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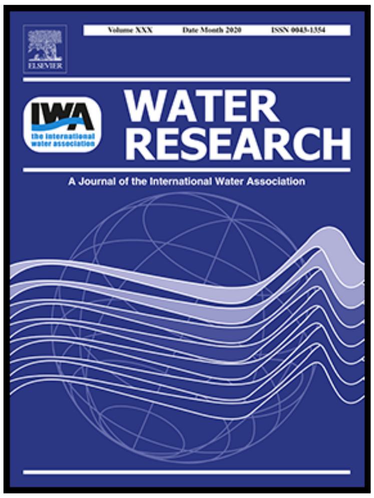

Global meta-analysis of microplastic contamination in reservoirs with a novel framework

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PII: S0043-1354(21)01022-8
DOI: https://doi.org/10.1016/j.watres.2021.117828
Reference: WR 117828

To appear in: *Water Research*

Received date: 4 July 2021
Revised date: 24 October 2021
Accepted date: 28 October 2021

Please cite this article as: Zhaofeng Guo , Wiebke J. Boeing , Yaoyang Xu , Edoardo Borgomeo , Sherri A. Mason , Yong-Guan Zhu , Global meta-analysis of microplastic contamination in reservoirs with a novel framework, *Water Research* (2021), doi: https://doi.org/10.1016/j.watres.2021.117828

Global meta-analysis of microplastic contamination in reservoirs with a novel framework

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Highlights

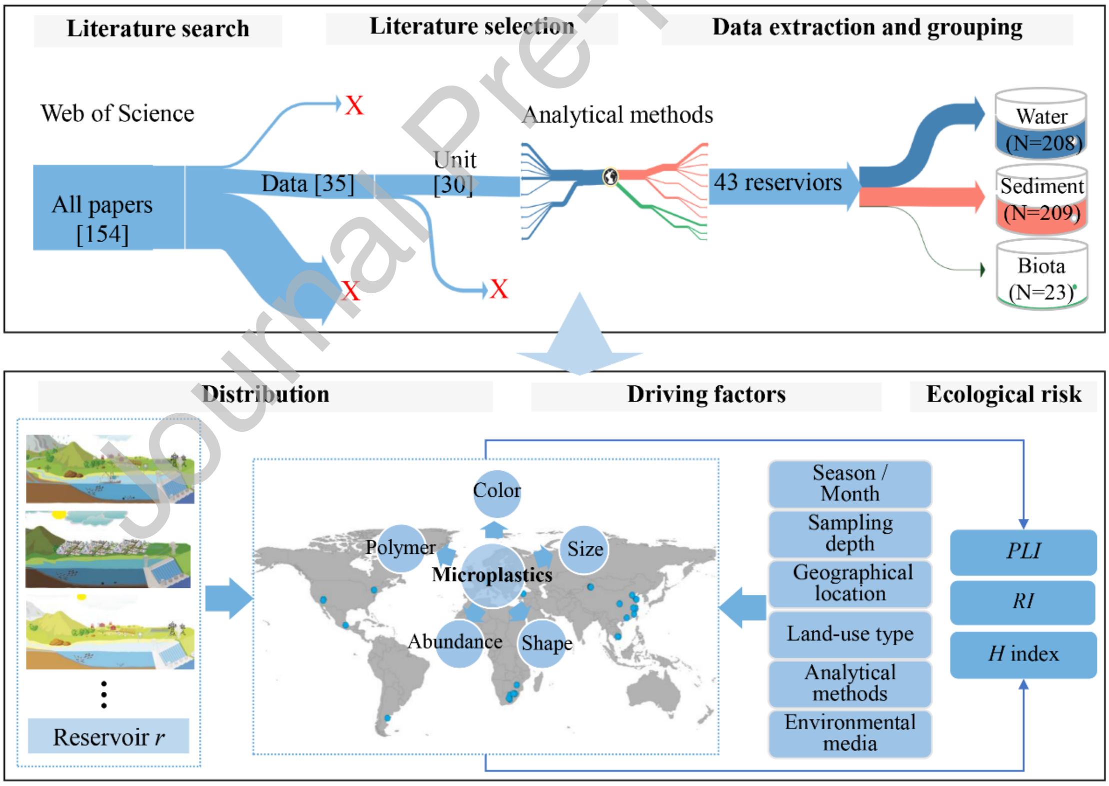
• A novel framework underlies first-ever meta-analysis of reservoir microplastics.

- Our meta-analysis showed distribution, drivers, and risks of reservoir microplastics.
- Reservoirs within urban areas were susceptible to microplastics contamination.
- The framework is applicable to other multi-attribute pollutants beyond microplastics.

Abstract

Microplastic contamination in reservoirs is receiving increasing attention worldwide. However, a holistic understanding of the occurrence, drivers, and potential risks of microplastics in reservoirs is lacking. Building on a systematic review and meta-analysis of 30 existing publications, we construct a global microplastic dataset consisting of 440 collected samples from 43 reservoirs worldwide which we analyze through a framework of Data processing and Multivariate statistics (DM). The purpose is to provide comprehensive understanding of the drivers and mechanisms of microplastic pollution in reservoirs considering three different aspects: geographical distribution, driving forces, and ecological risks. We found that microplastic abundance varied greatly in reservoirs ranging over 2-6 orders of magnitude. Small-sized microplastics (< 1 mm) accounted for more than 60% of the total microplastics found in reservoirs worldwide. The most frequently detected colors, shapes, and polymer types were transparent, fibers, and polypropylene (polyester within aquatic organisms), respectively. Geographic location, seasonal variation and land-use type were main factors influencing microplastic abundance. Detection was also dependent on analytical methods, demonstrating the need for reliable and standardized methods. Interaction of these factors enhanced effects on microplastic distribution. Microplastics morphological characteristics and their main drivers differed between environmental media (water and sediment) and were more diverse in waters compared to sediments. Similarity in microplastic morphologies decreased with increasing geographic distance within the same media. In terms of risks, microplastic pollution and potential ecological risk levels are high in reservoirs and current policies to mitigate microplastic pollution are insufficient. Based on the DM framework, we identified temperate/subtropical reservoirs in Asia as potential high-risk areas and offer recommendations for analytical methods to detect microplastics in waters and sediments. This framework can be extended and applied to other multi-scale and multi-attribute contaminants, providing effective theoretical guidance for reservoir ecosystems pollution control and management.

Graphical abstract



Keywords

Reservoir microplastics; Geographical distribution; Driving forces; Ecological risk; Global meta-analysis

1. Introduction

Microplastics are emerging contaminants frequently detected in aquatic environments due to their societal prevalence and durability. Microplastics reach freshwater ecosystems through runoff, sewage discharge, and atmospheric deposition in various colors, sizes (< 5 mm), shapes, and polymer types (Gall and Thompson, 2015; Li et al., 2018). Within global freshwater systems, artificial barriers (such as dams and weirs) intercept 65% of plastic waste before it reaches the oceans (Lebreton et al., 2017) and are prone to serve as key vectors for microplastic transport or long-term sinks for microplastics. When microplastics are transferred through, and possibly accumulate at the top of, the food chain, they can cause harm and have adverse effects on aquatic ecosystems and human health (Atugoda et al., 2021; Li et al., 2021). Given the steadily increasing human demand for plastics and the continuous breakage of plastic waste into smaller particles (PlasticsEurope, 2019), the amount of microplastics within the environment is expected to reach about 10 million tons by 2040 (Lau et al., 2020). This undoubtedly poses a serious challenge to water quality and safety in reservoir ecosystems, defined as the ecosystems associated with artificial lakes where water is stored behind artificial barriers for human purposes (Guo et al., 2021).

Reservoirs as the deepest points in a landscape are most representative of the entire surrounding area; furthermore, they are often important drinking water resources that potentially impact human health. Despite providing multiple ecosystem services, reservoirs have received limited attention on how they might be impacted by microplastic pollution. The first study of microplastics in reservoir waters was conducted in 2015 and the reservoir was found to be at risk for microplastic contamination (Zhang et al., 2015). Subsequently, the occurrence and distribution of microplastics in reservoir waters, sediments, and biotic tissues have been investigated in several countries at individual or localized areas, and monitoring data on reservoir microplastics have been increasing (e.g., Di and Wang, 2018; Lin et al., 2021; Martinez-Tavera et al., 2020; Watkins et al., 2019). However, differences in spatial coverage and sampling conditions have led to a diversity of microplastic detection methods and data analysis. The conclusions obtained for each case may not be directly applicable to other reservoir studies.

