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Effects of seasonal variation and resuspension on microplastics in river sediments☆

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ABSTRACT

Although microplastics are an emerging pollutant of global concern, little is known about the environmental behavior of microplastic in sediments. This study investigated the occurrence and seasonal variation of microplastics in the sediments of Liangfeng River, China with a fluorescence staining method, and then explored the transfer of microplastics at the water and sediment interfaces during resuspension. The results showed that smaller microplastics were detected in the sediments, which were concentrated in the size range of 50–500 μm. Microplastic abundance in the sediments in the dry season were slightly higher than those from the rainy season, and the rainy season promotes the accumulation of smaller microplastics in the sediment along the river-flow direction but not for the dry season. The shape of microplastics were predominantly fibers, followed by fragments and films. Polyethylene was the most abundant polymer, accounting for more than 50% of the total. Microplastics in the surface sediment move both to the overlying water and deeper sediment during the disturbance process. Disturbance-induced resuspension and vertical transport have significant effects on small-sized microplastics (50–500 μm). Small-sized microplastics can potentially migrate and redistribute via resuspension at different temporal and spatial scales, as some extent of resuspension is occurring in most river systems, especially in urban areas with boat traffic.

1. Introduction

Plastics are extensively used across the planet in peoples' daily lives because of their versatility, strong stability, and low cost. The global annual production of plastics has gradually increased from 1.7 million to 359 million tons from 1950 to 2018 (Wang et al., 2020). More importantly, plastic fragments are continually cracked into smaller plastic particles by the influences of physical, chemical, and microbial processes (Lin et al., 2018), and plastic particles with a particle size of fewer than 5000 μm are defined as microplastic (Cozar et al., 2014). Microplastics are smaller, lighter, and more easily ingested by organisms compared to large plastics. The ubiquitous presence of microplastics in the aquatic environment might be ingested by a variety of organisms, including zooplankton and fish (Zhang et al., 2021a). Also, the non-polar hydrophobic surface of microplastic can absorb pollutants such as persistent organic pollutants (POPs) (Yu et al., 2020) and heavy metals (Liao et al., 2020), thereby transferring these pollutants to organisms, which increases their bioavailability in the environment. The ingested microplastic particles can cause terrible damage to organisms (Krause et al., 2021), including growth inhibition, pathological reactions, and reproductive problems, with extreme damage that might lead to death (Bagheri et al., 2020). Microplastic is ubiquitous and have been found in various environmental matrices, such as rivers (Zhang et al., 2021b), lakes (Eriksen et al., 2013), and oceans (Abel et al., 2021). Thus, microplastic is a potential threat to the environment, both in densely populated areas and inaccessible remote areas (Horton et al., 2020).

River transport is the most important transport route for microplastic from land to sea, transport between 70 and 80% of plastic to these systems annually (Mani et al., 2020). Correspondingly, the problem of microplastic pollution in freshwater environments has gained increasing attention, and more rivers have been investigated and evaluated (Rodrigues et al., 2018). However, the abundance varies greatly

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between many studies, which is often due to differences in season, environmental conditions, and analytical methods (Mani and Burkhardt-Holm, 2020). Most importantly, most previous investigations of microplastic have relied on a single sampling assessment and been conducted within a narrow time frame (Blettler et al., 2018). By contrast, assessments of annual emissions often use theoretical modeling approaches, which are subject to a significant margin of error (Schmidt et al., 2017). Investigations of the temporal or seasonal variations and environmental behavior exploration of microplastic occurrence in rivers worldwide are relatively scarce. Several seasonal studies have demonstrated there are seasonal variations in the occurrence of microplastics in surface seawater in the bay, which are closely related to surface runoff flows and discharge loads (Ouyang et al., 2020). Plastic debris enters rivers, lakes, and oceans through surface runoff during the rainy season (Lima et al., 2014). Therefore, regions with significant seasonal rainfall have to take into consideration the variation over time when determining their representative abundance of microplastics (Cheung et al., 2016).

Sediment is commonly thought of as the "final settling tank" for microplastic (Nizzetto et al., 2016). High-density microplastics accumulate in sediment due to gravitational settling, while low-density microplastics accumulate in sediment due to physical, chemical, and biological factors (Li et al., 2019). In addition to gravitational settling, hyporheic exchange is also considered to be an important process for microplastic transport and fate in aquatic environments, especially for microplastics with small particle size (Drummond et al., 2020). Notably, immobilized microplastics in the sediment may be reactivated by disturbance at the water-sediment interface (Ji et al., 2021), thereby allowing them to migrate upward to the overlying water. Also, human activities such as shipping businesses and fishing activities can significantly alter the sediment environment and introduce microplastics into the water environment for subsequent river transport. However, the environmental behavior of microplastics in sediment is lacking in the current scientific literature. It was previously thought that microplastics mainly accumulated in surface sediment, and efforts have been devoted to studying microplastic contamination there. However, recent studies have found that microplastics might be stored in deeper sediment through vertical transport. Without considering microplastics in the deeper sediment layers, the global estimation of microplastic storage may be underestimated (Xue et al., 2020).

