Journal of Hazardous Materials 472 (2024) 134571

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Significant regional disparities in riverine microplastics

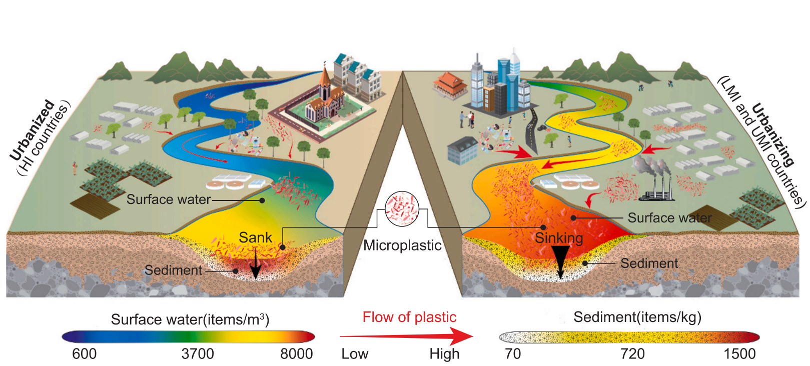
Cai Chen [a,b], Sheree A. Pagsuyoin [c], Tim H.M. van Emmerik [d], Yu-yao Xu [a,e], Yu-qin He [a,b], Zhao-feng Guo [a,e], Dong Liu [a,e], Yao-yang Xu [a,e,*]

[a] *Key Laboratory of Urban Environment and Health, Ningbo Observation and Research Station, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, PR China*
[b] *University of Chinese Academy of Sciences, Beijing 100049, PR China*
[c] *University of Massachusetts Lowell, Lowell, MA 01854, USA*
[d] *Hydrology and Environmental Hydraulics Group, Wageningen University, Wageningen 6700 AA, Netherlands*
[e] *Zhejiang Key Laboratory of Urban Environmental Processes and Pollution Control, CAS Haixi Industrial Technology Innovation Center in Beilun, Ningbo 315830, PR China*

HIGHLIGHTS

- Constructed a framework for large-scale regional river microplastic analysis.
- Integrated microplastic data from 76 rivers mainly in Asia, Europe, North America.
- Detected regional variation in microplastics in bulk water and volume methods.
- Contrasted microplastic pattern in water and sediment: Asia vs. Euro-America.
- Observed higher in mid-income water, more prevalent in high-income sediment.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Riverine microplastics
Regional variations
Literature synthesis
Income level
Urbanization

ABSTRACT

Research on riverine microplastics has gradually increased, highlighting an area for further exploration: the lack of extensive, large-scale regional variations analysis due to methodological and spatiotemporal limitations. Herein, we constructed and applied a comprehensive framework for synthesizing and analyzing literature data on riverine microplastics to enable comparative research on the regional variations on a large scale. Research results showed that in 76 rivers primarily located in Asia, Europe, and North America, the microplastic abundance of surface water in Asian rivers was three times higher than that in Euro-America rivers, while sediment in Euro-American rivers was five times more microplastics than Asia rivers, indicating significant regional variations ($p < 0.001$). Additionally, based on the income levels of countries, rivers in lower-middle and upper-middle income countries had significantly ($p < 0.001$) higher abundance of microplastics in surface water compared to high-income countries, while the opposite was true for sediment. This phenomenon was preliminarily attributed to varying levels of urbanization across countries. Our proposed framework for synthesizing and analyzing

* Corresponding author at: Key Laboratory of Urban Environment and Health, Ningbo Observation and Research Station, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, PR China.
E-mail address: yyxu@iue.ac.cn (Y.-y. Xu).

https://doi.org/10.1016/j.jhazmat.2024.134571
Received 8 March 2024; Received in revised form 7 May 2024; Accepted 8 May 2024
Available online 11 May 2024

microplastic literature data provides a holistic understanding of microplastic disparities in the environment, and can facilitate broader discussions on management and mitigation strategies.

1. Introduction

Microplastics (MPs), defined as plastic particulates with diameters less than 5 millimeters, are increasingly recognized as a critical environmental challenge. These small plastic particles, originating from diverse sources including cosmetic products, textile fibers, and fragmented plastic debris, infiltrate riverine ecosystems primarily through the discharge of both treated and untreated urban, industrial, and agricultural wastewater, as well as via urban stormwater runoff and drainage systems [1,2]. Rivers are regarded as dominant pathways and reservoirs for transmission of MPs from freshwater to marine ecosystems [3–6]. The spatiotemporal variations of MPs in rivers is predominantly driven by a combination of anthropogenic activities, precipitation and runoff patterns, fluvial hydrodynamic conditions, biological interactions, seasonal fluctuations, geographical positioning, and the diversity in sources and types of MPs [7–10]. However, the spatial variations of MPs in rivers across different regions are primarily influenced by anthropogenic activities, which are closely linked to local economic development and urbanization levels.

Comparative studies on the large-scale spatial variations of MPs in rivers across different regions are still relatively scarce. Current large-scale riverine MP research primarily used models to estimate the amount of plastic reaching the river mouth (upstream of the estuary) [3, 11–14]. However, these modeling studies have overlooked the spatial distribution differences in riverine MP flux. Although high-resolution studies within river basins can spatially visualize the issue of MP variability in rivers, yet high-resolution spatial research on MPs at larger regional scales, such as continental dimensions, remains relatively limited [15]. With the substantial increase in field observation data on riverine MPs, integrating these data from existing literature could provide a novel perspective for comparing spatial variations across different regions.

Published studies on riverine MPs have posed challenges for large-scale data synthesis due to inconsistent sampling methods and spatiotemporal heterogeneity. Inconsistent sampling methods constitute the primary impediment to comparisons of MPs in surface water [16], as different sampling methods and selected mesh sizes can lead to abundance errors [17–19]. There are two common methods for collecting MPs from surface water: bulk sampling using containers or pumps [20] and trawling sampling (i.e., volume-reduced) using manta trawl and neuston net, typically with a mesh size of 333 μm [16,21]. Spatial distribution of MPs in different river reaches shows obvious heterogeneity due to the transport characteristics of MPs [15,22,23]. Research indicated that spatial differences caused reported MP pollution levels within a river to vary by two orders of magnitude, while temporal variations reached up to an order of magnitude [23]. Furthermore, the highest riverine MP pollution may not observe at the estuary but rather near densely populated areas [17,24–26]. Although many studies have focused on entire or partial MP pollution in individual or several rivers [27–31], and have compared their findings with those of previous studies. However, these comparisons have mostly made in the form of tabulated results, without a comprehensive analysis [5,20,32]. In summary, although the systematic comparison of riverine MPs is challenging due to variances in sampling methodologies and temporal differences, the substantial volume of data on riverine MPs can enable a comprehensive data integration from existing publications, offering fresh insights into the characteristics and spatial variations of MPs in river systems.

Thus, we proposed a comprehensive framework for literature mining and data analysis of published articles on MP-contaminated river. Based on this framework, we try to synthesize the following aspects: (i) literature data mining on MP abundance, shapes, colors, polymers, and particle sizes; (ii) regional comparison of riverine MP abundance, differences in shapes, colors, polymers, and particle sizes; and (iii) differences in relation to economic development level. By utilizing an integrated framework of literature mining and data analysis, this study not only extensively uncovers the spatial distribution and characteristics of riverine MPs on a broader scale but also delves into the distribution variations in different geographical regions and across varying economic development levels. This comprehensive framework offers a unique perspective in understanding the spatial heterogeneity of riverine MPs, thereby laying a solid scientific foundation for devising more effective and targeted strategies for the prevention and control of MP pollution in rivers. Moreover, this approach is crucial for predicting future MP pollution trends, informing environmental policy-making, and raising public awareness about the MP issue.

