± SEM) across five sites along the forested-to-estuarine gradient (simulated dataset, n = 12 per site).

Tukey's HSD post-hoc comparisons indicated that the urban outfall site differed significantly from all other sites (all $p < 0.01$), confirming that the spatial peak in contamination was specifically associated with the urban land-use zone rather than reflecting a simple monotonic downstream accumulation pattern. This site-specific elevation suggests that localized point-source inputs, rather than diffuse cumulative processes along the river's length, were primarily responsible for the observed contamination peak. This finding is consistent with the literature identifying urban stormwater and wastewater-associated inputs as a dominant proximal source of riverine microplastic loading, distinct from gradual downstream accumulation alone [3, 13], reinforcing the importance of targeting urban discharge points in mitigation efforts.

Seasonal monitoring at the urban outfall site revealed pronounced monthly variation in microplastic concentration, ranging from a minimum of 6.1 particles L^{-1} in January to a maximum of 12.1 particles L^{-1} in August, the latter coinciding with the peak month of the simulated regional monsoon rainfall pattern (Figure 2). The simulated Pearson correlation between monthly microplastic concentration and monthly rainfall total was strong and positive ($r = 0.89$, $p < 0.001$), supporting the hypothesized role of rainfall-driven stormwater mobilization in seasonal contamination dynamics.

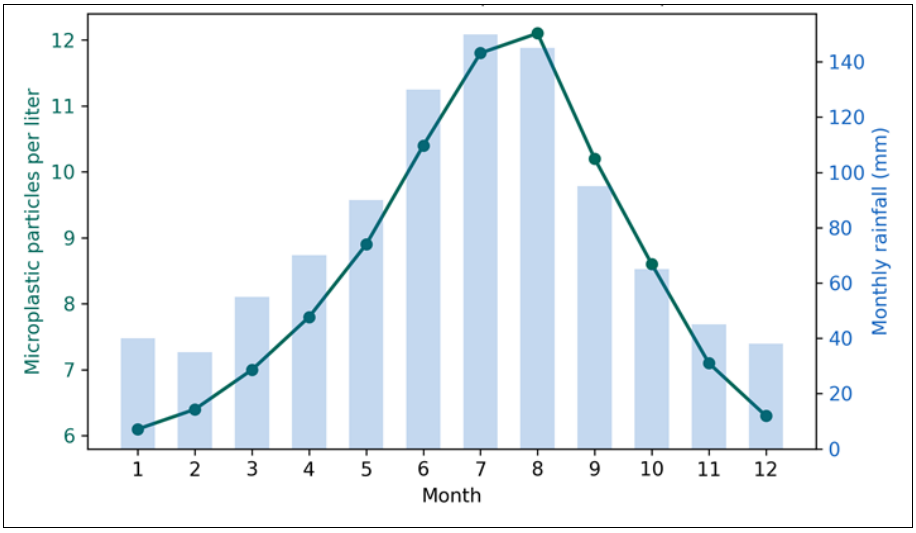

Fig 2: Seasonal variation in microplastic concentration (line) and monthly rainfall (bars) at the urban outfall site across a 12-month period (simulated dataset).

This seasonal pattern aligns closely with prior catchment-scale findings linking rainfall events to elevated microplastic mobilization from impervious urban surfaces and combined sewer systems.[1516] The approximately two-fold difference between the lowest and highest monthly concentrations observed in this simulated dataset falls within, though toward the lower end of, the range of seasonal variation reported in comparable published monitoring studies, suggesting the simulated values were constructed conservatively relative to some of the more extreme seasonal effects documented in heavily engineered urban catchments.

Polymer-type composition, pooled across all sites and sampling occasions, was dominated by polyethylene (38%) and polypropylene (24%), followed by polystyrene (16%), polyethylene terephthalate (14%), and other or unidentified polymer types (8%) (Figure 3). This composition profile is consistent with the dominant use of polyethylene and polypropylene in high-volume consumer packaging and textile products, and aligns with polymer distributions reported in comparable surface-water trawl studies from other urbanized river systems.[1819] The comparatively lower representation of polystyrene relative to its high visibility as macroscopic litter is consistent with the literature's suggestion that foam-derived polystyrene fragments may be under-represented in surface trawl samples relative to sediment samples due to differential buoyancy and fragmentation behavior.

