Review

Microplastics transferring from abiotic to biotic in aquatic ecosystem: A mini review

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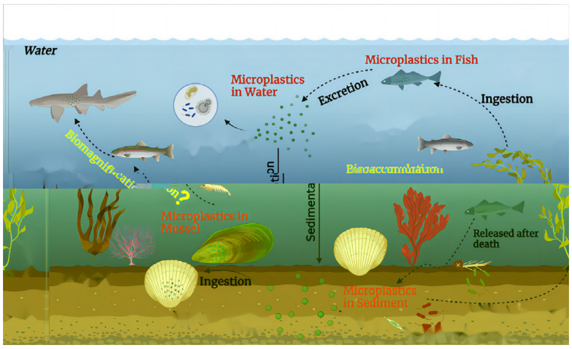
HIGHLIGHTS

- A growth body of concerns focuses on the adverse effects of microplastics.
- Microplastic abundance between mussels and sediments showed positive correlation.
- Microplastic abundance was higher in sediments than in water and biotic.
- Bioaccumulation of microplastics might be present in biotics.
- No significant trophic transfer from mussels to fish occurred.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Damià Barceló

Keywords:
Emerging contaminant
Trophic transfer
Bioaccumulation
Biomagnification
Field-based evidence

ABSTRACT

Microplastics have been detected in global aquatic ecosystems, so it is vital to understand the bioaccumulation and biomagnification of microplastics for ecological risk assessment. However, variability between studies, including sampling, pretreatment processes, and polymer identification methods have made it difficult to draw definitive conclusions. Alternatively, the compilation and statistical analysis of available experimental and investigation data provides insight into the fates of microplastics in an aquatic ecosystem. To reduce bias, we performed a systematic literature retrieval and compiled these reports on microplastic abundance in the natural aquatic environment. Our results indicate that microplastics are more abundant in sediments than in water, mussels, and fish. There is a significant correlation between mussels and sediments, but not between water and mussels or between water/sediment and fish. Bioaccumulation of microplastics appears to occur through water, but the route of biomagnification is unclear. More sound evidence is required to fully understand the biomagnification of microplastics in aquatic environments.

Microplastics have become a global cause of concern for the scientific community and the public. The term *microplastics* was coined in 2004 (Thompson et al., 2004), although they were found in the western Sargasso Sea as early as the 1960s (Carpenter and Smith Jr., 1972). Surprisingly, microplastics are nearly omnipresent in all aquatic compartments worldwide, ranging from inland to polar waterbodies and oceans (Issac and Kandasubramanian, 2021; Tursi et al., 2022; Vivekanand et al., 2021). Heterogenous microplastics of various polymers, shapes, and abundances have also been reported in organisms. Most microplastics are derived from the constant weathering and breakdown of plastic waste (Allen et al., 2022; K. Zhang et al., 2021; X. Zhang et al., 2021), resulting in microplastic contamination worsening due to existing and ongoing deposits of plastic waste. For instance, microplastic abundance in surface and subsurface seawaters on the South Korean coast will exceed predicted no-effect concentrations (12 particles/L) in the coming few decades (Jung et al., 2021) and might pose a threat to local marine biodiversity. Eventually, microplastic pollution brings serious concerns for ecological integrity and human health. It is thus not only an emerging global environmental issue but also a social concern.

Microplastics, especially small-sized particles and nanoplastics, may penetrate biological barriers and accumulate in tissues, potentially resulting in bioaccumulation and even biomagnification along trophic levels. Ingestion, translocation, and the hazardous effects of microplastics are mainly size-dependent (Wu et al., 2019; K. Zhang et al., 2021; X. Zhang et al., 2021). Growing evidence shows that microplastics are dangerous to the aquatic ecosystem at the sub-organismal, individual, and population levels, and reaches the level of human health (Koelmans et al., 2022), such as gut damage (Zhang et al., 2020), oxidative damage (Barboza et al., 2020; Cohen-Sánchez et al., 2023; Solomando et al., 2022), and disturbances of energy and lipid metabolism (Deng et al., 2017). In response to these concerns, the revised European Drinking Water Directive intended to incorporate microplastics in the "watch list" of pollutants by 2024 (EU, 2020) for their persistence and adverse effects on biota and humans. However, there is debate about the actual hazards of microplastic contamination because the environmental abundance data that underlie these concerns are mainly derived from unrealistic microplastic abundance under controlled conditions (Lenz et al., 2016; Sussarellu et al., 2016). That is, microplastic abundances known to threaten organisms via water are commonly significantly higher than those detected in the natural environment. Indeed, recent studies have suggested that ecologically relevant doses, sizes, and shapes of microplastics pose only minor threats to marine organisms (Hamm and Lenz, 2021; Niu et al., 2021). It is important to understand whether low-abundance environmental microplastics accumulate in organisms, known as bioaccumulation. Bioaccumulation, if it occurs, would mean a constant increase in the abundance of microplastics in organisms and the potential transfer to higher trophic levels, resulting in biomagnification. Though indirect, this may be the foremost exposure pathway for all biota throughout a lifetime and is crucial to conducting risk assessment. Nearly no information, however, is available due to limited data (Kim et al., 2021; Verla et al., 2019; Xu et al., 2021). These reviews are limited in utility because they approached biotic and abiotic microplastic abundance from different sources. These might result in unconscious bias when comparing data directly from different reports. There is currently no harmonized approach for the detection of microplastics in environments, including sampling and abundance units of measure.