2. Methods

2.1. Literature mining

Literature mining is a specialized data mining method that is used to extract information (facts or data) from text and can generate new hypotheses by systematically scrutinizing huge numbers of abstracts or full text versions, of scientific publications [33]. It is common to use statistical concepts and methods to collect, collate and analyze empirical meta-analysis from previous publications on a specific topic [16,34,35]. In our study, we focused on riverine MPs and established a literature data mining process. We conducted a Boolean search of published articles in the Web of Science (WoS) using the keywords *("river") AND ("microplastic*")* for the period 1992 to January, 2022 yielded 808 articles (Fig. 1a). Subsequent manual screening was conducted to exclude irrelevant articles (587) and articles without accessible MP data (63), resulting in 168 articles (Fig. 1a). Research on riverine MP pollution is usually conducted from the perspective of surface water and sediment [26,30,36], as such, we further excluded articles that focused on biota (59 articles).

Diversity characterizes research on MPs in rivers, with studies focusing on various aspects. Some emphasize a comprehensive examination of entire river systems [27,36,37] or specific river sections [38, 39], while others concentrate on investigating MPs in multiple rivers within a watershed [24], encompassing those flowing into lakes or seas [21]. Additionally, certain studies prioritize exploring temporal variations in MP abundance at a limited number of sampling points [17,40]. Of course, there are also investigations that specifically target MPs within urban river systems [31,41]. Due to pronounced spatial variations in the distribution of MPs in rivers, an insufficient number of sampling sites or overly concentrated distributions may compromise the comprehensive representation of MPs occurrences in entire rivers or specific river segments [17,40]. This is attributed to the susceptibility of abundance characteristics to the influence of surrounding environmental factors [38]. To enhance the credibility of abundance and other characteristic comparisons between rivers, we applied specific criteria during literature selection, requiring a minimum of 5 sampling points and a straight-line distance of 20 km or more between the first and last sampling points. The final database included 48 articles on MPs in surface water and 29 articles on MPs in sediment (Fig. 1a).

Dataset contained information on the basic river information (such as river name, latitude, longitude, country, income group, sampling method and mesh size), MP abundance, shapes, colors, particle sizes, polymers and source reference in surface water and sediment (see details in supporting materials). Riverine MP dataset was obtained from readily available data tables in the articles or in their supporting documents, or extracted from the articles' figures using *GetData Graph Digitizer* software (http://www.getdata-graph-digitizer.com/). The geolocations of the sampling sites (latitude and longitude) were either provided in the article or obtained via geolocation extraction with Google Earth using area maps. The MP abundance in surface water were usually reported in units of "items/m^3" or "items/L". The data was initially reported in "items/L" unit and was eventually converted to "items/m^3" based on the density of water. Furthermore, MP abundance of sediment was reported in unit of "items/kg", and all wet weight abundance was converted to dry weight abundance. Three articles did not conform to reporting MP abundance in these units (for surface water or sediment) and were excluded in the subsequent data analysis. Additionally, data on MP shapes, colors, polymers and particle sizes were standardized to express them as percentages.

2.2. *Data analysis*

The final MP dataset was classified and analyzed to gain a broad understanding of the current status and spatial variations of MPs in rivers (Fig. 1b). The analysis of riverine MPs focused on the abundance and characteristics of shapes, colors, polymers and particle sizes. The spatial distribution of sampling sites obtained through literature mining was executed in ArcGIS 10.5 software, primarily divided into surface water and sediment categories. Scatter box plots were used to demonstrate median abundance values, while pie charts depicted the proportions of shapes, colors, and polymers. Violin plots illustrated particle size distribution and peak trends, and these visualizations were implemented in Origin 2021. To minimize potential issues arising from inconsistent riverine MP sampling methods hindering comparisons, different sampling methods were classified into two groups for statistical description, namely, bulk water sampling and volume-reduced sampling, to avoid errors caused by pore size differences. Meanwhile, we used the Mann-Whitney U test, also known as the Wilcoxon rank-sum test, which is a non-parametric statistical test method used to compare whether there is a significant difference in the central tendency between two independent samples in the SPSS 26 software [42]. In our discussion, we employed random sampling to observe the pattern of change in the median values of data with increasing sample sizes [43]. By progressively increasing the sample size, we monitored the variations in the median values, with a specific focus on the rate of change in the first-order difference of the medians. This approach was aimed at identifying the interval where the rate of change in the median values was minimal as the sample size increased, thereby pinpointing the range where the median values tended to stabilize. The methodology for sampling and calculating the first-order difference in change rates was implemented in Python.

In the analysis of surface water MPs, 64.5% of the sampling points were located in Asia, trailed by North America (20.1%) and Europe (14.1%). In the sediment MP dataset, Asia accounted for 53.1% of the locations, while Europe and North America were represented by 20.4% and 15.5%, respectively. This distribution underscores the primary focus of riverine MP research within these three regions: Asia, Europe, and North America. To facilitate comparative analysis of riverine MPs across regions, data from Europe and North America, sharing economic development parallels, were merged into a single category termed "Euro-America". This combined data was then contrasted with the predominantly Asian dataset, which represented over half of the

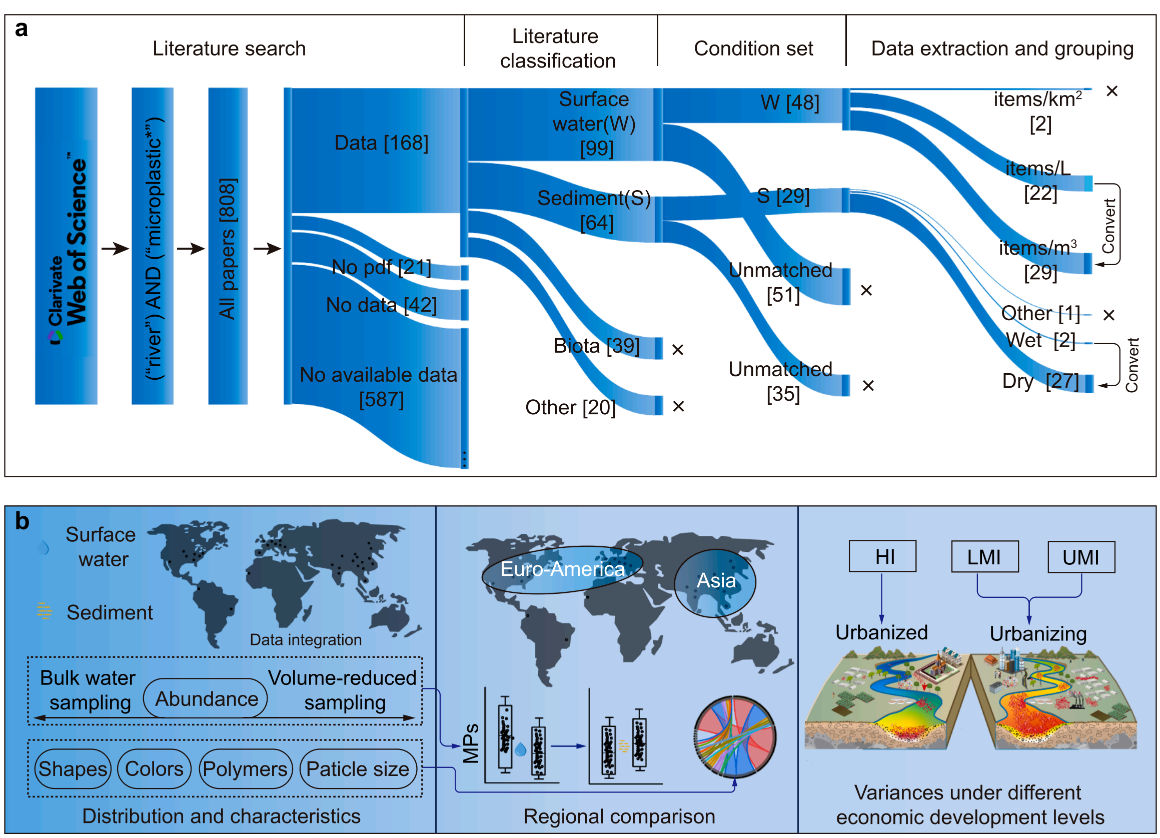


Fig. 1. Schematic diagrams of the literature mining and the spatial variations analysis workflow. (a) Represents the process of literature search, screening, and data integration for riverine MPs; [number] indicates the number of articles; × denotes non-compliance with the criteria for riverine MP data mining. (b) Represents the main aspects of spatial disparity analysis for riverine MPs identified through literature data mining, including spatial distribution, characteristic integration, comparison across different regions, and comparison among varying economic levels. Euro-America: European and North American countries; high income (HI), upper-middle income (UMI), lower-middle income (LMI).

sampling sites. Scatter box plots and chord diagrams were utilized to illustrate and compare the regional variations in riverine MP characteristics, with these analyses conducted using Origin 2021. The Jaccard similarity coefficient [44] was used to compare the similarity in shapes, colors, and polymers of riverine MPs between Asian and Euro-America countries, with calculations based on Eq. (1).

$$Jaccard(A,B) = \left|\frac{A \cap B}{A \cup B}\right| \tag{1}$$

A represents Asia, and B represents Euro-America. The Jaccard similarity coefficient measures how similar two sets are. A coefficient near 1 suggests high similarity, while a coefficient close to 0 indicates significant dissimilarity. Generally, Jaccard ≥ 0.7 suggests high similarity, indicating a substantial overlap. $0.5 \leq$ Jaccard < 0.7 implies moderate similarity, Jaccard < 0.5 indicates low similarity.