To explain the factors controlling microplastic characteristics and distribution within reservoirs, studies have considered several variables, such as sampling location relative to the dam (Watkins et al., 2019), sampling tools (Tavşanoğlu et al., 2020), land-use types and seasonal variation (Weideman et al., 2019). Different statistical methods were applied including nonparametric Mann-Whitney-U test, Spearman's correlation, two-way ANOVA, and generalized linear model. Most of these studies focused on a single factor that influenced microplastic abundance distribution. Little is known about the relative importance of multiple potential factors in driving microplastic distribution or interactions between effects. Unlike conventional contaminants, microplastics contain multivariate morphological and compositional features (various colors, shapes, particle sizes, and polymer components), which have different ecological impacts. For example, microplastics with low-density and small particle sizes are more likely to be mistakenly eaten by various organisms due to long-term suspension, while those with large particle sizes and strong hydrophobicity can adsorb a variety of pollutants, thus synergizing and amplifying pollution (Akdogan and Guven, 2019). Yet, these multivariate attributes have not been taken into account in current studies to explain distribution differences. In view of potential risks faced by reservoirs and gaps in understanding of microplastic pollution in reservoirs, there is an urgent need for a comprehensive analysis of microplastic distribution, how multiple drivers influence those characteristics, and the ecological risks for reservoirs on a global scale.

Here, we propose a meta-analysis framework of Data processing and Multivariate statistics (DM) to systematically integrate and interpret data from the literature. This DM framework was constructed and applied to explore three key questions: (i) How are different characteristics (particle abundance, size, color, shape, and polymer type) of microplastics distributed in reservoirs? (ii) How do potential variables such as geographic location, season, land-use type, analytical methods, and their interactions impact microplastic distribution? (iii) What is the ecological risk of microplastic pollution in reservoirs? We used a multivariate assessment index system to elucidate the current status of microplastic pollution in reservoirs and identify key drivers. Our framework provides scientific guidance for reservoir pollution control and management.

2. Materials and methods

The meta-analysis framework illustrates data processing and multivariate statistical workflow (Fig. 1). First, we retrieved, filtered, and extracted data from the literature. Acquired data were grouped and organized according to environmental media and analytical methods used in the reviewed papers. Data were then analyzed using multivariate statistical techniques to evaluate the distribution, driving forces, and ecological risks of microplastics.

2.1. Data processing

In August 2021, a search of the peer-reviewed literature on reservoir microplastics was conducted in the Web of Science database. We searched for: Topic = (“reservoir” OR “dam”) AND (“microplastic*”). The literature type was limited to ‘Article’ and ‘Review’ and we excluded non-English articles. We retrieved a total of 124 articles from this search. To avoid incomplete searches, we ran the same retrieval strategy in Scopus, Science Direct, PubMed, and Google Scholar databases to supplement the relevant literature. After importing Endnote removing duplicates, we obtained a total of 154 articles (Fig. 1a) and selected articles by hand according to the following criteria: (i) Study was conducted on a reservoir, and (ii) At least one microplastic characteristic was investigated in the field, including microplastic abundance or microplastic morphological characteristics (particle size, color, shape, and/or polymer type).

Based on the above criteria, 119 articles had to be excluded because they did not conduct their research on reservoirs (115 articles), or we were unable to extract the data regarding microplastic characteristics (4 articles). Of the 35 remaining articles for which microplastic data in reservoirs were available, we extracted the following information: (i) latitude and longitude of sampling sites, sampling time, location of sampling site in regard to reservoir morphology (above, within, or below reservoir), land-use type surrounding the reservoir, and environmental media (water, sediment, or biotic tissue); (ii) analytical methods of the study (microplastics sampling, extraction, and identification methods); and (iii) reported data on microplastic characterization, directly from the tables or figures using GetData Graph Digitizer software (http://www.getdata-graph-digitizer.com/). To facilitate subsequent comparative analysis, we excluded 5 studies in which "items/m^2" or "items/km^2" was used as the unit of microplastic abundance. In the remaining 30 studies, the unit of microplastic abundance in waters "items/L" was converted to "items/m^3" and other units were normalized to "items/kg" in sediments. In all 7 studies investigating biota, the unit in biotic samples collected was "items/sample" and no conversion was required. Furthermore, to increase reliability and comparability of results, wet weights of sediments from 6 studies were converted to dry weight by dry-to-wet weight ratio (Table S1; Karlsson et al., 2017).

Overall, from the 30 eligible studies, we obtained a microplastics dataset consisting of 440 collected samples from 43 reservoirs (Table S1, Fig. 2). The number of studies examined was limited by the nascent field of microplastic pollution leading to the continued evolution of study methodologies. Here, we offer an early perspective to guide future research and allow the ability to focus on the most pressing issues.

2.2. Multivariate statistics

2.2.1 Identification of microplastic drivers

The GeoDetector model includes four detectors: factor, interaction, risk, and ecological detection (Wang et al., 2010). The factor detector was applied to quantify the degree to which our explanatory variables such as geographic location, seasonal variation, land-use types and analytical methods influence the dependent variables such as microplastic abundance and small-sized (< 1 mm) abundance (the proportion and hazards are greater for this latter type of microplastics; see Section 3.1.2). The interaction detector is used to assess whether factors X_1 and X_2 interact ($X_1 \cap X_2$) or independently influence microplastic distribution Y. Potential high-risk areas for microplastic contamination were identified in combination with risk detectors (for a detail information, see Text S1).

Microplastic colors, shapes, and polymer types were used as multiple response variables for redundancy analysis (RDA), while numerical factors (including microplastic abundance, minimum collection size of microplastics (Min-size), sampling time, sampling depth, and geographic location) were used as explanatory variables to identify differences driving microplastic morphological characteristics. Factors significantly associated with microplastic morphological characteristics were identified by stepwise forward selection and Monte Carlo permutations tests ($p < 0.05$; n = 499) using CANOCO 5. The "vegan" package in R (version 3.5.3) was applied to perform Permutational multivariate analysis (Permanova) and analysis of similarities (ANOSIM) to examine for statistical differences in the microplastics due to different environmental media or analytical methods used by the papers' authors. Mantel test was used to verify correlations between microplastic characteristics (1-Bray-Curtis) and geographical distances before establishing distance decay relationships. If correlations existed, linear regressions were performed to analyze the distance decay model using the "vegan" and "SoDA" packages.

2.2.2. Risk assessment methods for microplastics

We used pollution load index, polymer risk assessment index, and potential ecological risk index to assess microplastic contamination in reservoir waters and sediments. Based on the three indices, potential risks from microplastic abundance and polymer type were considered simultaneously.

Pollution load index (*PLI*) as a pollution assessment index that effectively evaluates regional risk levels and has been widely used to reflect integrated pollution levels of microplastics in environmental media such as waters and sediments (Pico et al., 2021; Ranjani et al., 2021; Xu et al., 2018). *PLI* was calculated as follows:

$$CF_i = C_i / C_0 \quad (1)$$

$$PLI = \sqrt{CF_i} \quad (2)$$

$$PLI_r = \sqrt[n]{PLI_1 \times PLI_2 \times \cdots PLI_n} \quad (3)$$

where CF_i is the contamination factor of microplastics at sampling point i in reservoir r, expressed as the ratio of measured concentration (C_i) to background concentration of microplastics (C_0). The lowest detected microplastic abundance is considered as the background concentration (in this study, 0.28 items/m^3 for water and 1.79 items/kg for dry sediment). n is the number of sampling points in reservoir r. PLI_r was classified into four categories: < 10 (low level of pollution), 10-20 (medium), 20-30 (high), and > 30 (extremely high).

Microplastic risk assessment analysis used the polymer risk assessment index (Li et al., 2020) calculated as:

$$H = \sum_{n=1}^{n} P_n \times S_n \quad (4)$$

where H is the calculated polymer risk index; P_n is the proportion of each polymer in each sample and S_n is the hazard score of the corresponding polymers in microplastics. Polypropylene (PP), polyethylene terephthalate (PET), polyethylene (PE), polystyrene (PS), Expanded Polystyrene (EPS), Polyamide (PA), Polycarbonate (PC), and Polyvinylchloride (PVC) have hazard score values of 1, 4, 11, 30, 44, 47, 610, and 5001, respectively (Lithner et al., 2011). The H value was classified into four categories: < 10 (level I), 10-100 (level II), 100-1000 (level III), and > 1000 (level IV).

Potential ecological risk index (RI) comprehensively considers ecological effects, environmental effects and toxicology of microplastics (Ranjani et al., 2021). Its calculation formula is as follows:

$$C_f = C_i / C_0 \qquad (5)$$

$$T_i = \sum_{n=1}^{n} \frac{P_n}{C_i} \times S_n \qquad (6)$$

$$RI = T_i \times C_f \qquad (7)$$

C_f is the enrichment coefficient of microplastics in sampling point i and T_i represents toxicity coefficient of microplastics. When the RI values are < 150, 150-300, 300-600, 600-1200 and >1200, the corresponding pollution levels are II, II, III, IV and V, respectively.