The sediment from a typical river in the Li River basin was selected as the study target. The goals of this study were to (1) investigate the seasonal variations of the occurrence of microplastics in the sediment, including the morphology, abundance, distribution, size, and type; and (2) explore the transfer and flux change of microplastics at the water-sediment interface during resuspension.

2. Materials and methods

2.1. Study area and sample collection

The Liangfeng River is located in Guilin, which belongs to the subtropical warm and humid monsoon region. As the most important tributary of the Li River and the only link between the two major aquatic ecosystems of the Li River and the Hui-xian wetland, it has an important role to play in ecosystems and in supporting biodiversity. Rainfall in this region is mostly concentrated from March to August, accounting for 77.7% of the annual total rainfall. Its average annual flow of 9.2 m^3/s, a maximum flow during the rainy season of 560 m^3/s, and a minimum flow during the dry season of 0.463 m^3/s. There is a huge difference in the runoff volume between the rainy and dry seasons of the Liangfeng River.

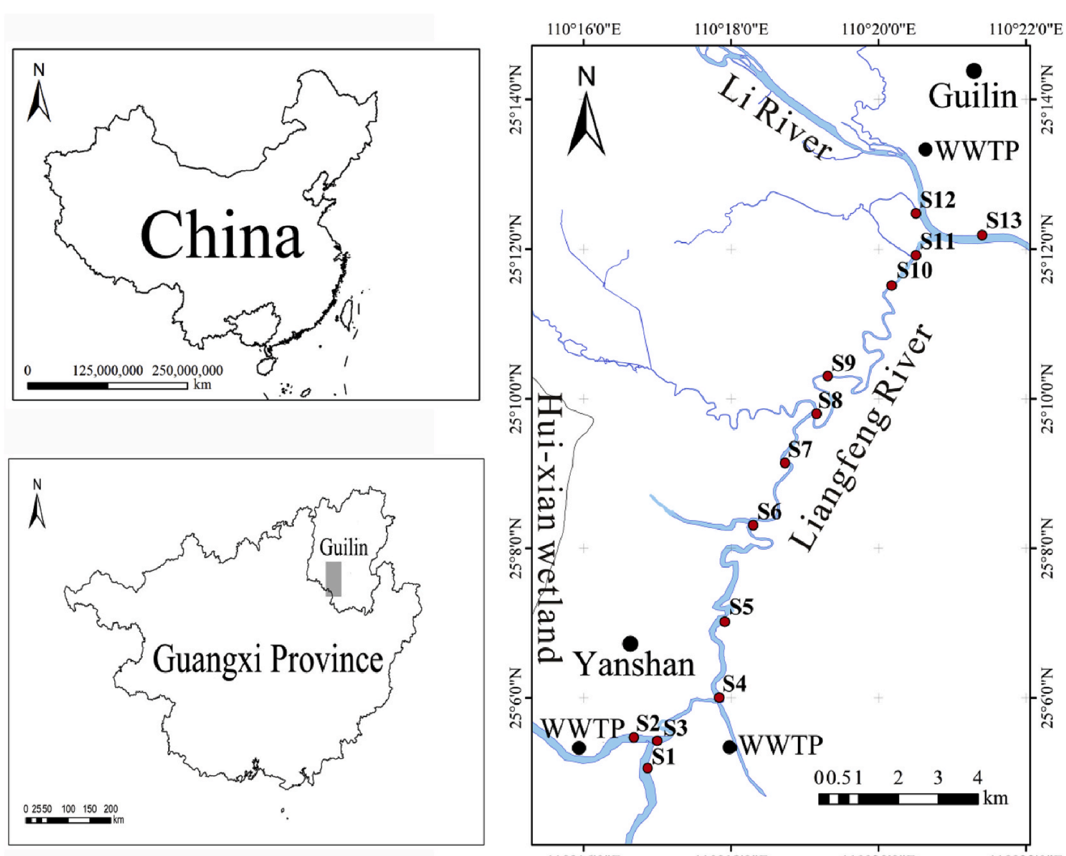

Fig. 1. Geographic location and sampling sites in the sediment of the Liangfeng River.

Thirteen sediment sampling spots were established along the Liangfeng River (Fig. 1), and samples were collected in May and October 2019 for the dry and rainy seasons, respectively. Samples for the dry season were collected on consistently sunny days, and samples for the rainy season were collected on the 2nd day after heavy rainfall. Surface sediment samples (0–5 cm) were collected in triplicate at each site using stainless steel shovel, and each sample was placed in an aluminum foil bag and transferred from the field to the laboratory. Three replicate sediment samples were collected at the interval of 20 m along the same riverside. The sediment sample was then spread on a stainless-steel tray to be air-dried. The dried sediment was gently crushed to disaggregate. All sediment samples were analyzed for grain size by a laser particle size analyzer (MasterSizer, 2000; Malvern, UK). After removing large impurities such as rocks, leaves, and large plastic debris, the sample was placed in a new aluminum foil bag for subsequent processing.