Pollution rivers vary for different economic development levels of the watershed and MP abundance is closely related to the level of urbanization [45,46]. Hence, this study also compared the economic development level where the river was located with the corresponding MP abundance, and further summarized this into two development categories: urbanized and urbanizing. The countries' economic development levels were based on the World Bank's World Development Indicators [47], which classify countries' economies as high income (HI), upper-middle income (UMI), lower-middle income (LMI), and low income (LI). In this study, no river data were available for LI countries. Finally, we define rivers in HI countries as "Urbanized" rivers and rivers in UMI and LMI countries as "Urbanizing" rivers. Additionally, our analysis employed the Kruskal-Wallis H test, a non-parametric statistical test utilized for comparing three or more independent groups [48].

3. Results

3.1. Distribution and characteristics of MPs in rivers

In surface water, MP median abundance was 2030 items/m^3 with bulk water sampling, and the range from the 25th percentile to the 75th percentile (interquartile range, IQR) was 658–6250 items/m^3 (Fig. 2b). MP median abundance was 1.6 items/m^3 with volume-reduced sampling, and IQR was 0.5–8.3 items/m^3 (Fig. 2b). The shapes were mainly fiber (52.7%), fragment (25.90%), film (9.30%), and pellet (6.30%) (Fig. 2c). The colors were mainly transparent, accounting for 25.20%, followed by white, blue, and black, accounting for 21.20%, 17.30%, 13.60%, respectively. Transparent, white, and blue-colored MPs comprised more than half (63.70%) of the dataset (Fig. 2d). The most common polymers were polypropylene (PP) and polyethylene (PE), accounting for 31.6% and 30.7%, respectively, followed by polystyrene (PS), accounting for 13.5%. The remaining polymers with higher proportion were polyethylene terephthalate (PET), rayon, polycarbonate (PC) accounting for 4.8%, 4.6% and 3.4%, respectively (Fig. 2e). The particle size of 0–0.5 mm accounted for 55.4%, 0.5–5 mm accounted for 44.6% and 0–1 mm accounted for 72.5%, 1–5 mm accounted for 27.5% (Fig. 2f).

In sediment, MP median abundance was 274 items/kg, and the IQR was 77–1407 items/kg (Fig. 2b). The shapes were mainly fiber, accounting for 44.5%, followed by fragment, film, and pellet, accounting for 34.4%, 9.1%, 5.2%, respectively (Fig. 2c). The colors were mainly transparent, accounting for 29.0%, followed by white, blue, and black, accounting for 22.2%, 16.1%, 12.5%, respectively. As with the surface water, transparent, white and blue-colored MPs also comprised more than half of the dataset (Fig. 2d). The most common polymers was PE, accounting for 37.1%, followed by PP and PS, accounting for 19.1% and 15.6%, respectively. The remaining polymers with higher proportion

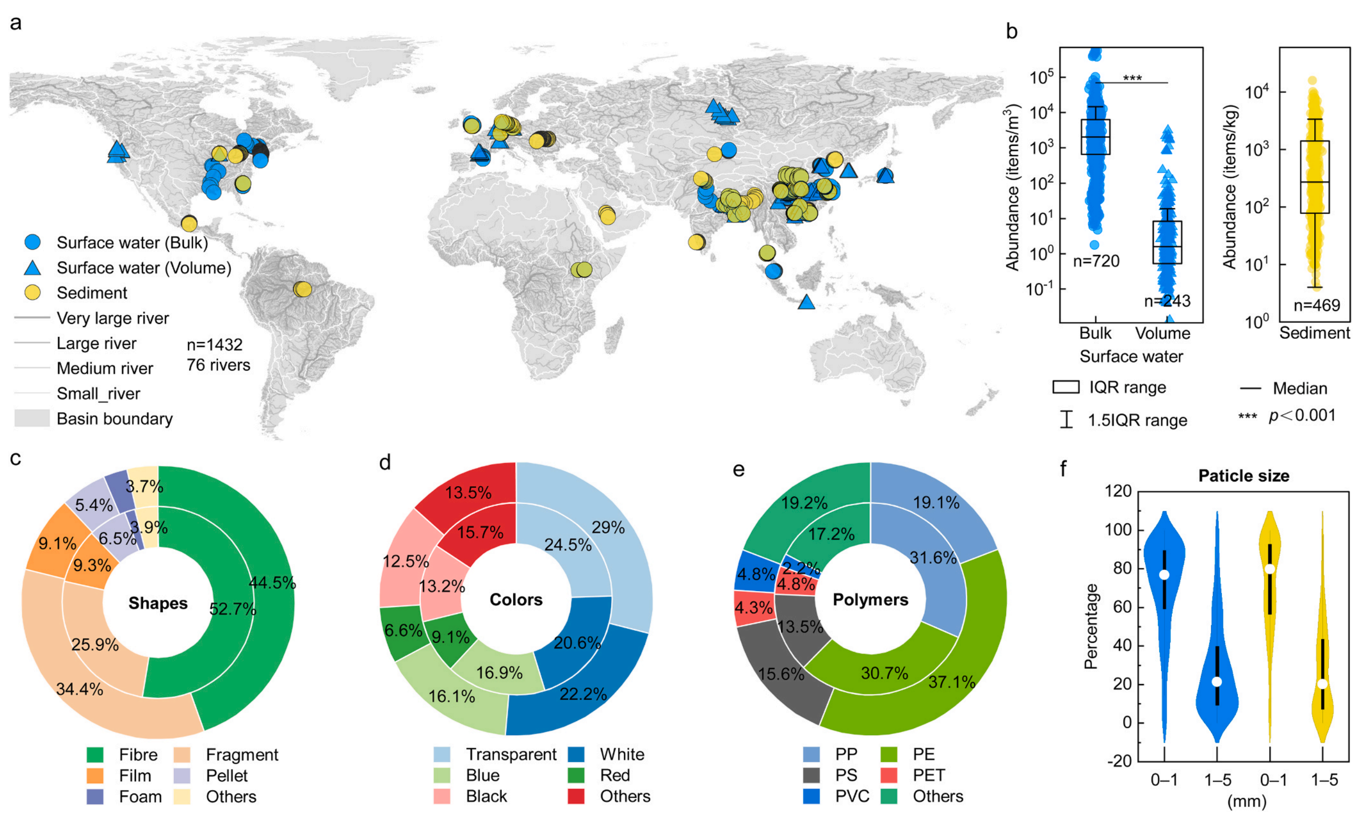


Fig. 2. Integrated literature data on riverine MPs: Spatial distribution of sampling sites (a) and characteristics including MP abundance (b), shapes (c), colors (d), polymers (e) and particle sizes (f) in surface water (in c-e, the inner circle represents surface water) and sediment (in c-e, the outer circle represents to sediment). (Bulk: Bulk water sampling; Volume: Volume-reduced sampling; ***indicates $p < 0.001$).

were polyvinylchloride (PVC), PET, polyamide (PA) accounting for 4.8%, 4.3% and 3.8%, respectively (Fig. 2e). The particle size of 0–0.5 mm accounted for 53.7%, 0.5–5 mm accounted for 46.3% and 0–1 mm accounted for 72.9%, 1–5 mm accounted for 27.1% (Fig. 2f).