3. Results

3.1. Distribution of microplastics in reservoirs

3.1.1. Distribution of microplastic abundance

Studies on microplastics in reservoirs have only emerged within the last six years, but microplastics were already detected in reservoirs on all five continents where studies regarding microplastics were conducted (no microplastics studies have been conducted in Oceania). Thirty reviewed studies demonstrated the occurrence, temporal, or spatial distribution of microplastics characteristics in 43 reservoirs (Fig. 1a). Geographic coverage of microplastic occurrence was wide, with detections in reservoirs located in North America (9 reservoirs), South America (1), Europe (6), South Africa (6), and Asia (21) (Fig. 2). Environmental media studied were mainly waters (21 studies) and sediments (17 studies), while less attention has been paid to biotic tissue (7 studies). Nearly 44% of these reservoirs are used primarily for drinking water supply. Analytical methods for microplastics in environmental media lacked uniformity in terms of sample collection, extraction, and identification (Fig. 1a).

Distribution of microplastic abundance in different reservoirs waters, sediments, and biotic issues varied widely. Microplastic abundance in water ranged from 0.28 to 181927.71 items/m^3 with an average of 10129.19 ± 25272.92 items/m^3 (mean ± standard variation) (Fig. 3a). Within each reservoir, the coefficient of variance of microplastic abundance in water ranged from 0 to 250%. The four reservoirs with coefficients of variance greater than 100% had samples collected in upper, middle, and lower reaches of the reservoirs, over a relatively large latitudinal range or different seasons. Most studies focused on investigation of microplastic abundance in surface waters. Stratified sampling of waters was only conducted in one single reservoir (Danjiangkou Reservoir, China) and showed that the average abundance of microplastics in the middle layers of waters (at the middle depth of the water) was significantly higher than that in the surface (≤ 1 m below the water surface) or bottom layers (0.5 m above the bottom of the reservoir). Overall, reservoirs with a higher average abundance of microplastics were located in temperate and subtropical regions.

Microplastic abundance in sediments ranged from 1.79 to 9,677.00 items/kg (dry weight), with an average of 1289.39 ± 2072.66 items/kg (Fig. 3b). Within each reservoir, coefficients of variance for sediment microplastic abundance ranged from 0 to 300%. The largest coefficient of variance was found in Nandoni Reservoir (ND, South Africa), where samples were collected along a population density gradient spanning three seasons. Similar to water samples, coefficient of variance in microplastic abundance was greater than 100% when sediment samples from upper, middle, and lower reaches of a reservoir were collected.

Microplastic abundance in biotic tissues ranged from 0.20 to 51.70 items/sample, with an average of 7.60 ± 12.17 items/sample. Biota surveyed were mainly fish (e.g. striped bass, Tilapia fishes and Gudgon fish; see Table S1), followed by shellfish (Asian clams) (Fig. 3c). In Lake Mead and Lake Mohave, the average abundance of microplastics in their shellfish was one order of magnitude higher than that of fish (striped bass), reaching 51.70 items/sample in shellfish compared to 4.20 items/sample in fish.

3.1.2. Microplastic morphological characteristics

Since there is no standard protocol for particle size fractionation, the range of microplastic particle sizes detected and the classification of particle sizes in different studies varied widely. Across all studies the particle size of microplastics can be classified into two main categories: ⩽1 mm and 1-5 mm (Fig. S1). Three studies included particle sizes exceeding the upper size limit of 5 mm. The lower size limits (minimum collection size of microplastics) ranged from 0.45 to 355 μm depending on mesh size of sampling net, sieve mesh and pore size of filter membrane selected. Microplastics with particle sizes < 2 mm were detected with high frequency in reservoir waters and sediments, reaching 89% and 90% of total microplastics detected on average, respectively. The average proportion of small-sized microplastics (< 1 mm), which are more harmful to ecosystems, was as high as 75% in waters and 64% in sediments.

Color, shape, and polymer type of microplastics in reservoirs are shown in Fig. 3d-3f. Transparent was the most abundant color in waters (33%) and sediments (24%) (Fig. 3d). Other common colors were blue, black, and brown. Microplastic shape and polymer type composition or abundance varied considerably in different environmental media. Although fibers were the dominant microplastic shapes in waters, sediments, and biotic tissue samples, they accounted for different proportions of 65%, 63%, and 90%, respectively. This was followed by fragments, with 27% in waters and 20% in sediments (Fig. 3e). Polypropylene and polyethylene were the dominant polymer types in both waters and sediments, with percentages higher than 15% (Fig. 3f), while the majority of polymers within biotic tissue samples were polyester (41%).

3.2. Driving factors of microplastics characteristics

3.2.1. Impacts on microplastic abundance and small-sized microplastic abundance

The dominant factors affecting distribution of microplastic abundance in waters were extraction and identification methods. Secondary factors were seasonal variation, geographical location, and land-use type (Fig. 4a). Notably, effects of sampling method, sampling depth, and sampling location relative to the reservoir (above, within, and below) on microplastic abundance were low or not significant ($p > 0.05$). However, interactions between all of the considered factors had a significant effect on distribution of microplastic abundance. In particular, the *q*-values of extraction method ∩ seasonal variation, extraction method ∩ land-use type, extraction method ∩ geographical location, geographical location ∩ seasonal variation, and extraction method ∩ identification method were greater than 0.90, denoting that interaction of these factors all produced nonlinear / linear, mutually enhancing effects (symbol '∩' represents the interaction between two factors).

The main factors influencing microplastic distribution in sediments were extraction method, sampling location relative to the reservoir, and latitude; the secondary factors were seasonal variation, longitude, identification method, and land-use type (Fig. 4b). The interaction of extraction method and seasonal variation had the greatest power to explain the distribution of microplastics in sediments, reaching 70%. It is noteworthy that effects of these factors on microplastic distribution were not independent, but showed a two-factor mutual or nonlinear enhancement effect.

Distribution of small-sized microplastics (< 1 mm) in waters were driven by sampling method and seasonal variation, which explained up to 61% and 50%, respectively (Fig. 4c), followed by extraction method, land-use type, microplastic abundance, and sampling location relative to the reservoir. The explanatory power of both seasonal variation and sampling method, as well as their interactions with these other factors, were all greater than 50%. In the sediment, identification method and land-use type were the main factors influencing small-sized microplastics, followed by latitude variation (Fig. 4d). Seasonal variation and land-use type had a greater impact on small-sized microplastics in waters as compared to sediments.

According to the GeoDetector's risk detector results (Table S3), we found the highest abundance of microplastics in waters of temperate reservoirs, especially those located in the Asia. In the sediment, microplastic abundance was relatively higher in subtropical Asian reservoirs. In terms of land-use type, reservoirs near urban or industrial areas are prone higher abundance of microplastics. Sampling location relative to the reservoir influenced the distribution of microplastics in sediments, with higher microplastic abundance within the reservoir compared to that above the reservoir. This phenomenon was not observed in the water of reservoirs, except when only small-sized microplastics were considered (Tables S3 and S4). In terms of seasonal variation, microplastic abundance in waters was relatively higher from the Autumn (i.e., December to February in the Northern Hemisphere and June to August in the Southern Hemisphere), while in sediments more microplastic pollution risk was detected in the Summer (June to August in the Northern Hemisphere and December to February in the Southern Hemisphere). Additionally, a higher abundance of microplastics in waters was detected using the bulk sampling method, with chemical digestion and density separation for sample extraction processing, and identification using Raman spectroscopy.

Although higher microplastic abundance was detected in sediments using Fourier-transform infrared spectroscopy, small-sized microplastics were better detected using Raman spectroscopy (Tables S3 and S4).

3.2.2. Impacts on microplastic morphological characteristics

Results of analysis of similarity (ANOSIM) demonstrated that microplastic morphological characteristics in environmental media were significantly different ($r = 0.44$, $p < 0.01$), and the variability was higher in waters than in sediments (Fig. 5a). There was a distance decay relationship for similarity of microplastic morphological characteristics in both environmental media (Mantel test: in waters $r = 0.25$, $p < 0.01$; in sediments $r = 0.34$, $p < 0.01$). A linear model of distance decay indicated that similarity of microplastic morphological characteristics in waters and sediments decreased with increasing geographic distance ($p < 0.01$) (Fig. 5b). Furthermore, decay rate of microplastics in sediments was greater than in water (Slope: $2.12 * 10^{-5} > 1.43 * 10^{-5}$).

Factors affecting distribution of microplastic morphological characteristics varied in waters and sediments. In waters, microplastic abundance and sampling depth influenced microplastic color composition, explaining 17% and 8% of the variation, respectively (Fig. 6a). In sediments, microplastic color was mainly influenced by abundance (18%) and latitude (17%) of microplastics (Fig. 6b). Microplastic polymer type was mainly influenced by sampling depth (14%) in waters (Fig. 6c). Microplastic abundance explained 17% of the microplastic polymer type and latitude explained 26% of the shape in sediments (Fig. 6d and 6e). The above factors were not found to influence microplastic shape within waters. In terms of analytical methods, differences in identification methods had a more significant effect on color, shape, and polymer type of microplastics (Fig. 6f). Most of the sampling methods for microplastics in reservoir sediments used the bulk sampling method, so the effect of sampling methods on their microplastic characteristics was not observed.