Given the broad variance of sampling and analytical methods among microplastics studies, we reviewed literature in which microplastic abundance in abiotic and biotic matrices were simultaneously detected. Data were extracted and compiled from these studies in hopes of eliminating data bias caused by different sampling, pretreatment, and analytical methods as much as possible, aiming to evaluate the potential occurrence of bioaccumulation and biomagnification of microplastics in aquatic environments. A random model was also used to improve outcomes reliability. We also tried to incorporate nanoplastics into our review because nanoplastics are also a significant presence in the environment and have the greatest capacity to translocate and accumulate in tissues due to their small size (Kokilathasan and Dittrich, 2022). However, no data on nanoplastics are available because it is extremely difficult to reliably detect and quantify particle counts of plastics <1 μm in size. This study should incorporate into the existing body of knowledge to promote an understanding of the hazards of microplastic pollution as they correlate with environmental dose. This mini review also provides an important framework for future risk assessments.

1. Materials and methods

1.1. Literature search

A systematic literature retrieval was conducted to collect data on microplastic abundance both in aquatic abiotic and biotic compartments from the same sites or regions. Biotics included invertebrates and vertebrates, such as mollusks, fish, sea mammals, and seabirds; abiotic sources consisted of water and sediment, and excluded atmosphere and soil. The search focused mainly on the Google Scholar and PubMed databases using an integrated keyword of ('MPs' OR 'microplastic') AND ('biotic' OR 'fish' OR 'mussel' OR 'oyster') AND ('abiotic' OR 'sediment' OR 'water' OR 'environment' OR 'freshwater' or 'lake' or 'river' or 'marine' or 'seawater'). The cutoff publication date for inclusion was January 31, 2023. All academic articles and scientific reports were extracted, including online Supplementary materials.

1.2. Data compilation

The protocol was implemented according to the updated guidelines set by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses protocols (PRISMA-P) (Page et al., 2021). Papers were removed from the dataset if they did not meet the following criteria: (1) microplastics were confirmed by spectroscopy, including FT-IR, μFT-IR, and Raman, but not inspection with the naked eye or needle; detected in biotics (2) in the gastrointestinal tract (GIT) of fish or (3) in whole soft tissue (WST) for invertebrates; and abundance was quantified as (4) particles/kg or particles/g in biotics, or particles/individual; (5) as particles/L or particles/m^3 in water; or (6) as particles/kg or particles/g in sediment, including dry weight (dw) or wet weight (ww). Investigations of artificial waterbodies such as aquaculture ponds and fish farms were also excluded although microplastic contamination has been reported in these settings.

Included literature was analyzed by country, location, matrix (organisms, water, and sediment), freshwater, and marine. Microplastic abundance was converted to unified units to evaluate their potential abiotic to biotic transfer in food webs. That is, microplastic abundance in water was converted to items/L, items/kg dw in sediment, items/GIT in fish, and items/g ww WST in mollusks (oyster and mussel) based on the available information in the main text and Supplemental materials. When reported as mean ± sd or numeric ranges, this format was retained. If data were not reported in the main text and Supplemental materials, we sent e-mails to the corresponding authors to request numeric values and the weights of soft tissues. If the feedback was positive, the paper was included and the data compiled; otherwise, the paper was excluded, despite its potential significance. Additionally, analysis was based on an assumption of random ingestion in biologically realistic food webs, regardless of polymer or shape. Thus, this review only focused on the total abundance of microplastics in the environment.