3.2. Comparative analysis of riverine MPs across different regions

Differences in surface water and sediment MP abundance were found between Asian and Euro-America regions. For bulk sampling in surface water, the median abundance of MPs in Asia was 2823 items/m^3, with an IQR of 1022–7903 items/m^3. In Euro-America, the median abundance of MPs was 900 items/m^3 and the IQR was 135–2100 items/m^3. The median MP abundance in Asia was 3.1 times higher than in Euro-America (Fig. 3a). For volume-reduced sampling in surface water, the median abundance of MPs in Asia was 3.7 items/m^3 and IQR was 0.7–27.7 items/m^3. In Euro-America, the median abundance of MPs was 2.1 items/m^3 and the IQR was 0.3–5.4 items/m^3. The median in Asia was 1.8 times higher than in Euro-America (Fig. 3a). The median abundance of MPs for sediment in Asia was 186 items/kg and the IQR was 55–602 items/kg. In Euro-America, the median was 795 items/kg and the IQR was 137–2513 items/m^3. In contrast to the trend for surface water, the median for river sediment in Euro-America was 4.3 times higher than in Asia (Fig. 3d).

Riverine MPs from Asia and Euro-America showed moderate similarity in shapes and polymers in surface water. In Asia, the MP shapes in surface water were mainly fiber and fragment, accounting for 53.5% and 24.4% of samples, respectively. Other shapes accounting for a relatively large proportion were film (10.2%) and pellet (6.5%). In Euro-America, fiber (44.2%) and fragment (38.7%) were also the predominant shapes, accounting for more than 80% of the total, while pellet (6.4%) and line (5.2%) were the other predominant shapes. The Jaccard similarity coefficient between Asia and the Euro-America was 0.64, indicating a moderate similarity (Fig. 3b). In Asia, PP (31.6%) and PE (30.4%) were the most common polymers. Others common polymerss were PS (15.0%) and PET (6.5%). In Euro-America, PE (47.5%) and PP (45.0%) were also the most common polymers and accounted for more than 90% of the total. The Jaccard was 0.53, also indicating a moderate similarity (Fig. 3c). In the dataset compiled for this study, there were no available data on the colors of MPs in Euro-America, therefore, this section only describes the MP colors in Asia, which were mainly transparent, white, blue and red, accounting for 24.4%, 20.5%, 16.8% and 9.1% respectively. Additionally, all the data obtained through text mining regarding the proportion of particle sizes were exclusively from Asia.

Riverine MPs from Asia and Euro-America also showed moderate similarity in shapes, colors and polymers in sediment. The shapes of MPs in Asian riverine sediment were also mainly fiber and fragment (41.2% and 36.8%, respectively), cumulatively accounting for nearly 80% of total, while film and sheet only accounted for 12.1% and 4.3%, respectively. In Euro-America, fiber and fragment were also the main shapes of sediment MPs, accounting for more than 80% (51.9% and 30.4%, respectively), while pellet (11.9%) and line (3.7%) accounted for the other shapes. The Jaccard was 0.64, also indicating a moderate similarity (Fig. 3e). The colors of MPs in Asian river sediment were also transparent, white, blue and black, accounting for 33.1%, 21.8%, 14.8% and 11.3%, respectively. The colors of MPs in Euro-America river sediment were mainly white, blue, black, and transparent, accounting for 24.3%, 22.2%, 18.8% and 9.6%, respectively. There were slight differences in the proportion of colors between the two regions, mainly in the proportion of transparent MPs. The Jaccard was 0.54, still indicating a moderate similarity (Fig. 3f). PE accounted for 36.6% of the MPs in Asian river sediment, while PP and PS accounted for 19.1% and 15.7% respectively. Among the polymer of MPs in river sediment in Euro-America, PE accounted for the highest proportion, 41.4%. Other polymers with relatively high proportion were PP and PS, accounting for 18.9% and 14.4%, respectively. The Jaccard was 0.71, indicating a high similarity (Fig. 3g).

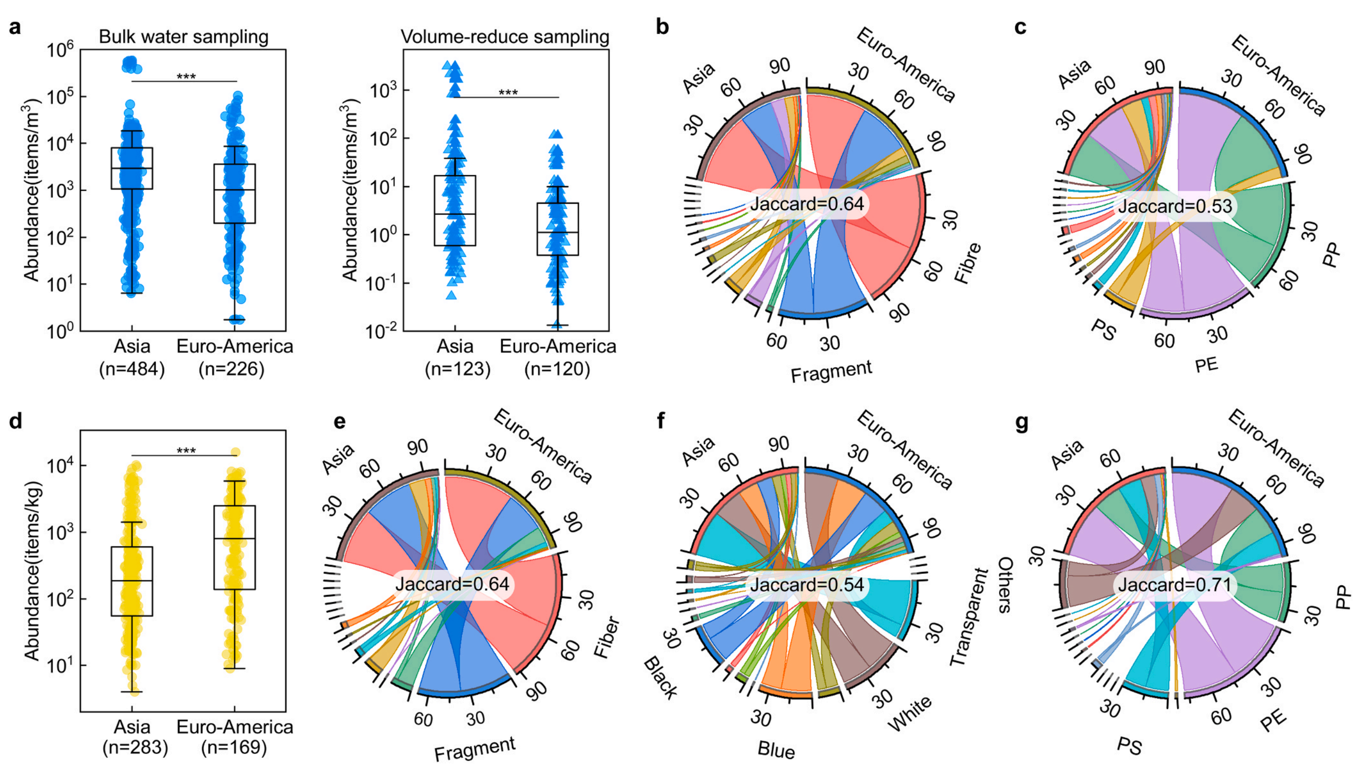


Fig. 3. Characteristics of regional riverine MPs in surface water and sediment. (a) MP abundance in surface water via bulk water sampling and volume-reduced sampling; (b-c) MP shapes and polymers in surface water; (d) MP abundance in sediment; e-g: shapes, colors and polymers, respectively in sediment; Euro-America: European and North American countries; PP: Polypropylene; PE: Polyethylene; PS: Polystyrene; Jaccard: Jaccard similarity coefficient. ***indicates $p < 0.001$.