3.3. Microplastics risk in reservoirs

According to the pollution assessment of the pollution load index (*PLI*), 18%, 8%, 13%, and 61% of the reservoir waters suffered from low, moderate, high, and extremely high levels of microplastic pollution, respectively (Fig. 7a). Forty-three percent of the reservoir sediments had low-risk levels for microplastic contamination, while 33% and 24% suffered moderate and severe levels of contamination, respectively (Fig. 7b). However, the percentage of hazard category III (high level) or IV (extremely high level) of pollution load index would be higher when considering differences in sampling methods and minimum collection size. For example, three sampling campaigns were conducted in Danjiangkou Reservoir (DJ), corresponding to DJa, DJb and DJc in order of detection time (Fig. 7a and b). DJb, which used the bulk sampling method and had a smaller collection size (0.45 µm; PLI_{water} = 142, $PLI_{sediment}$ = 31), had a higher level of microplastic contamination, compared to DJa (48 µm; PLI_{water} = 75, $PLI_{sediment}$ = 6) and DJc (20 µm; PLI_{water} = 38, $PLI_{sediment}$ = 7). The degree of microplastics contamination in waters and sediments was not necessarily consistent within the same reservoir. However, except for individual reservoirs, pollution load index values of microplastics in waters were usually greater than those in sediments.

The percentage of reservoirs in which the risk category of microplastic polymers in waters was determined to be hazard level I, II, or III was 20%, 20%, and 60%, respectively, compared to 40%, 30%, and 30% in sediments (Fig. 7c and d). Reservoirs with a high polymer risk index (*H*) did not necessarily have a high corresponding *PLI* value. That is, reservoirs with high levels of microplastic contamination did not necessarily have a high polymer risk level. Of the reservoirs that were examined for microplastic abundance, approximately 50% were analyzed for polymer types. The studies that examined both were mainly concentrated in China and showed that polymer type risk was not negligible.

Results of potential ecological risk index (*RI*) considering microplastic abundance and polymer composition showed that risk levels of microplastics in reservoir waters were 35%, 15% and 50% for hazard categories I, III and IV, respectively (Fig. 7e and f). Potential ecological risk in sediments was relatively low, with a low-risk level (category I) of 80%. In the same reservoir, potential ecological risk levels of microplastics in waters were usually higher than those in sediments. Overall, potential ecological risk level is not necessarily related to the degree of microplastic pollution. That is, reservoirs with high *PLI* value are not necessarily rich in microplastics.

4. Discussion

4.1. Microplastics distribution in reservoirs and driving factors

Geographic location, seasonal variation, land-use type, and analytical method were driving forces of microplastic abundance distribution in reservoirs. Microplastic abundance in reservoir waters and sediments ranges across 2 to 6 orders of magnitude due to distribution heterogeneity. Microplastics are mainly derived from human production and consumption of plastic products (Eerkes-Medrano et al., 2015). As a result, reservoirs in densely populated areas – temperate / subtropical regions – were highly contaminated with microplastics, especially in Asia (where a significant amount of plastic products are produced). Similarly, reservoirs located in urban and industrial areas with high human activity are at a higher risk of microplastic contamination compared to less developed areas. In brief, urbanization drives the spatiotemporal distribution of reservoir microplastic abundance (Alfonso et al., 2020). Furthermore, microplastic abundance within the waters of reservoirs in densely populated areas is higher in dry season than in rainy season, possibly as a result of continuous input from anthropogenic sources and reduced water storage in dry season (leading to higher concentrations). By contrast, microplastic abundance in sparsely populated areas is higher in rainy season than in dry season. This suggests that wet deposition (Brahney et al., 2020) or microplastic resuspension due to rainfall disturbance (Zhang et al., 2020) probably leads to increased microplastic pollution in less sparsely populated areas. Microplastic abundance in sediments was higher in the rainy season as compared to the dry season, suggesting that sediments were more likely to be a sink for terrestrial-derived microplastics during the hot-rainy season.

The degree to which analytical methods influenced detection varied depending on environmental media, but the interaction of sampling and identification methods had the greatest effect on microplastic abundance in waters and sediments. In water, microplastics with particle size < 0.3 mm accounted for 22-38% of the microplastics in several reservoirs. Volume-reduced sample collection often captures microplastics in this particle size range, resulting in a significantly lower proportion of small-sized microplastic particles compared to the bulk sampling method. Effect of sample collection on microplastic abundance was not observed in sediments due to relatively homogenous sampling methods.

Extraction methods had a greater influence on microplastic abundance found within sediments as compared to water. Risk detection revealed that extraction using a combination of chemical digestion and density separation was more efficient compared to other extraction methods. In terms of identification methods, Raman spectroscopy was superior in detection of small-sized microplastics (Li et al., 2018), especially in sediments.

The sampling location relative to the reservoir influenced the distribution of microplastics found within sediments. As relatively closed and static water bodies, reservoirs are susceptible to accumulation of microplastics in their sediments from upstream inflow (Mazurek et al., 2017). We observed that small-sized microplastics were more easily trapped in the reservoir waters, but no increase in the total abundance detected was found within reservoir waters as compared to the sampling location (either above or below the reservoir, i.e., inbound tributary or outlet streams). Microplastics with relatively large particle sizes could be more susceptible to contamination or biofilm growth under slow water flow, leading to an increase in density, which in turn leads to deposition (Nizzetto et al., 2016). Flood discharge can transfer a large number of microplastics to areas below a reservoir leading to a decrease in microplastic abundance within the reservoirs (Song et al., 2020). This is consistent with our findings. Interestingly, sampling location relative to the reservoir and sampling depth as single factors did not significantly affect microplastic abundance in waters, but the interaction of these factors did enhance the explanatory power of microplastic abundance (Fig. 4a).

Patterns of microplastic behavior may be influenced by thermal stratification of reservoirs, and vertical distribution research of reservoir microplastics helps us understand the variation of microplastics along the water-depth gradient. A relatively high abundance of microplastics in the middle depths of reservoir water may result from significant thermal stratification during summer and formation of a metalimnion in the middle layer. The metalimnion of a water body is the layer where the temperature and thus the density gradient changes fastest. Therefore, particles often accumulate in the metalimnion. A stratified reservoir prevents water mixing and slows down sinking rate of microplastics in the bottom water (Uurasjarvi et al., 2021), thus presenting a higher abundance of microplastics in deeper water layers than in the surface layer. In addition, microplastics with different polymer types are distributed at different water depths due to differences in density and shape and change their characteristics such as color and shape in response to abiotic and biotic interactions (Cole et al., 2011). More research is needed to validate thermal stratification drives movement of reservoir microplastics to better understand vertical transport behavior of microplastics throughout water column and to develop effective monitoring programs and microplastic pollution mitigation strategies accordingly.

Microplastic morphological characteristics varied among different environmental media, but all of them conformed to distance decay relationships within the same medium. Heterogeneity of microplastic morphology in waters was higher as compared to sediments, indicating greater diversity of microplastic sources in waters. Microplastics in reservoirs could have been derived from long distances, but their similarities decreased with increasing geographic distance. Moreover, difference in morphological characteristics of microplastics in waters was affected by microplastic abundance, seasonal variation, sampling depth, and analytical methods. In sediments the driving factors were geographic location, microplastic abundance, and minimum collected particle size. Regional anthropogenic disturbances such as seasonal discharges, consumption patterns and land use type changes are the main causes of differences in microplastic morphological characteristics (Everaert et al., 2018; Mbedzi et al., 2020). As dominant polymer types in reservoirs, polyethylene and polypropylene products have short lifetimes (Geyer et al., 2017). Higher rates of plastic production and discharge, i.e., abundant sources of microplastics, may lead to higher detection frequencies and relative abundances of these two polymer types. In contrast to sampling and extraction methods, the identification method yielded a higher degree of variability in color and polymer type of microplastics. This is mainly due to the visual inspection used for microplastic pre-classification and accuracy of currently used Fourier-transform infrared spectroscopy and Raman spectroscopy techniques depending in part on features such as microplastic color, particle size and polymer type (Veerasingam et al., 2020).

4.2. Microplastic impacts and potential risks

Microplastics in reservoirs possess high contamination and potential ecological risk levels, but emphasis on polymer risk has been inadequate. Compared to sediments, reservoir waters are the most direct receptors of pollution discharge and, as such, had higher levels of microplastic contamination. In terms of polymer risk, over half of the reservoirs had high levels of polymer risk and polyvinyl chloride was detected in all of these high-risk reservoirs. Given differences in sampling methods and minimum collection size, the degree of microplastic risk in reservoirs may be higher than the actual assessed value. This is significant since polyvinyl chloride continues to accumulate and is more hazardous than the more common polyethylene and polypropylene polymers (Zhu et al., 2018). Thus, level of polymer risk is not necessarily related to total microplastic contamination and studies assessing microplastic risk by only considering polymer type or microplastic abundance are not comprehensive. Additionally, background values used to assess microplastic contamination are derived from the lowest values of microplastic detection in reservoirs. With the continuous development and expansion of monitoring technology and monitoring scope, the lowest values of detection may decrease. Thus, the studies used in our review systematically underestimated the ecological risk of microplastics in reservoirs. In short, determining the background values of microplastics in reservoir environmental media is significant for accurately quantifying microplastic pollution levels and ecological risks as well as setting priorities for reservoir microplastic pollution management.