1.3. Microplastic analysis in biotic and abiotic samples

Microplastic abundance in all studies was clustered into fish, mollusk, water, and sediment groups, respectively. Data were assigned to a one-to-one correspondence. Correlations between groups were analyzed using a random sampling model (Supplementary material 1) to understand the bioaccumulation and biomagnification of microplastics in aquatic environments, that is, fish vs. water, fish vs. sediment, mollusks vs. water, and mollusks vs. sediment. Notably, abundances were often reported as ranges rather than exact numbers. To account for this, the correlations between two variables were calculated based on the numeric format of microplastic abundance as follows:

(1) "a ± b": The data is assumed to be a normal distribution. A random number was generated with a normal distribution (a: mean value; b: standard deviation) to describe microplastic abundance in studies;
(2) "a − b": The data was assumed to be a uniform distribution. A random number generated with a normal distribution (a: lower limit; b: upper limit) to describe microplastic abundance in studies;
(3) "a ± b - c ± d": The lower and upper limits were defined using Step 1, then abundance was determined using Step 2;
(4) Four sequences of microplastic abundance were generated by repeating Steps 1–3. The Pearson correlation was analyzed among sequences and the corresponding coefficient was generated. Correlation tests were also performed;
(5) Analysis from Steps 1–4 was repeated for 1000 cycles, then the correlation coefficients in each cycle and the significant frequency ($p < 0.05$) were recorded individually;
(6) Density plots of correlation coefficients were prepared with the mean correlation coefficient of 1000 cycles as a final index. The frequency of results >300 was statistically significant.

2. Results and discussion

2.1. Literature overview

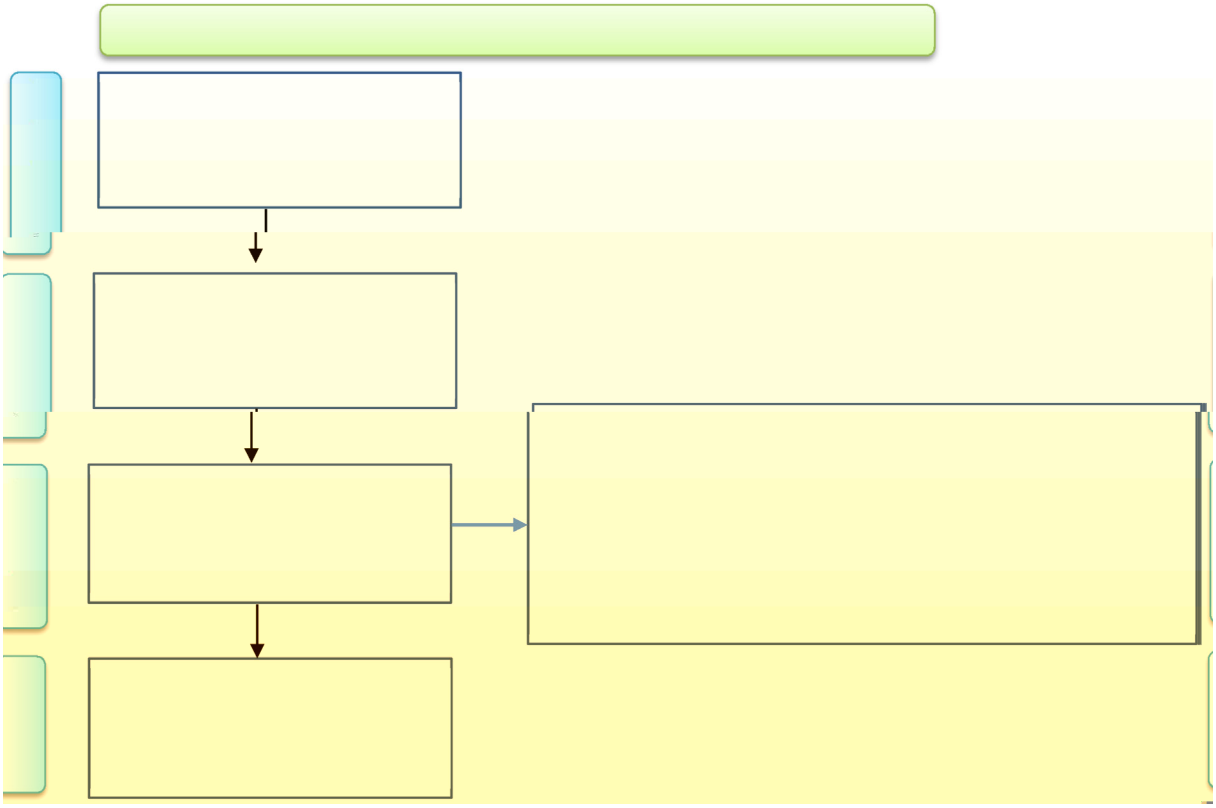
As a hotspot in the field of environmental studies, many studies on microplastic contamination have been published in recent years. After reviewing records with titles and abstracts and then removing duplicate records, 70 candidates were downloaded individually and verified to ensure the main body of each paper reported microplastic abundance in both biotic and abiotic matrices (Supplemental material 2). After verification, 14 articles were excluded because microplastics were detected using a hot needle, microscope, stereomicroscope, dissection microscope, or SEM/EDS only, all of which are prone to overestimation of microplastic abundance. Another two articles were excluded for focusing on artificial fish ponds, where microplastic contamination is not representative of the natural environment. An additional six articles were excluded for quantifying microplastic abundance in water as items/km^2 or items/m^2 in sediments, formats that cannot be harmonized directly with other studies. Finally, five articles were excluded because they provided no exact values even though microplastics were detected in biotic and abiotic matrices and neither the first authors or corresponding authors replied (or replied effectively) to inquiries for further information. An investigation on microplastic pollution in aquatic species from the Buriganga River was also removed because microplastics were extracted from the gills of fish, but not from GITs (Haque et al., 2023). After exclusion, 42 research studies that investigated microplastic contamination in environments and were published from 2017 to 2023 were included for analysis (Fig. 1).