3.3. *Difference under different economic development levels*

Significant variations in riverine MP abundance were identified among countries with varying economic development levels (Fig. 4a). In the bulk sampling method of river surface water, significant differences ($p < 0.001$) were observed in MP abundance between high income (HI), upper-middle income (UMI), and lower-middle income (LMI). The UMI displayed a higher median abundance at 3330 items/m^3 . The HI had a median abundance of 992 items/m^3 , while the LMI recorded the lowest median abundance at 373 items/m^3 . When river surface water was collected via volume-reduced sampling method, there were significant differences ($p < 0.01$) in MP abundance between UMI and HI, with UMI showing a median abundance of 2.68 items/m^3 , in contrast to HI with 1.2 items/m^3 . On average, MP abundance in UMI was 2–3 times that observed in HI. In sediment analysis, significant differences ($p < 0.01$) emerged in MP abundance, with HI presenting the highest median abundance at 934 items/kg. The LMI showed a median abundance of 200 items/kg, while UMI had a slightly lower median abundance at 166 items/kg. Ultimately, the median abundance in HI was approximately fivefold that of both LMI and UMI.

The association between the degree of MP pollution in surface water and sediment and the level of urbanization was inversely related (Fig. 4b). The results showed that the median abundance of riverine MPs undergoing urbanization in LMI and UMI countries was 2834 items/m^3 when sampled using the bulk sampling method, and 2.78 items/m^3 with the volume-induced method. In contrast, the median MP abundance in rivers within highly urbanized HI countries was 992 items/m^3 with bulk sampling, and 1.2 items/m^3 with volume-induced sampling. The abundance of MPs in the rivers of urbanizing countries was approximately 2 to 3 times higher than that in highly urbanized rivers. However, the abundance of MPs in sediment from highly urbanized rivers was five times higher than that in rivers from urbanizing countries. This indicated that river surface water, as a direct recipient of MPs, recorded the pollution status in countries experiencing urbanization, while sediment archived the historical use and pollution levels.

4. Discussion

4.1. *Analysis of sample size in riverine MP dataset*

The two main factors affecting the comparative assessments among riverine MPs are the differences in environmental sampling methodologies, which can present challenges in compiling data across studies, and the fact that MP abundance is affected by river characteristics and consequently result in significant spatial and temporal differences in data [16,35,49]. Due to the two inherent characteristics of MPs in rivers at present, the integration of their data has become exceedingly challenging. Despite our attempts to categorize the sampling methods for river surface water into two classes [16,50] to mitigate method-induced variations, it remains difficult to circumvent differences arising from both temporal and spatial dimensions. Nevertheless, despite these spatiotemporal variations, a sufficiently large dataset can still effectively reflect changes in MP abundance, facilitating a comprehensive understanding [35,51–53]. Therefore, careful consideration must be given to

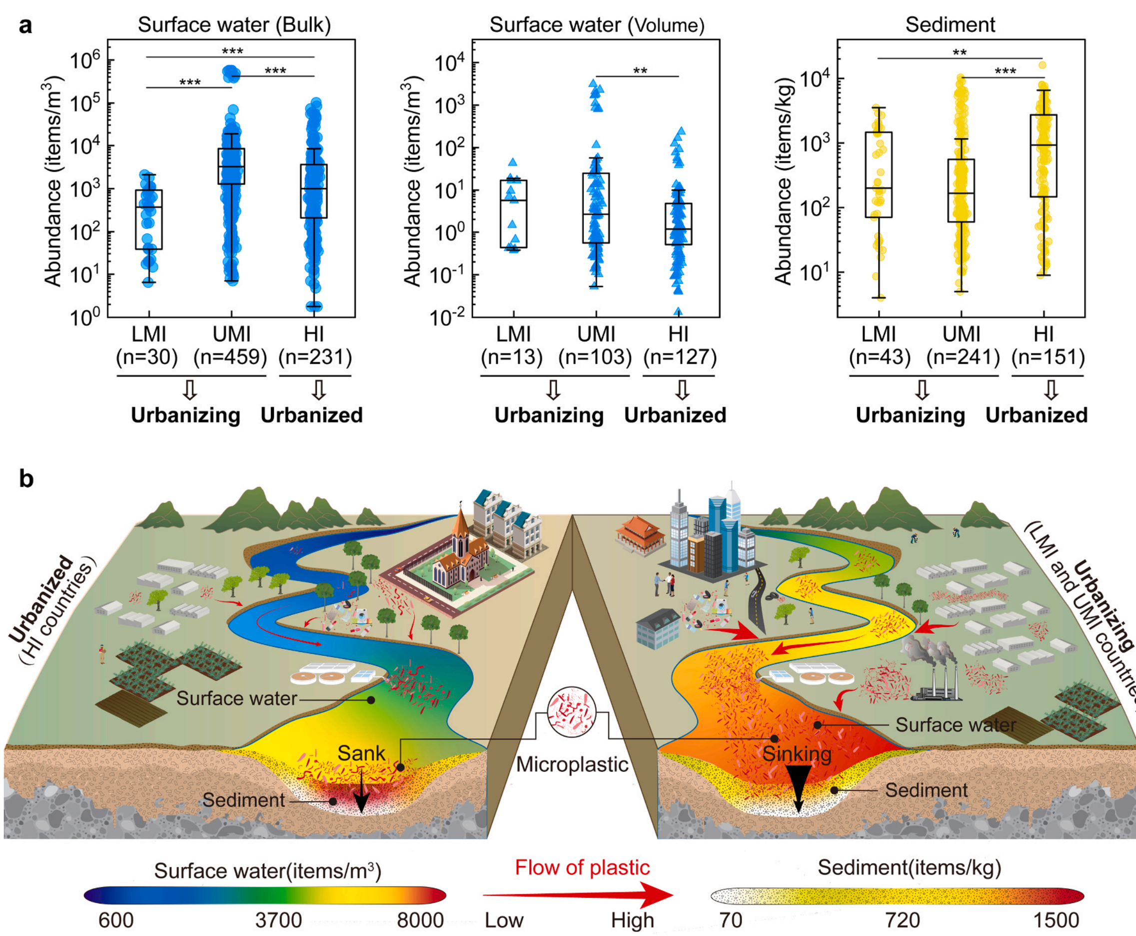


Fig. 4. Differences in riverine MPs in surface water and sediment between urbanized and urbanizing regions. LMI: lower-middle income; UMI: upper-middle income; HI: high income; the minimum and maximum values of MP abundance in surface water in the legend of the concept map are the approximate integer value of the 25% and 75% quartiles of the bulk water sampling method; the minimum and maximum values of MP abundance in sediment are the approximate integer values of the 75% and 25% quartiles. ***indicates $p < 0.001$, **indicates $p < 0.01$.

the adequacy of the dataset to ensure that riverine MPs comprehensively mirror the current situation [43].

The sample size for riverine MPs were limited, yet the abundance values consistently exhibited variation within a stable range. Through an analysis of the variance in MP abundance in both surface water and sediment as the sample size increases, specific results are detailed in supplementary Fig. S2. The surface water with bulk water sampling method displayed the smallest data variation, with a median abundance of 1929.11 items/m^3 and a rate of change within ± 20%. Subsequently, the median MP abundance in the sediment was 300 items/kg, with a constant range within ± 50%; the surface water using the volume-reduced sampling method exhibited the greatest rate of change, with an interval of ± 100%, and a median abundance value of 2.16 items/m^3. Typically, if the change in the first-order difference fluctuates within a small range (for example, a rate of change within ± 5% or lower), it may indicate that the data are tending towards stability. Consequently, it is evident that the dataset involved in this study have not reached stability. To obtain a constant value, a larger sample size is required, especially for the dataset of surface water with volume-reduce sampling method, which has the largest range of rate of change. However, it was feasible to approximate the general range of abundance values, thereby providing valuable reference insights for interpreting the MP abundance in rivers. We argue that the reported median abundance values in this study could be used as an environmental reference or baseline for measuring riverine MP contamination level.