To date, research on environmental effects and health risks of microplastics in reservoirs is still very limited, mainly because no environmental risk assessment framework and standardized analytical methods have been developed for microplastics. Microplastic risks are a combination of physical and chemical effects (Machado et al., 2018). On the one hand, microplastics might easily be inhaled or ingested, triggering multiple health risks by virtue of their small particle size (Lusher et al., 2013; von Moos et al., 2012), and the toxic effects are significantly dependent on relationship between particle size of microplastics and length of the organism (Jams et al., 2020). On the other hand, microplastics can act as both sources and sinks for pollutants (Alimi et al., 2018). Toxic plastic additives and polymers leach out after consumption of microplastics, causing persistent and pervasive adverse effects on organisms. Even worse, surfaces of low-density microplastics floating for a long time within reservoirs are prone to adsorb or act as carriers of various hydrophobic pollutants or harmful organisms, inevitably increasing their hazards (Guan et al., 2020; Leiser et al., 2021). In brief, diversity of microplastics characteristics and their interactions in ecosystems further complicate their risk (Mitrano and Wohlleben, 2020). Thus, microplastic risk assessment needs to incorporate characteristics, bioaccessibility, and bioavailability of microplastics, as well as toxicity data of environmental contaminants associated with microplastics (Koelmans et al., 2019). These parameters should also be priorities when developing an ecological risk assessment system for microplastics.

4.3. Challenges and prospects

Current studies on microplastics in reservoirs have covered a wide geographic area, but there is a need to expand the scope of research and further explore pollution mechanisms.

As the country supporting one-third of global plastic production (PlasticsEurope, 2019), China is also the hardest hit by plastic pollution and has received the most attention regarding microplastic pollution in its reservoirs. However, given the current status of microplastic contamination in reservoirs and the potential risk areas, we call for scaling up field monitoring in regions such as South America and Asia to capture microplastic distribution especially in areas with high population densities and urbanization rates (Blettler et al., 2018). To radically reduce or mitigate microplastic pollution, stricter adherence to the 3R (reduce, reuse, and recycle) principles of waste disposal, and enhanced international interdisciplinary collaborative research on degradable, sustainable plastic production, use, and disposal, are key (Thompson et al., 2009). Sustainable consumption and production goals have been proposed within the 2030 United Nations Agenda for Sustainable Development (Goal 12; UN, 2015) and are useful in guiding environmentally sound management of the plastic life cycles.

The distribution of microplastic characteristics and their driving factors varied in different environmental media. To fully understand the microplastic pollution status of reservoirs, it is necessary to monitor microplastic characteristics in waters, sediments, and biotic tissue simultaneously. Studies on microplastics in reservoirs were mainly focused on waters and sediments, and there was a lack of studies focusing on microplastic occurrence in biotic tissues as a potential indicator of microplastic entering into food webs (Alimi et al., 2021). Due to the small sample size of the papers reviewed, this study did not investigate factors impacting microplastic distribution in biotic tissues and their potential risks.

Conducting additional studies and producing quantitative data to identify the main causes of microplastic intake by aquatic organisms and to understand risks of microplastic accumulations in biotic tissues is a pressing need for future research (Kukkola et al., 2021).

Microplastic distribution might also be related to other potential variables such as hydraulic residence time, flow velocity, distance of sampling site from the dam, nutrient status of the water body, industrial structure, and level of wastewater treatment in the surrounding catchment area (Liu et al., 2020; Mason et al., 2016). For example, a slower flow rate favors deposition of microplastics, thus increasing the abundance of microplastics in these waters (Hübner et al., 2020). Effects of these potential variables were not considered in our study due to the limitations of available data. Given this, in future studies, authors are encouraged and even expected to include these parameters in the text or supplemental data to provide data support for further explorations of microplastic pollution drivers.

Recording detailed sampling information can help improve data availability and reduce uncertainty in results. Some studies did not indicate information such as sampling tools, sampling depth, minimum microplastic particle size collected, number and specific location of sampling points as well as sampling time, which affects the usability of article data. These are critical data that need to be included in all studies. To improve the availability and comparability of data from microplastic studies, reporting guidelines have been developed for researchers to standardize information such as field sampling and to safeguard the quality of studies (Cowger et al., 2020). Using this set of reporting guidelines will facilitate comparative analysis of data across sources and geographies.

Analytical methods for microplastics in reservoirs have not been standardized and different studies have varied in their sampling, extraction, and identification methods. The diversity of extraction methods, especially, varied widely among studies. Unfortunately, analytical methods have a strong influence on the reported composition and distribution of microplastics. Different studies used dry weight or wet weight of sediments as mass unit to normalize microplastic abundance, which is not conducive to the comparison of microplastic pollution levels at different spatiotemporal scales. Therefore, it is urgent to standardize analytical methods and units to increase comparability and reproducibility among studies.

In terms of sampling methods, the bulk sampling method is most suitable to retain small-sized microplastics and is more accurate than the volume-reduced sampling method. It has been shown that abundance of detected microplastics is related to particle size, while range of particle sizes detected depends on sampling method and sampling tools (Baldwin et al., 2016; Lindeque et al., 2020). The smaller the mesh size, the easier it is to capture microplastics with smaller particle size (Schonlau et al., 2020). Selection of sieves, nets, and filter membranes need to able to capture small-sized microplastics, especially since reservoirs tend to be a sink for the more toxic small-sized microplastics. Establishing standard analytical methods for each medium (water, sediment, biotic tissue) to classify microplastic particle size would facilitate comparative analyses and a general understanding of environmental factors on microplastic characteristics. In terms of extraction methods, chemical digestion and multi-step density separation extraction can both remove organic matter (Yang et al., 2021) and improve separation efficiency of microplastics. For qualitative and quantitative identification of microplastics, Raman spectroscopy seems to be the most efficient method to detect small-sized microplastics (Zarfl, 2019) and is suitable for both sediment and biotic tissue samples.

In summary, the four most important foci for future studies regarding microplastic pollution should be: (i) expanding surveys of microplastic pollution in reservoirs globally; (ii) compare and contrast microplastic pollution in water, sediment, and biotic tissue in each reservoir; (iii) include detailed information about sampling methods; and (iv) standardize analytical methods as to not influence findings on microplastic characteristics. Solving these issues would allow for analyses that elucidate the complete story of microplastic pollution.

5. Conclusions

We propose a meta-analysis framework of Data processing and Multivariate statistics (DM) for a systematical understanding of distribution, drivers, and ecological risks of microplastic pollution in reservoirs. Around the world, reservoir microplastics abundance was highly variable, spanning 2-6 orders of magnitude. To identify potential drivers of microplastic distribution, a GeoDetector model was used to quantify the influence of geographic location, seasonal variation, sampling depth, sampling location relative to the reservoir, land-use type and analytical methods on distribution of total microplastic abundance and abundance within the small-sized (< 1 mm) category. We found that interactions among all of these factors mentioned above enhanced the explanatory power of microplastic distribution. During the rainy season, reservoirs typically intercept small-sized microplastics, and sediments were more likely to be storage sites for terrestrial sources of microplastics. Due to multivariate properties of microplastic morphological characteristics, redundancy analysis, analysis of similarity, Permutational multivariate analysis, and distance decay models were applied to identify driving factors on microplastics dynamics. Distribution of microplastic morphological characteristics in waters and sediments varied, but microplastic morphological characteristics within the same environmental medium were consistent with distance decay relationships. Heterogeneity of microplastic morphological characteristics in waters was more pronounced, indicating a higher diversity of their pollution sources.

Standardizing and specifying microplastic sampling, extraction, and identification methods would help expand the scope of comparative studies and reduce uncertainties. Application of the DM framework revealed that bulk sampling, chemical digestion and density separation extraction, and identification by Raman spectroscopy can improve the accuracy of microplastics detection. In terms of pollution risk, assessment of pollution load index, polymer risk index, and potential ecological risk index indicated that levels of microplastic pollution and ecological risk in reservoirs were both high. Both, abundance and polymer type should be considered when assessing risk.

It is necessary to expand the scale and dimensionality of reservoir microplastic pollution studies in general. The DM framework proposed in this study can be applied for reservoir microplastic pollution analyses, and it can also be extended to other multi-scale and multi-attribute pollutants. Analyses of how characteristics of various pollutants are influenced by an array of explanatory factors would build a valuable foundation for comprehensive ecosystem pollution mechanisms and management.