Investigations were carried out in 23 countries, but nearly 30 % (12/42) were based in China. The *Science of Total Environment* (15) was the most frequently included journal, followed by the *Marine Pollution Bulletin* (5), *Chemosphere* (3), *Environmental Pollution* (3), and other journals (16). Fish was the most common organism investigated for microplastic contamination in an aquatic environment (70 %, 30/42 studies), and the remainder sampled mollusks, including oysters and mussels (12/42). Twenty-two studies investigated microplastics both in water and sediments, while 12 were only in water, and 8 only in sediments. Investigations focused on contamination in a stream (1), reservoir (1), lagoon (1), mangrove forest (1), estuary (1), ocean (2), bays (5), lakes (5), rivers (11), and coasts (14), and one study investigated both bay and coast. FT-IR and ATR-FTIR were the most popular instruments for identifying microplastic polymers; however, the lower limits of detection ranged from 0.22 μm (Primus and Azman, 2022) to 700 μm (Garcia et al., 2021), and some studies didn't report particle size. Furthermore, the detection limits based on microplastic size were reported to be instrument-independent, which was unexpected. The quality of published articles should be fully assessed to ensure essential information is included to eliminate uncertainty.

2.2. Microplastic abundance in biotic and abiotic samples

Microplastic abundance varied greatly, ranging from 0 to 153 items/GIT in fish, 0.07 ± 0.19 to 12.83 ± 1.47 items/g WST in mollusks, 0.00009 ± 0.00002 to 2.66 × 10^3 particles/L in water, and 0 to 30,890 ± 11,560 particles/kg in sediments. No data on microplastics in freshwater mussels were reported, reflecting the fact that studies primarily focus on marine rather than freshwater species. To better understand the contamination profile, microplastic abundance values were converted to items/g in biotic sources and sediment based on sample weight and as items/L in water based on volume. A random sampling model was used to compare the logarithm of microplastic abundance in different matrices. The average abundance of microplastics was highest in sediments, followed by in biotics including fish and mussels, both significantly higher than in waters ($p < 0.05$) (Fig. 2). This result indicated that the majority of microplastics in aquatic environments are deposited in sediments. Generally, high-density microplastics such as PVC (>1.0 g/cm^3) easily sink into sediments, while low-density plastics float on the surface or remain suspended in the water column (Li et al., 2020). These floating and suspended microplastics, however, are also deposited into the sediment after the aggregate into large particles or interact with other matrices (Leiser et al., 2021). Additionally, the deposition of microplastics is also related to factors such as size, shape, and hydrodynamic properties (Besseling et al., 2017; Klein et al., 2015), which significantly favor the higher abundance of microplastics in sediments than in water. The data also suggest a tendency for bioaccumulation from water to organisms, such as oysters sampled from the Yellow Sea (Zhu et al., 2020) and estuarine organisms from the Yangtze River (Li et al., 2022). Bioaccumulation in aquatic organisms is also related to the physicochemical properties such as shape. For instance, fragments are more frequently ingested by and accumulated in grass shrimp than spheres and fibers (Gray and Weinstein, 2017). However, the abundance of microplastics was not greater in fish than in mussels, indicating an absence of biomagnification through trophic levels. This finding was discordant from other studies that have reported slight or unclear biomagnification of microplastics from pelagic to benthic fish with different feeding habits (Bhatt and Chauhan, 2023; Gao et al., 2022; Zhang et al., 2022).