4.2. Spatial variation analysis of riverine MPs

The riverine MPs in the regions with different development stages showed heterogeneity. At present, research on riverine MPs was mainly concentrated in three regions: Asia, Europe and North America. A substantial body of data has demonstrated that the abundance of MPs in surface water in Asia, especially in Chinese rivers, exceeded that of Euro-America countries by several orders of magnitude, at times [3,11,12]. However, the abundance of MPs in sediment was higher in Euro-America than Asia. We assumed and summarized that, the variations in MP levels in river surface water and sediment between Asia and Euro-America, as well as between nations in different stages of urbanization, revealed a counterintuitive association between the degree of MP pollution and the level of urbanization. The distinct temporal misalignment in the stages of MP usage and management during various phases of urbanization was evident. The primary reasons for these variations may be attributed to the rapid industrialization and urbanization experienced by Asian and urbanizing nations, leading to extensive plastic utilization and production [45,54]. Simultaneously, these regions or nations may have grappled with inadequate waste management practices, including a lack of effective waste disposal and recycling systems, resulting in the substantial influx of plastic waste into rivers [54,55]. In contrast, regions such as Euro-America, or fully urbanized nations, exhibited relatively well-established infrastructure and environmental management policies, contributing to lower MP abundance in water [56]. Having undergone prolonged urbanization phases, rivers in these regions have become significant plastic reservoirs, with MP transitioning and accumulating in the sediment under various conditions, consequently leading to a higher abundance of MPs in these sedimentary environments [4].

From a river dynamics perspective, the differential distribution of MPs in urbanized and urbanizing regions can be significantly influenced by the hydraulic characteristics and geomorphological changes within river systems due to urbanization. In urbanizing areas, where infrastructure development is nascent, rivers often undergo extensive modifications such as channel straightening and hardening to accommodate increased runoff and mitigate flood risks [57]. These alterations generally accelerate water flow, which reduces the residence time of water and suspended particles, including MPs, thus diminishing their opportunity to settle in the sediment [58]. As urbanization progresses, the establishment of more sophisticated stormwater management systems and the implementation of erosion control measures tend to stabilize the riverbeds [59]. In highly urbanized areas, engineered structures like weirs and dams are introduced, which alter flow regimes significantly [58]. These structures can create areas of reduced flow velocity downstream, which are conducive to the deposition of suspended particles [59]. Slow-moving waters facilitate the settling of heavier MPs into the sediment, leading to a higher MP abundance in the sediment of fully urbanized regions compared to those in flux [22]. Thus, understanding the interplay between urban landscape changes and river hydrodynamics is essential for predicting and managing MP pollution in urban waterways. This insight is crucial for developing strategies that mitigate the environmental impact of urban runoff laden with MPs.

4.3. Outlook

The study of MPs in large-scale river systems is a multidisciplinary endeavor, integrating environmental science, geography, chemistry, and data science. In this study, we primarily used dataset from Asia and Euro-America, and we must acknowledge that this approach has neglected low-income countries, thereby limiting the global representativeness of our research [60]. Future efforts should broaden data sources, particularly with increased focus on low-income areas, to promote a fairer understanding and response to global MP pollution. International collaboration is vital for methodological standardization and data sharing, given the global nature of MP pollution [9]. It hinges on establishing standardized methodologies for the systematic collection and analysis of MP samples across diverse riverine environments [9,61–63]. Transnational research necessitates refined sampling techniques and advanced MP extraction and identification methods [64]. High spatial resolution is crucial, requiring extensive geographic sampling to accurately represent the spatial distribution patterns of MPs [15]. Factors such as the physical, chemical, and biological characteristics of rivers, and the impact of nearby human activities, are integral to understanding MP distribution [65,66]. Data analysis employing statistical methods and Geographic Information Systems (GIS) is essential, alongside developing predictive models for future MP pollution trends [15,67]. The waste processing and recycling policies of different countries, especially regarding plastic waste, are crucial for reducing MP inputs into rivers [54,55]. Studies should evaluate the effectiveness of these policies and explore their correlations with MP pollution. This research aims not just to deepen scientific understanding of MP distribution but also to inform policy-making and riverine environmental management, ultimately mitigating the impact of MP pollution. Through interdisciplinary efforts, this research addresses a crucial environmental challenge, protecting water resources and ecosystems from MP contamination.

5. Conclusions

Through literature data mining, we integrated the characteristics of 1432 MP sampling sites from 76 rivers, encompassing abundance, shapes, colors, polymers, and particle sizes. We found that these riverine MP research were predominantly located in Asia (64.5%), Europe (20.1%), and North America (14.1%), and a significant variation ($p < 0.001$) between the abundance of MPs obtained through bulk water and volume-reducing sampling methods in surface water. A comparison across different regions revealed a mismatch between Asian and Euro-America, with MP abundance in Asian rivers being 2–3 times higher than those in the Euro-America, whereas Euro-America abundance was found to be 5 times those in Asia. In addition to differences in abundance, other characteristics of riverine MPs also exhibited regional variations, showing moderately similar features. Higher abundance in water samples were observed in urbanizing countries, while higher abundance in sediment were noted in urbanized countries. This spatial disparity in riverine MPs warrants an interpretation from varying economic development perspectives, prompting us to reconsider the focus of riverine MP management measures at different stages of economic development.

Environmental implication

Through literature synthesis, we gathered data on microplastics from 76 rivers, mainly distributed in Asia and the Euro-American regions. Our extensive regional analysis showed notable variations in the presence of microplastics within surface water and sediment across these regions, underlining crucial aspects of managing riverine microplastic pollution. It suggests that developed countries need to concentrate on sediment-based microplastics, whereas developing countries should give precedence to microplastics found in water samples.

CRediT authorship contribution statement

Yu-qin He: Visualization, Formal analysis, Data curation. **Zhao-feng Guo:** Writing – review & editing, Funding acquisition, Formal analysis, Data curation. **Tim H.M. van Emmerik:** Writing – review & editing, Validation, Methodology, Formal analysis. **Yu-yao Xu:** Writing – review & editing, Formal analysis, Conceptualization. **Dong Liu:** Writing – review & editing, Formal analysis. **Yao-yang Xu:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Cai Chen:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Sheree A Pagsuyoin:** Writing – review & editing, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have uploaded the data at the attach file step.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (No: 42307066), the Open Competition Mechanism to Select the Best Candidates Program (No: IUE-JBGS-202203), the Ningbo S&T project (No: 2021-DST-004). We thank four anonymous reviewers and editor for their careful reviews and suggestions in improving this manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2024.134571.