Conflict of interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Acknowledgments

This work was financial supported by the Ministry of Science and Technology of China (MSTC) with the National Key Research and Development Program (2017YFE0119000) and the National Natural Science Foundation of China (NSFC) with the Young Scientists Programs (No. 31200358; 31300397). We thank Prof. Gregory V. Korshin and the three anonymous reviewers for the constructive comments and suggestions on the revision of this manuscript, and Mr. Cai Chen for the help on the utilization of GeoDetector model. The views expressed are those of the authors and do not necessarily reflect the views of MSTC and NSFC.

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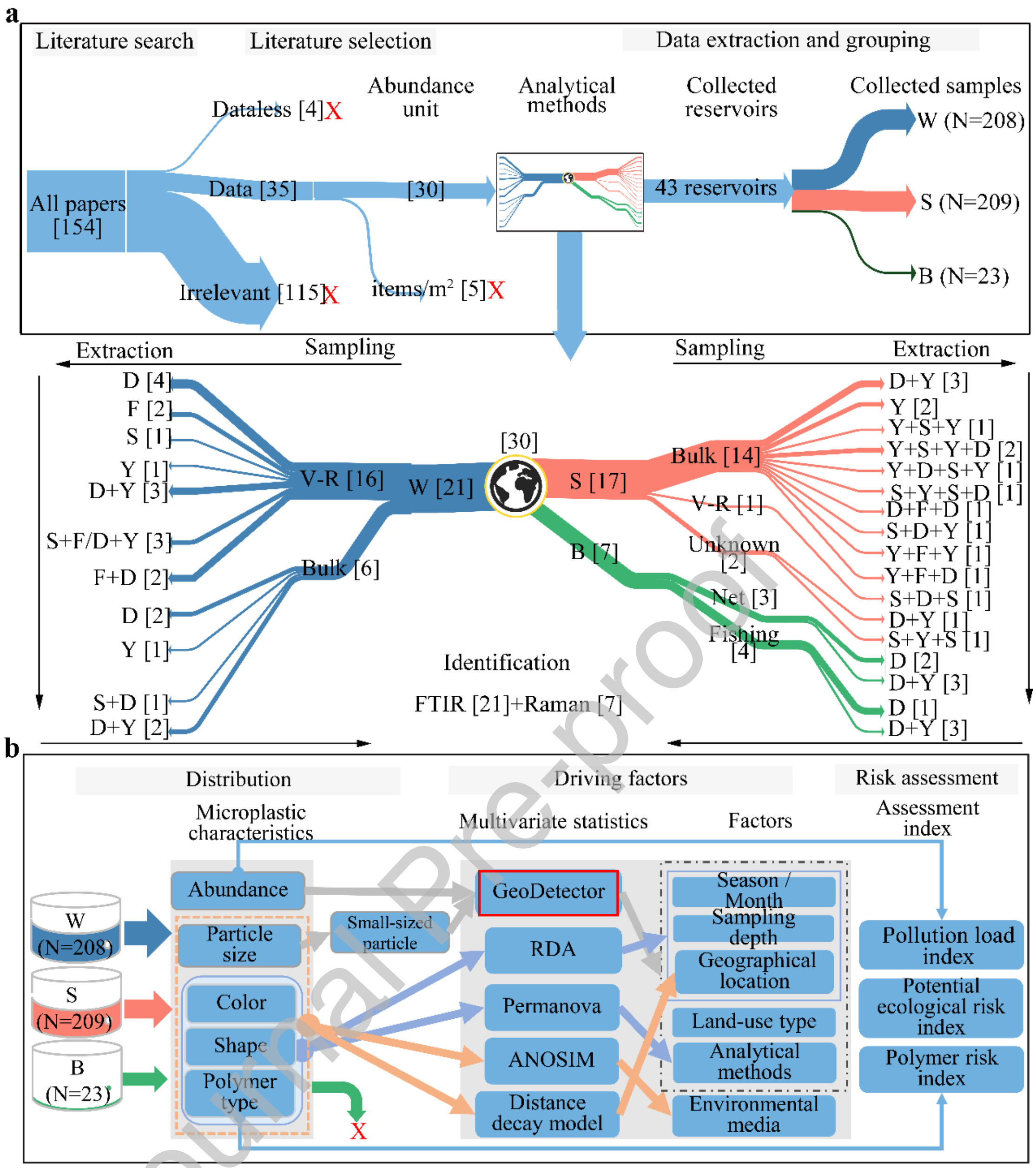

Fig. 1. A schematic representation of our literature search and Data processing and Multivariate statistics for extraction of data for the systematic review and meta-analysis.

(a) Data processing. A red "X" indicates that article or data was excluded. Environmental media: W – Waters, S – Sediments, B – Biota. The values after environmental media represent the number of samples. V-R and Bulk represent two sampling methods of collecting waters and sediments: volume-reduced sampling and bulk sampling method; D, F, S and Y represent four sample extraction methods: digestion, filtration, sieving and density separation, respectively. Samples were extracted and then filtered through membranes for visual identification and spectroscopic analysis of microplastics. Among the analytical methods, there were studies that used multiple sampling methods or investigated multiple environmental media, resulting in a total number of studies that exceeded thirty.

(b) Multivariate statistics. Small-sized particle is defined as microplastics with particle size < 1 mm.

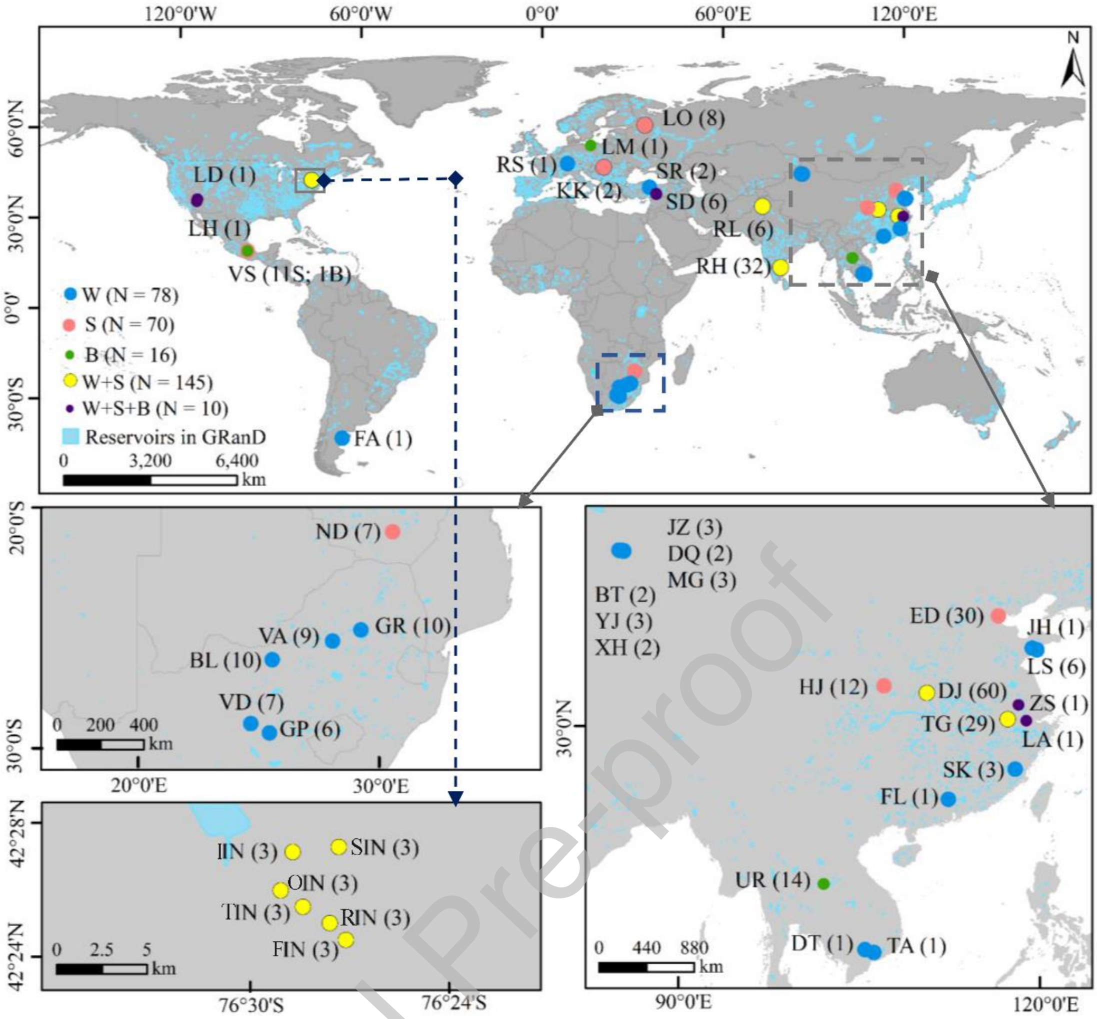

Fig. 2. Distribution map of samples for microplastics in reservoirs (from 43 reservoirs in 30 studies). The letters and numbers next to samples are the abbreviated name of reservoir and the number of microplastic sampling sites, respectively (Table S1). Blue dots are water samples (W); Orange are sediment samples (S); Green are biotic tissue samples (B); Yellow are water and sediment samples collected simultaneously (W+S); Black represent water, sediment, and biotic tissue samples collected simultaneously (W+S+B).