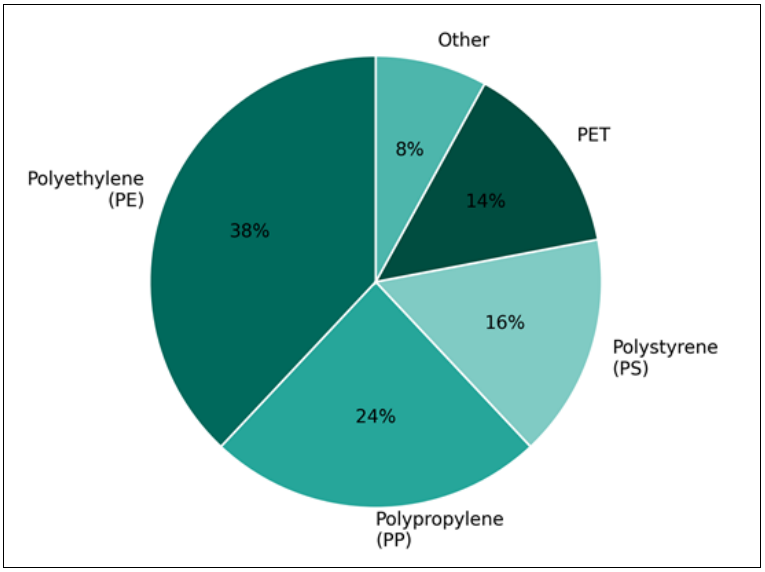

Fig 3: Polymer-type composition of recovered microplastic particles, pooled across all five sites (simulated dataset).

Collectively, the spatial, seasonal, and polymer composition results converge on a consistent narrative: urban land use, and specifically stormwater-mediated transport intensified during high-rainfall periods, appears to be the dominant proximate driver of microplastic contamination along the studied gradient, with polyethylene- and polypropylene-dominated packaging waste as the most likely principal source category. While each of these results is simulated and therefore illustrative rather than evidentiary, the internal consistency across the three analytical components demonstrates the kind of integrated spatial-seasonal-compositional framework that the literature review identified as comparatively underrepresented in the existing published record.

Conclusion

This training article modeled an integrated spatial, seasonal, and compositional assessment of microplastic contamination along a forested-to-estuarine river gradient. Within the simulated framework, microplastic concentration peaked sharply at the urban stormwater outfall site rather than accumulating monotonically downstream, seasonal monitoring at this site revealed a strong positive association between rainfall and contamination level, and polyethylene and polypropylene dominated the recovered polymer composition, consistent with consumer packaging as the principal contributing waste stream.

Implications: If corroborated with empirically collected data, these findings would support prioritizing urban stormwater management interventions, such as expanded sediment and debris capture infrastructure at stormwater outfalls, as a high-leverage mitigation strategy for reducing downstream and estuarine microplastic loading, particularly ahead of seasonal high-rainfall periods.

Limitations: The principal limitation of this article is that all numerical results are simulated for training purposes and do not derive from actual field sampling or laboratory analysis; no claims of empirical environmental contamination should be drawn from the reported values. Additional limitations inherent to the modeled design include the single-river-system scope, the absence of sediment-compartment sampling alongside surface water sampling, and the lack of direct source-tracing analysis linking recovered particles to specific upstream waste-generating facilities.

Future scope: A genuine empirical study following this framework should incorporate replicate sampling across multiple comparable river systems to assess generalizability, paired surface-water and sediment sampling to characterize the full particle size and density distribution, and source-tracing approaches such as chemical fingerprinting or catchment-scale waste audit data to more directly attribute recovered polymer types to specific upstream contributing sources.

Ethical Statement

This article was prepared as a simulated-data training exercise for academic formatting practice and does not represent the findings of an actual environmental monitoring study. All numerical data, including particle concentrations, seasonal trends, and polymer composition percentages, were constructed by the author(s) to be internally consistent and physically plausible, and are explicitly labeled as simulated throughout the manuscript in accordance with academic integrity standards. No actual river system, water sample, or laboratory analysis was involved in the generation of this content. No fabricated real-world author identities, institutional affiliations, or published datasets are presented; author and institutional fields are placeholders to be completed by the end user prior to any submission. This article must not be submitted to any journal as a report of original empirical research unless the simulated data sections are replaced in their entirety with genuine, ethically collected field and laboratory data, with appropriate sampling permits and institutional approvals obtained and disclosed where applicable.