References

[1] Rochman, C.M., 2018. Microplastics research—from sink to source. Science 360 (6384), 28–29. https://doi.org/10.1126/science.aar7734.
[2] Rochman, C.M., Hoellein, T., 2020. The global odyssey of plastic pollution. Science 368 (6496), 1184–1185. https://doi.org/10.1126/science.abc4428.
[3] Lebreton, L.C.M., Van der Zwet, J., Damsteeg, J.W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat Commun 8. https://doi.org/10.1038/ncomms15611.
[4] van Emmerik, T., Mellink, Y., Hauk, R., Waldschläger, K., Schreyers, L., 2022. Rivers as plastic reservoirs. Front Water 3, 786936. https://doi.org/10.3389/frwa.2021.786936.
[5] Wang, C., Zhao, J., Xing, B., 2021. Environmental source, fate, and toxicity of microplastics. J Hazard Mater 407, 124357. https://doi.org/10.1016/j.jhazmat.2020.124357.
[6] Xia, F., Tan, Q., Qin, H., Wang, D., Cai, Y., Zhang, J., 2023. Sequestration and export of microplastics in urban river sediments. Environ Int 181, 108265. https://doi.org/10.1016/j.envint.2023.108265.
[7] Koelmans, A.A., Mohamed Nor, N.H., Hermsen, E., Kooi, M., Mintenig, S.M., De France, J., 2019. Microplastics in freshwaters and drinking water: critical review and assessment of data quality. Water Res 155, 410–422. https://doi.org/10.1016/j.watres.2019.02.054.
[8] Rillig, M.C., Lehmann, A., 2020. Microplastic in terrestrial ecosystems. Science 368 (6498), 1430–1431. https://doi.org/10.1126/science.abb5979.
[9] Nava, V., Chandra, S., Aherne, J., Alfonso, M.B., Antão-Geraldes, A.M., Attermeyer, K., et al., 2023. Plastic debris in lakes and reservoirs. Nature 619 (7969), 317–322. https://doi.org/10.1038/s41586-023-06168-4.
[10] Windsor, F.M., Durance, I., Horton, A.A., Thompson, R.C., Tyler, C.R., Ormerod, S. J., 2019. A catchment-scale perspective of plastic pollution. Glob Chang Biol 25, 1207–1221. https://doi.org/10.1111/gcb.14572.
[11] Mai, L., Sun, X.F., Xia, L.L., Bao, L.J., Liu, L.Y., Zeng, E.Y., 2020. Global riverine plastic outflows. Environ Sci Technol 54 (16), 10049–10056. https://doi.org/10.1021/acs.est.0c02273.
[12] Meijer, L.J.J., van Emmerik, T., van der Ent, R., Schmidt, C., Lebreton, L., 2021. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Sci Adv 7 (18), eaaz5803. https://doi.org/10.1126/sciadv.aaz5803.
[13] Schmidt, C., Krauth, T., Wagner, S., 2017. Export of plastic debris by rivers into the sea. Environ Sci Technol 51 (21), 12246–12253. https://doi.org/10.1021/acs.est.7b02368.
[14] Strokal, M., Vriend, P., Bak, M.P., Kroeze, C., van Wijnen, J., van Emmerik, T., 2023. River export of macro- and microplastics to seas by sources worldwide. Nat Commun 14 (1), 4842. https://doi.org/10.1038/s41467-023-40501-9.
[15] Mennekes, D., Nowack, B., 2023. Predicting microplastic masses in river networks with high spatial resolution at country level. Nat Water 1, 523–533. https://doi.org/10.1038/s44221-023-00090-9.
[16] Bai, M., Lin, Y., Hurley, R.R., Zhu, L., Li, D., 2022. Controlling factors of microplastic riverine flux and implications for reliable monitoring strategy. Environ Sci Technol 56 (1), 48–61. https://doi.org/10.1021/acs.est.1c04957.
[17] Eo, S., Hong, S.H., Song, Y.K., Han, G.M., Shim, W.J., 2019. Spatiotemporal distribution and annual load of microplastics in the Nakdong River, South Korea. Water Res 160, 228–237. https://doi.org/10.1016/j.watres.2019.05.053.
[18] Scircle, A., Cizdziel, J.V., Missling, K., Li, L., Vianello, A., 2020. Single-pot method for the collection and preparation of natural water for microplastic analyses: microplastics in the Mississippi River system during and after historic flooding. Environ Toxicol Chem 39 (5), 986–995. https://doi.org/10.1002/etc.4698.
[19] Wang, Z., Su, B., Xu, X., Di, D., Huang, H., Mei, K., et al., 2018. Preferential accumulation of small (<300 μm) microplastics in the sediments of a coastal plain river network in eastern China. Water Res 144, 393–401. https://doi.org/10.1016/j.watres.2018.07.050.
[20] Barrows, A.P.W., Christiansen, K.S., Bode, E.T., Hoellein, T.J., 2018. A watershed-scale, citizen science approach to quantifying microplastic concentration in a mixed land-use river. Water Res 147, 382–392. https://doi.org/10.1016/j.watres.2018.10.013.
[21] Baldwin, A.K., Corsi, S.R., Mason, S.A., 2016. Plastic debris in 29 great lakes tributaries: relations to watershed attributes and hydrology. Environ Sci Technol 50 (19), 10377–10385. https://doi.org/10.1021/acs.est.6b02917.
[22] Drummond, J.D., Schneidewind, U., Li, A., Hoellein, T.J., Krause, S., Packman, A.I., 2022. Microplastic accumulation in riverbed sediment via hyporheic exchange from headwaters to mainstems. Sci Adv 8 (2), eabi9305. https://doi.org/10.1126/sciadv.abi9305.
[23] Mintenig, S.M., Kooi, M., Erich, M.W., Primpke, S., Redondo-Hasselerharm, P.E., Dekker, S.C., et al., 2020. A systems approach to understand microplastic occurrence and variability in Dutch riverine surface waters. Water Res 176. https://doi.org/10.1016/j.watres.2020.115723.
[24] Hurley, R., Woodward, J., Rothwell, J.J., 2018. Microplastic contamination of river beds significantly reduced by catchment-wide flooding. Nat Geosci 11 (4), 251–257. https://doi.org/10.1038/s41561-018-0080-1.
[25] Mani, T., Hauk, A., Walter, U., Burkhardt-Holm, P., 2015. Microplastics profile along the Rhine River. Sci Rep 5 (1), 17988. https://doi.org/10.1038/srep17988.
[26] Yuan, W., Christie-Oleza, J.A., Xu, E.G., Li, J., Zhang, H., Wang, W., et al., 2022. Environmental fate of microplastics in the world's third-largest river: basin-wide investigation and microplastic community analysis. Water Res 210, 118002. https://doi.org/10.1016/j.watres.2021.118002.
[27] Corcoran, P.L., Belontz, S.L., Ryan, K., Walzak, M.J., 2020. Factors controlling the distribution of microplastic particles in benthic sediment of the Thames River, Canada. Environ Sci Technol 54 (2), 818–825. https://doi.org/10.1021/acs.est.9b04896.
[28] Klein, S., Worch, E., Knepper, T.P., 2015. Occurrence and spatial distribution of microplastics in river shore sediments of the Rhine-Main area in Germany. Environ Sci Technol 49 (10), 6070–6076. https://doi.org/10.1021/acs.est.5b00492.
[29] Li, Q., Han, Z., Su, G., Hou, M., Liu, X., Zhao, X., et al., 2023. New insights into the distribution, potential source and risk of microplastics in Qinghai-Tibet Plateau. Environ Int 175, 107956. https://doi.org/10.1016/j.envint.2023.107956.
[30] Zhang, K., Xiong, X., Hu, H.J., Wu, C.X., Bi, Y.H., Wu, Y.H., et al., 2017. Occurrence and characteristics of microplastic pollution in Xiangxi Bay of Three Gorges Reservoir, China. Environ Sci Technol 51 (7), 3794–3801. https://doi.org/10.1021/acs.est.7b00369.
[31] Zhang, X., Leng, Y.F., Liu, X.N., Huang, K., Wang, J., 2020. Microplastics' pollution and risk assessment in an urban river: a case study in the Yongjiang River, Nanning city, South China. Expo Health 12 (2), 141–151. https://doi.org/10.1007/s12403-018-00296-3.