Similar to the present result, a meta-analysis of field and laboratory-derived contamination data on marine organisms also showed that



bioaccumulation occurs across five trophic levels in the marine food web, but biomagnification along the food chain did not (Miller et al., 2020). Generally, the biomagnification of microplastics depends on factors such as size. For example, Covernton et al. (2022) reported that microplastics >100 μm did not tend to biomagnify along the trophic levels in the food chain, indicating that large plastic particles do not cross the digestive tract to accumulate in tissue. Small plastic particles, especially nanoplastics, easily cross size-dependent epithelial barriers via endocytosis and then accumulate in tissues (DeLoid et al., 2021; Stock et al., 2019). Vancamelbeke and Vermeire (2017) reported that the defense mechanism is also involved in internalizing larger molecules, pathogens, and microorganisms in GIT. Garcia et al. (2021) showed that microplastic abundance

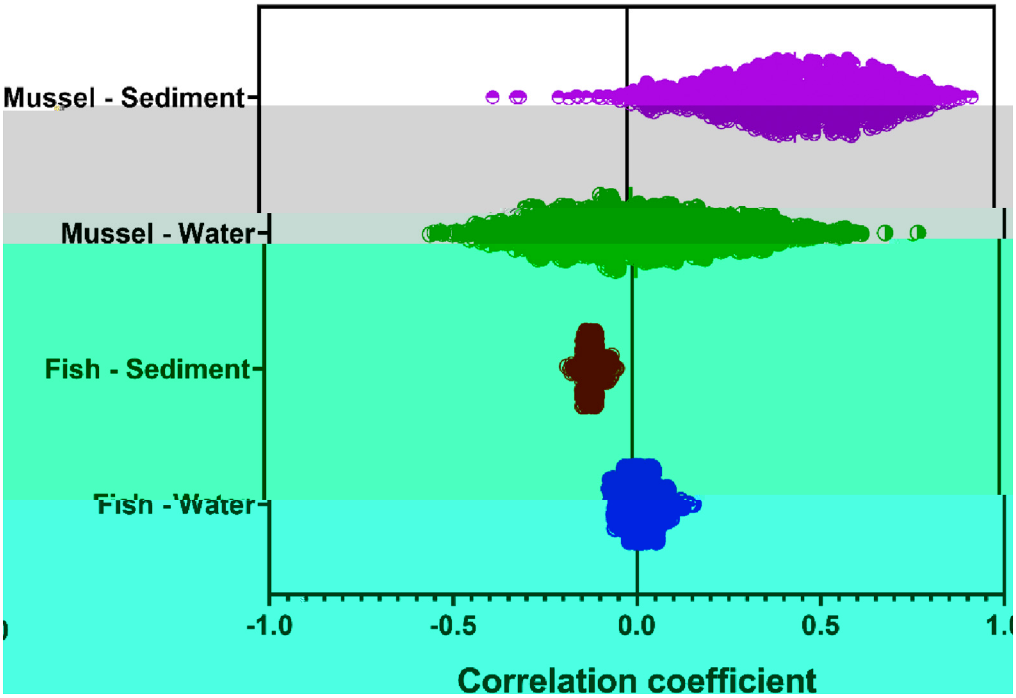


Fig. 3. Correlations of microplastic abundance between biotic and abiotic.