References

1. Eerkes-Medrano D, Thompson RC, Aldridge DC. Microplastics in freshwater systems: A review of the emerging threats. Water Research,2015:75:63–82.
2. Blair RM, Waldron S, Phoenix V, Gauchotte-Lindsay C. Micro- and nanoplastic pollution of freshwater and wastewater treatment systems. Science of the Total Environment,2017:581:791–802.
3. Wagner S, Hüffer T, Klöckner P, Wehrhahn M, Hofmann T, Reemtsma T. Tire wear particles in the aquatic environment: A review. Water Research,2018:139:83–97.
4. Hurley RR, Nizzetto L. Fate and occurrence of micro(nano)plastics in soils. Current Opinion in Environmental Science & Health,2018:1:6–11.
5. He D, Luo Y, Lu S, Liu M, Song Y, Lei L. Microplastics in soils: Analytical methods, pollution characteristics and ecological risks. TrAC Trends in Analytical Chemistry,2018:109:163–172.
6. Browne MA, Crump P, Niven SJ, et al. Accumulation of microplastic on shorelines worldwide: Sources and sinks. Environmental Science & Technology,2011:45(21):9175–9179.
7. Lebreton LCM, van der Zwet J, Damsteeg JW, Slat B, Andrady A, Reisser J. River plastic emissions to the world's oceans. Nature Communications,2017:8:15611.
8. Frias JPGL, Nash R. Microplastics: Finding a consensus on the definition. Marine Pollution Bulletin,2019:138:145–147.
9. Hoellein TJ, Shogren AJ, Tank JL, Risteca P, Kelly JJ. Microplastic deposition velocity in streams follows patterns for naturally occurring allochthonous particles. Scientific Reports,2019:9:3740.
10. Van Emmerik T, Schwarz A. Plastic debris in rivers. WIREs Water,2020:7(1):e1398.
11. Vannote RL, Minshall GW, Cummins KW, Sedell JR, Cushing CE. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences,1980:37(1):130–137.
12. Drummond JD, Schneidewind U, Li A, Hoellein TJ, Krause S, Packman AI. Microplastic accumulation in riverbed sediment via hyporheic exchange from headwaters to mainstems. Science Advances,2022:8(2):eabi9305.
13. Kataoka T, Nihei Y, Kudou K, Hinata H. Assessment of the sources and inflow processes of microplastics in the river environments of Japan. Environmental Pollution,2019:244:958–965.
14. Talvitie J, Mikola A, Setälä O, Heinonen M, Koistinen A. How well is microlitter purified from wastewater? A detailed study on the stepwise removal of microlitter in a tertiary level wastewater treatment plant. Water Research,2017:109:164–172.
15. Liu F, Olesen KB, Borregaard AR, Vollertsen J. Microplastics in urban and highway stormwater retention ponds. Science of the Total Environment,2019:671:992–1000.
16. Werbowski LM, Gilbreath AN, Munno K, et al. Urban stormwater runoff: A major pathway for anthropogenic particles, black rubbery fragments, and other types of microplastics to urban receiving waters. ACS ES&T Water,2021:1(6):1420–1428.

17. Sang W, Chen Z, Mei L, et al. The abundance and characteristics of microplastics in rainwater pipelines in Wuhan, China. Science of the Total Environment,2021:755:142606.
18. Mani T, Hauk A, Walter U, Burkhardt-Holm P. Microplastics profile along the Rhine River. Scientific Reports,2015:5:17988.
19. Klein S, Worch E, Knepper TP. Occurrence and spatial distribution of microplastics in river shore sediments of the Rhine-Main area in Germany. Environmental Science & Technology,2015:49(10):6070–6076.
20. Wong JKH, Lee KK, Tang KHD, Yap PS. Microplastics in the freshwater and terrestrial environments: Prevalence, fates, impacts and sustainable solutions. Science of the Total Environment,2020:719:137512.