[32] Feng, S.S., Lu, H.W., Yao, T.C., Liu, Y.L., Tian, P.P., Lu, J.Z., 2021. Microplastic footprints in the Qinghai-Tibet Plateau and their implications to the Yangtze River Basin. J Hazard Mater 407. https://doi.org/10.1016/j.jhazmat.2020.124776.
[33] Stagge, J.H., Rosenberg, D.E., Abdallah, A.M., Akbar, H., Attallah, N.A., James, R., 2019. Assessing data availability and research reproducibility in hydrology and water resources. Sci Data 6 (1), 190030. https://doi.org/10.1038/sdata.2019.30.
[34] van Klink, R., Bowler Diana, E., Gongalsky Konstantin, B., Swengel Ann, B., Gentile, A., Chase Jonathan, M., 2020. Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances. Science 368 (6489), 417–420. https://doi.org/10.1126/science.aax9931.
[35] Weiss, L., Ludwig, W., Heussner, S., Canals, M., Ghiglione, J.-F., Estournel, C., et al., 2021. The missing ocean plastic sink: gone with the rivers. Science 373 (6550), 107–111. https://doi.org/10.1126/science.abe0290.
[36] Rico, A., Redondo-Hasselerharm, P.E., Vighi, M., Waichman, A.V., Nunes, G.Sd.S., de Oliveira, R., et al., 2023. Large-scale monitoring and risk assessment of microplastics in the Amazon River. Water Res 232, 119707. https://doi.org/10.1016/j.watres.2023.119707.
[37] Dhivert, E., Phuong, N.N., Mourier, B., Grosbois, C., Gasperi, J., 2022. Microplastic trapping in dam reservoirs driven by complex hydrosedimentary processes (Villerest Reservoir, Loire River, France). Water Res 225, 119187. https://doi.org/10.1016/j.watres.2022.119187.
[38] Woodward, J., Li, J., Rothwell, J., Hurley, R., 2021. Acute riverine microplastic contamination due to avoidable releases of untreated wastewater. Nat Sustain 4 (9), 793–802. https://doi.org/10.1038/s41893-021-00718-2.
[39] Xia, F., Liu, H., Zhang, J., Wang, D., 2022. Migration characteristics of microplastics based on source-sink investigation in a typical urban wetland. Water Res 213, 118154. https://doi.org/10.1016/j.watres.2022.118154.
[40] Mughini-Gras, L., van der Plaats, R.Q.J., van der Wielen, P.W.J.J., Bauerlein, P.S., de Roda, H.A.M., 2021. Riverine microplastic and microbial community compositions: a field study in the Netherlands. Water Res 192, 116852. https://doi.org/10.1016/j.watres.2021.116852.
[41] Fang, Q., Niu, S.P., Yu, J.H., 2021. Characterising microplastic pollution in sediments from urban water systems using the diversity index. J Clean Prod 318. https://doi.org/10.1016/j.jclepro.2021.128537.
[42] Mann, H.B., D. Whitney, R., 1947. On a test of whether one of two random variables is stochastically larger than the other. Ann Math Stat 18 (1), 50–60. https://doi.org/10.1214/aoms/1177730491.
[43] Sapra, R.L., 2022. How to calculate an adequate sample size. In: Nundy, S., Kakar, A., Bhutta, Z.A. (Eds.), How to practice academic medicine and publish from developing countries? A practical guide. Springer Nature Singapore, Singapore, pp. 81–93. https://doi.org/10.1007/978-981-16-5248-6_49.
[44] Jaccard, P., 1912. The distribution of the flora in the alpine zone. N Phytol 11 (2), 37–50. https://doi.org/10.1111/j.1469-8137.1912.tb05611.
[45] Strokal, M., Bai, Z., Franssen, W., Hofstra, N., Koelmans, A.A., Ludwig, F., et al., 2021. Urbanization: an increasing source of multiple pollutants to rivers in the 21st century. npj Urban Sustain 1 (1), 24. https://doi.org/10.1038/s42949-021-00026-w.
[46] Wagner, S., Klöckner, P., Stier, B., Römer, M., Seiwert, B., Reemtsma, T., et al., 2019. Relationship between discharge and river plastic concentrations in a rural and an urban catchment. Environ Sci Technol 53 (17), 10082–10091. https://doi.org/10.1021/acs.est.9b03048.
[47] World Bank, 2022. World Development Indicators. https://datacatalog.worldbank.org/search/dataset/0037712/World-Development-Indicators.
[48] Wallace, D.L., 1959. Simplified beta-approximations to the Kruskal-Wallis H-test. J Am Stat Assoc 54 (285), 225–230. https://doi.org/10.1126/science.abl4649.
[49] Mai, L., You, S.N., He, H., Bao, L.J., Liu, L.Y., Zeng, E.Y., 2019. Riverine microplastic pollution in the Pearl River Delta, China: are modeled estimates accurate? Environ Sci Technol 53 (20), 11810–11817. https://doi.org/10.1021/acs.est.9b04838.
[50] Weiss, L., Ludwig, W., 2022. Response to comment on "The missing ocean plastic sink: gone with the rivers. Science 377 (6608). https://doi.org/10.1126/science.abm7305.
[51] Guo, Z., Boeing, W.J., Xu, Y., Borgomeo, E., Mason, S.A., Zhu, Y.G., 2021. Global meta-analysis of microplastic contamination in reservoirs with a novel framework. Water Res 207, 117828. https://doi.org/10.1016/j.watres.2021.117828.
[52] Hua, F., Bruijnzeel, L.A., Meli, P., Martin, P.A., Zhang, J., Nakagawa, S., et al., 2022. The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. Science 376 (6595), 839–844. https://doi.org/10.1126/science.abl4649.
[53] Liu, D., Xu, Y.Y., Junaid, M., Zhu, Y.G., Wang, J., 2022. Distribution, transfer, ecological and human health risks of antibiotics in bay ecosystems. Environ Int 158, 106949. https://doi.org/10.1016/j.envint.2021.106949.
[54] Xu, Z., Xu, J., Yin, H., Jin, W., Li, H., He, Z., 2019. Urban river pollution control in developing countries. Nat Sustain 2 (3), 158–160. https://doi.org/10.1038/s41893-019-0249-7.
[55] Kumari, T., Raghubanshi, A.S., Singh, P., Verma, P., Singh, R., Ahamad, A., Batalhão, A.C.S., 2023. Waste management and resource recycling in the developing world. Elsevier, pp. 773–797. https://doi.org/10.1016/B978-0-323-90463-6.00017-8.
[56] Mahtta, R., Fragkias, M., Güneralp, B., Mahendra, A., Reba, M., Wentz, E.A., et al., 2022. Urban land expansion: the role of population and economic growth for 300+ cities. npj Urban Sustain 2 (1), 5. https://doi.org/10.1038/s42949-022-00048-y.
[57] Chin, A., 2006. Urban transformation of river landscapes in a global context. Geomorphology 79 (3), 460–487. https://doi.org/10.1016/j.geomorph.2006.06.033.
[58] G.J. Vietz B.L. Finlayson A.C. Horne J.A. Webb M.J. Stewardson B. Richter M. Acreman Water for the environment 2017 Academic Press 83 100 doi: 10.1016/B978-0-12-803907-6.00005-X.
[59] Arya, S., Kumar, A., 2023. Evaluation of stormwater management approaches and challenges in urban flood control. Urb Clim 51, 101643. https://doi.org/10.1016/j.uclim.2023.101643.
[60] Zhang, Y., Pu, S., Lv, X., Gao, Y., Ge, L., 2020. Global trends and prospects in microplastics research: a bibliometric analysis. J Hazard Mater 400, 123110. https://doi.org/10.1016/j.jhazmat.2020.123110.
[61] Allen, D., Allen, S., Abbasi, S., Baker, A., Bergmann, M., Brahney, J., et al., 2022. Microplastics and nanoplastics in the marine-atmosphere environment. Nat Rev Earth Environ 3 (6), 393–405. https://doi.org/10.1038/s43017-022-00292-x.
[62] Eerkes-Medrano, D., Thompson, R.C., Aldridge, D.C., 2015. Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. Water Res 75, 63–82. https://doi.org/10.1016/j.watres.2015.02.012.
[63] Rozman, U., Kalčíková, G., 2022. Seeking for a perfect (non-spherical) microplastic particle—the most comprehensive review on microplastic laboratory research. J Hazard Mater 424, 127529. https://doi.org/10.1016/j.jhazmat.2021.127529.
[64] Singh, B., Kumar, A., 2024. Advances in microplastics detection: a comprehensive review of methodologies and their effectiveness. TrAC Trends Anal Chem 170, 117440. https://doi.org/10.1016/j.trac.2023.117440.
[65] Huang, Q.E., Liu, M., Cao, X., Liu, Z., 2022. Occurrence of microplastics pollution in the Yangtze River: distinct characteristics of spatial distribution and basin-wide ecological risk assessment. Water Res, 119431. https://doi.org/10.1016/j.watres.2022.119431.
[66] Messager, M.L., Lehner, B., Cockburn, C., Lamouroux, N., Pella, H., Snelder, T., et al., 2021. Global prevalence of non-perennial rivers and streams. Nature 594 (7863), 391–397. https://doi.org/10.1038/s41586-021-03565-5.
[67] Newbould, R., 2021. Understanding river plastic transport with tracers and GPS, 591-591 Nat Rev Earth Environ 2 (9). https://doi.org/10.1038/s43017-021-00212-5.