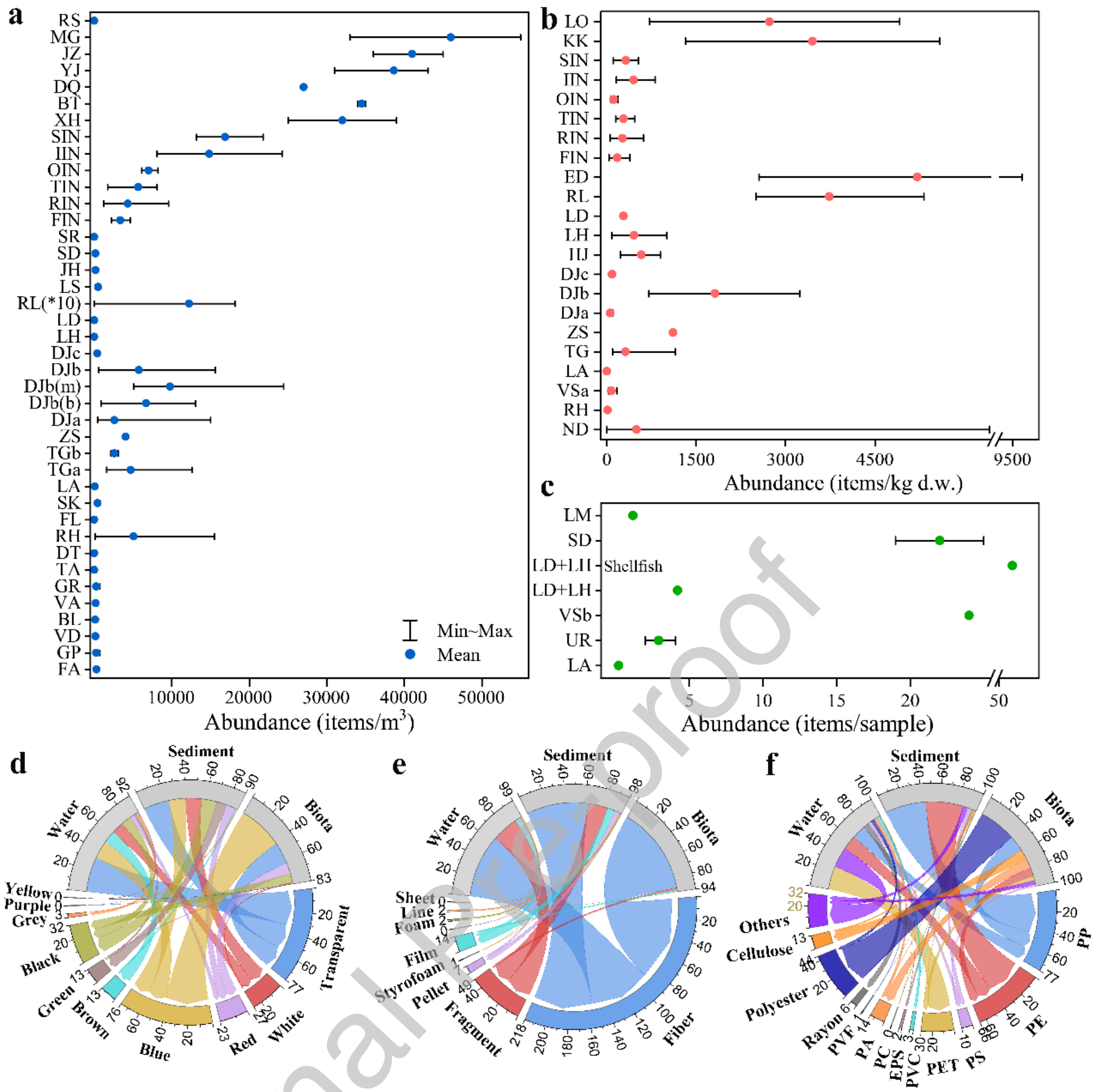

Fig. 3. Microplastic abundances in waters (a), sediments (b) and biota (c) of reservoirs. Distribution of color (d), shape (e) and polymer type (f) of microplastics in waters, sediments, and biota samples. The lowercase letters *a, b, and c* were marked after the abbreviated names of reservoirs in order to distinguish the order of the detection time. "(m)" and "(b)" represent water samples collected in the middle and bottom layer, respectively. The remaining unlabeled ones are surface waters. Values on the chord diagram are the percentages of microplastic characteristics.

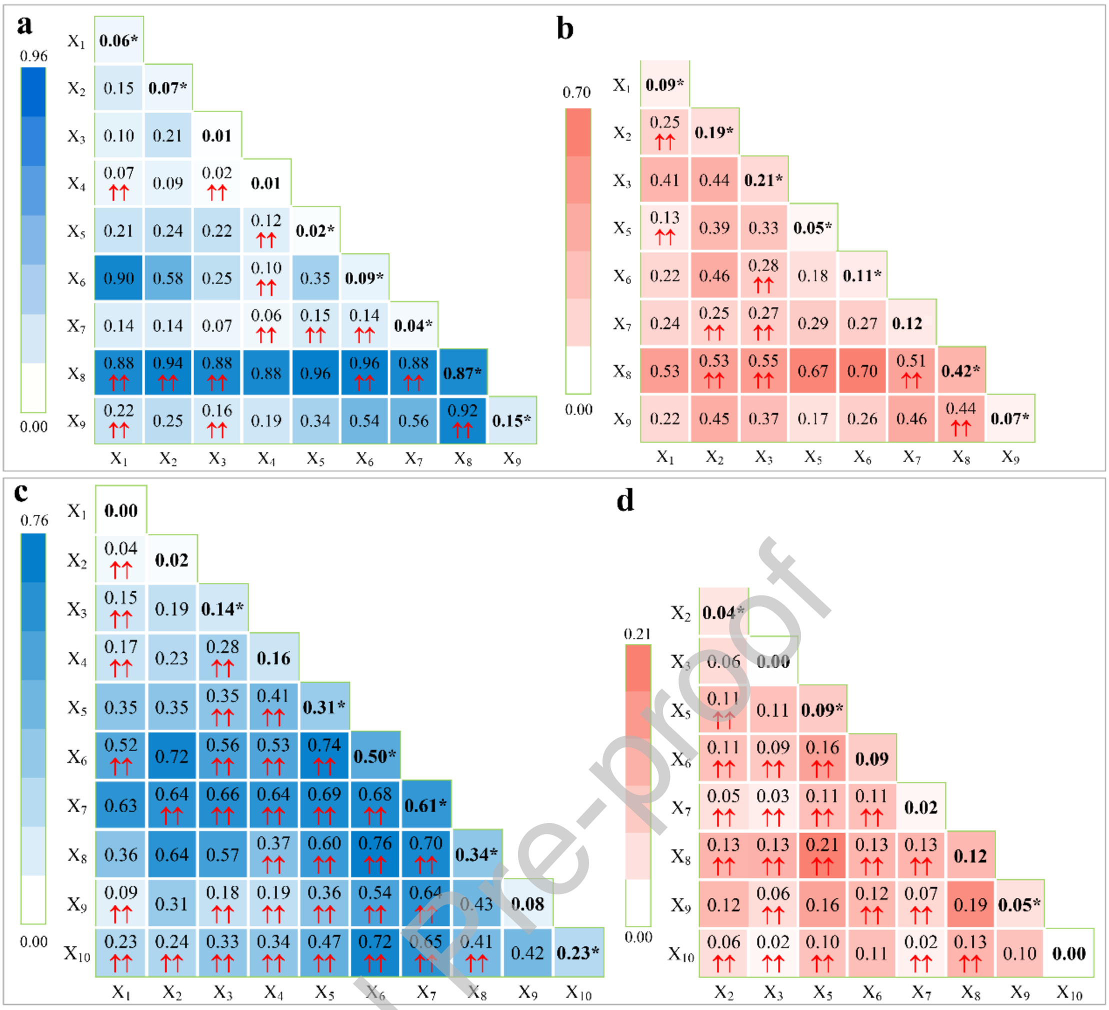

Fig. 4. Driving forces of microplastic abundance (a and b) and relative abundance of small-sized microplastics (c and d) in waters (a and c) and sediments (b and d). The *q*-values on diagonal line are driving forces of individual factors, and "*" represent 5% significance levels. The larger the *q*-values, the greater the influence degree of dependent variable by factor or interaction. Left triangular matrix shows *q*-values for interaction between pairs of factors. "↑↑" means that two-factors enhanced each other. The rest are nonlinear enhancement. Factors: X_1 – longitude, X_2 – latitude, X_3 – sampling location relative to the reservoir, X_4 – sampling depth, X_5 – land-use type, X_6 – seasonal variation, X_7 – sampling method, X_8 – extraction method, X_9 – identification method, X_{10} –

microplastics abundance.