increased with increasing body size in fish and macroinvertebrates ($p < 0.011$), but tended to increase with trophic level only in macroinvertebrates. As one of the vital factors related to the presence of microplastics in the environment, microplastic density might also influence their translocation along the food web. Namely, the ingestion of microplastics is also dependent on the distribution of microplastics in aquatic environments and ultimately drives the presence of microplastics in the GITs of fish (Borges-Ramírez et al., 2020). Additionally, microplastics were commonly detected in fish GIT which is a part of fish body, while the whole body was analyzed to detect microplastics in mussel. This operation might also affect the conclusion of biomagnification. Microplastics are distributed widely and randomly in tissues, including in the GIT of fish (Abbasi et al., 2018; Atamanalp et al., 2021; Ding et al., 2018) because they are insoluble and their distribution is driven by physical features rather than thermodynamic energy gradients, which drives the distribution of soluble chemicals. Thus, microplastics detected in GIT do not represent the total microplastic load in fish, and cannot fully mirror microplastic contamination status in the aquatic environment. A recent study reported selective microplastic accumulation in fish guts versus random microplastic accumulation in fish gills (Yin et al., 2022). Most importantly, data quality in published articles is essential for accurately assessing microplastic contamination. For example, Pang et al. (2023) reported that nearly 96 % of the data records on microplastics/nanoplastics in food were unreliable based on a 10-point quality assessment. The bioaccumulation and biomagnification of microplastics in food webs must be described with high-quality data-based evidence to evaluate the potential adverse impacts of microplastics on wildlife at high trophic levels.

2.3. Potential correlation of biotic and abiotic microplastic abundance

Based on the unified abundance units, the outputs of the random sampling model showed the average correlation coefficient of microplastic abundance was 0.455 between mollusks and sediments (Fig. 3), indicating that the microplastic abundance in mussels mirrored the contamination levels in sediment. It has also been demonstrated that the highest polymer similarity overlapped between caged mussels and sediments (Kazour and Amara, 2020). However, no remarkable correlation was found between mollusks and water with an average correlation coefficient of 0.010, between fish and water (−0.109), or between fish and sediment (0.017), implying the absence of any relationships between them. A potential reason for this lack of correlation is that mussels inhabit the bottom of the aquatic environment where the microplastic pollution level is highest. Microplastics in sediment are nonspecifically consumed with food, resulting in more microplastics accumulation in mussels. Compared to mussels, however, fish often swim in the water column where the microplastic abundance in low, so they ingest and accumulate fewer contaminants. Moreover, fish with chemosensory foraging strategies are better able to discriminate microplastics as inedible food items (Roch et al., 2020), also resulting in less microplastic ingestion. On all accounts, this data-based evidence illustrated that mollusks, including mussels and oysters, could be used as sentinel organisms for monitoring microplastic contamination in sediment, but not in water.

Ward et al. (2019) drew a different conclusion. They found that bivalves, mainly mussels and oysters, do not consume particles passively but have selection mechanisms against plastic particles, resulting in a bias in representations of microplastic contamination in the environment. Similarly, Ding et al. (2021) proposed that clams could be developed as microplastic pollution bioindicators in sediment, while mussels could be used for microplastic monitoring in water because of the significant differences in microplastic abundance among species. At the same time, Li et al. (2019) discussed suitability and challenges of using mussels as indicators for monitoring microplastics in the marine environment. More field-based evidence is needed to evaluate the suitability of mussels as bioindicators for the detection and monitoring of microplastic contamination in aquatic environments. In addition, more accurate detection methods are needed to improve data accuracy in biotic and abiotic sample matrices.

In conclusion, this mini-review and meta-analysis showed that microplastics in aquatic environments are mainly deposited in sediments, where a higher abundance of microplastics was detected compared to water and biotics. A slight trend of microplastic bioaccumulation occurred in biotics compared to water, and it may be possible to develop mussels as a bioindicator of microplastic contamination in sediment, but not in water. Moreover, mussels are superior to fish for monitoring microplastics in an aquatic environment.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164686.

CRediT authorship contribution statement

Mingdong Ma: Data collection and analysis, original draft preparation; **Zhixin Wu**: Data collection and analysis; **Lihui An**: Data analysis and Editing; **Qiujin Xu**: Data analysis and Editing; **Hongwei Wang**: Data analysis; **Yang Zhang**: Ideas, Reviewing, and Editing; **Yulin Kang**: Reviewing and Editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare no competing financial interests or personal relationships that may influence the work reported in this paper.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (22276179), Major Project of Wuxi Health Committee (Z 202214), and the Scientific Research Innovation Project of Global Health Center Open Cooperation Project: "Science and Technology Climbing Project" (JX103SYL202200313).

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