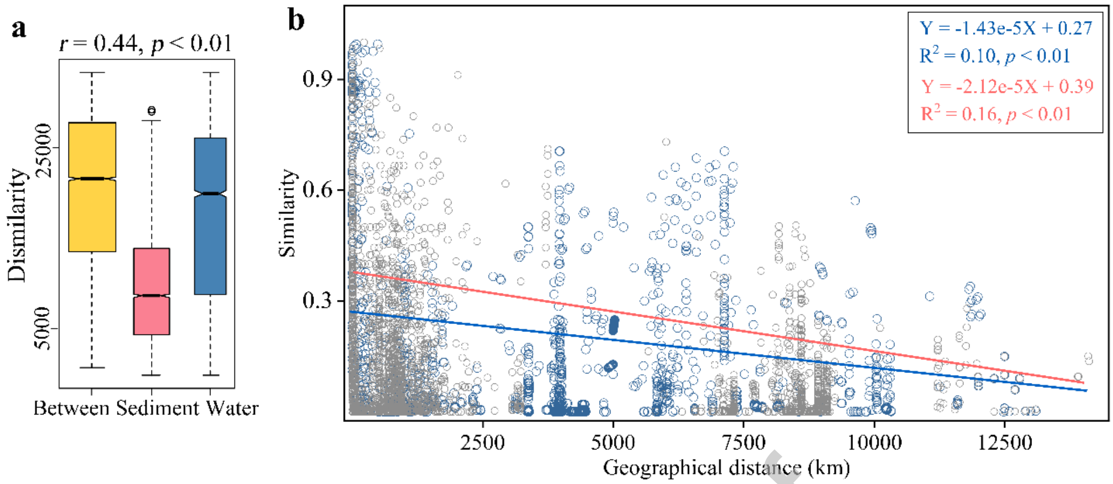

Fig. 5. Differences of microplastic morphological characteristics in waters and sediments (a). Distance decay of microplastic characteristics similarity (1-Bray-Curits) versus geographic distance in waters and sediments (b). The line indicates regression line.

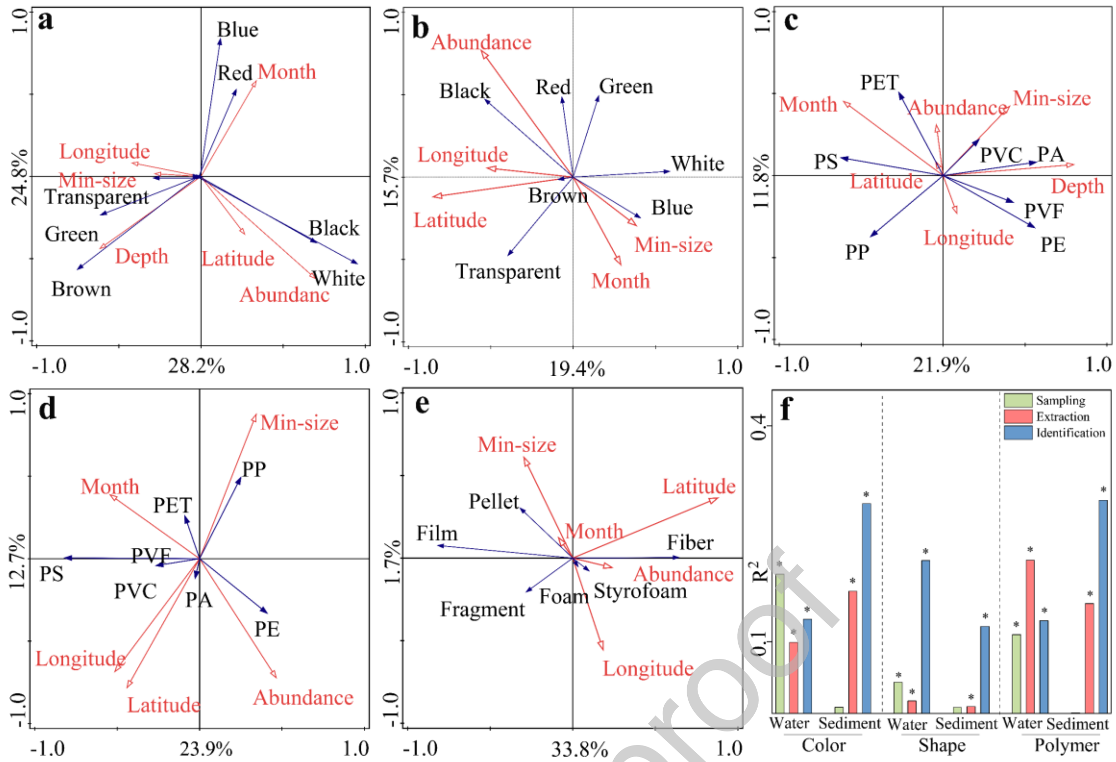

Fig. 6. Redundancy analysis (RDA) of common colors (a and b), polymer types (c and d), and shapes (e) of microplastics with explanatory variables in waters (a and c) and sediments (b, d and e). (f) Permutational multivariate analysis tests (Permanova) tests explanation degree (R^2) for differences in color, shape, and polymer type of microplastic by analytical methods. Marked "*" represents 5% significance level and unmarked indicates results at significant level of $p > 0.05$.

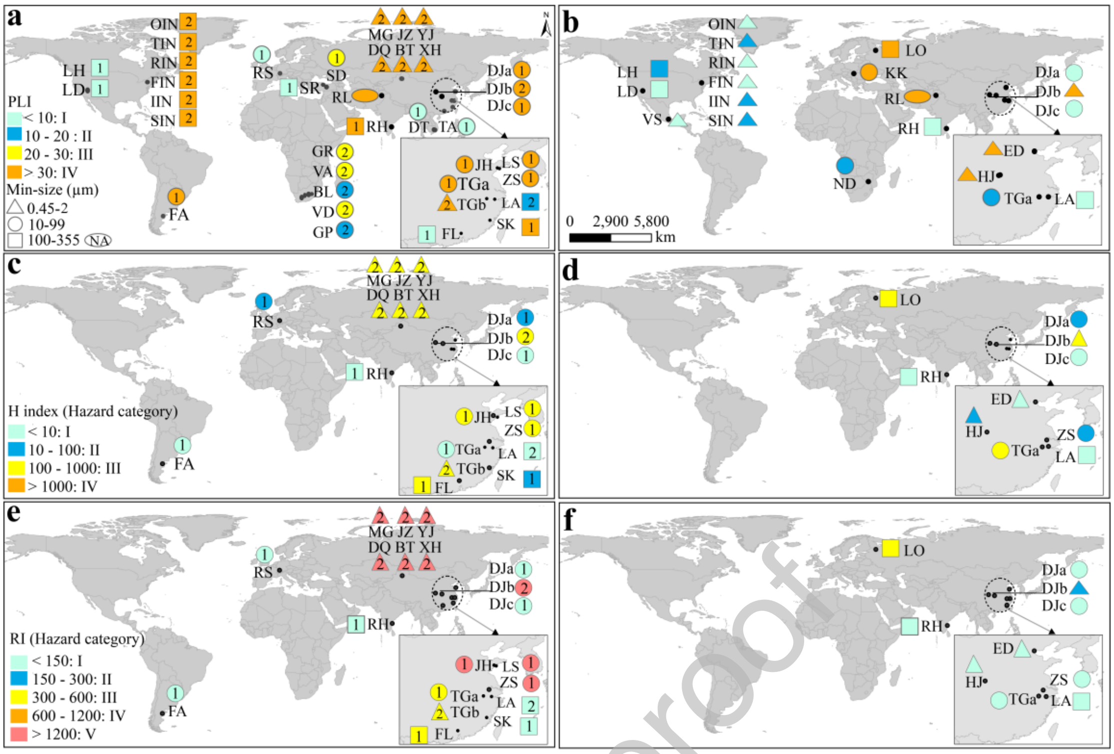

Figure 7. Risk of microplastics pollution in reservoirs. Pollution load index (*PLI*) in waters (a) and sediments (b); (b) Polymer risk assessment index (*H* index) in waters (c) and sediments (d); (c) Potential ecological risk index (*RI*) in waters (e) and sediments (f). Different shapes represent different orders of magnitude of the minimum collection size (Min-size). The ellipse indicates Min-size unknown. Values in the boxes indicate sampling methods of microplastics. Sampling methods: 1 – volume-reduced sampling method, 2 – bulk sampling method.