2.2. Resuspension design

Four replicate columns of sediment sample (inner diameter of 130 mm, depth of 10 cm) were collected at site S5 to investigate the resuspension of the microplastics. This site was chosen because the fine-grained sediment particles, uniform particle size distribution, and low human activities at this site. Microplastic resuspension studies were conducted using a customized particle entrapment simulator (PES) device with an inner diameter of 130 mm and height of 280 mm. Porous plexiglass perforated plate (diameter of 100 mm) is used to run an up-down movement with a distance of 20 mm (height 120–160 mm) to disturb only the overlying water. The sampling port is made of stainless steel, parallel to the lowest part of the perforated plate (height 120 mm). The perforated plate was driven to vibrate up and down by a variable speed motor, which simulated the resuspension of the sediment. The resuspension study established a total of four disturbance levels: level 1 (127 ± 15 r/min), level 2 (172 ± 5 r/min), level 3 (219 ± 15 r/min), and level 4 (293 ± 5 r/min).

Among four sediment columns, two were used as the control group and the others as the experimental group. The grain size distribution of the sediment samples was 18.57%, 72.05%, 8.93%, 0.46% for the size range of 0.01–2 μm, 2–50 μm, 50–2000 μm, and 2000–5000 μm, respectively. The samples of the control group were divided into four layers 0–1, 1–3, 3–5, and 5–10 cm, and samples from each layer were frozen and stored separately. Then, for the two experimental sediment samples, raw overlying water from site S5 was added to the top of the sediment in the resuspension device while minimizing any disturbance to the sediment. The samples were allowed to stand overnight at room temperature (25 °C) away from light. Before the start of the test, 100 mL of the initial water sample from the resuspension device was collected into a 500 ml brown bottle to determine the initial concentration of microplastics in the overlying water. The initial concentration of overlying water is indicated by "level 0″, while "Finished" is used to indicate the concentration of overlying water 30 min after the termination of the disturbance. Subsequently, the disturbance level was gradually adjusted from level 1 to level 4, with a duration of 65 min at each disturbance level. In the interval between two disturbance levels, 100 mL water samples were collected from the sampling port. 100 ml of raw water from site S5 was replenished into the resuspension device after each sampling while minimizing disturbance to the sample in the device. After completing four-level resuspension, the device was turned off and after 30 min another 100 mL water sample was collected. Then, the overlying water was completely drained off to collect the resuspended sediment, which was also separated into four layers as previously described.

The overlying water samples were pre-sieved with a 50 μm stainless steel sieve, followed by rinsing the residues on the sieve with saturated NaCl solution (1.2 g/mL) into a 500 mL beaker.

2.3. Separation and extraction of microplastics

Microplastics in the sediment were separated by a density-flotation separate technique (Lin et al., 2018). Sediment samples (20 g dry weight) were weighed into a beaker (500 mL), approximately 400 mL of saturated NaCl solution (1.2 g/mL) was added to each beaker (500 mL). The beakers were placed under an electric stirrer and the sediment samples were stirred for 15 min (600 r/min) to completely separate the microplastics from the sediment aggregates. The stirred samples were allowed to stand overnight in the dark at room temperature, followed by a collection of the supernatant into a 200 mL beaker (the beaker was covered with aluminum foil to prevent air contamination). The supernatant was filtered through a stainless-steel sieve (50 μm) and the residue on the sieve was washed with ultrapure water into a new 200 mL beaker. The flotation process was repeated three times to improve flotation efficiency. The walls of the beaker were flushed three times, followed by filtration of the rinsed solution and mixing with the supernatant. In the pretreatment process, particles smaller than 50 μm were excluded due to the pore size limitation of the sieve, particles larger than 5000 μm were also manually excluded. The samples were treated with a 30% H_2O_2 solution for 24 h at room temperature in the dark to remove any natural organic matter from the sediment sample until no natural ingredients were visible. However, if natural organic ingredients were found in the beaker, the digestion process was repeated. Then, the digested solution was suction filtered through a polycarbonate filter membrane (10 μm, diameter 25 mm, Whatman) using a vacuum pump and dried for 24 h at 35 °C in an oven.

2.4. Microplastics identification

The detection method used in this study has been improved based on the methods of Shim (Shim et al., 2016) and Erni-Cassola (Erni-Cassola et al., 2017) without an additional calibration process. Approximately 0.001 g/L Nile Red-methanol solution (>95%, Aladdin, China) was used for staining identification and the counting of microplastics, combined with a laser confocal microscope (Fig. S1 in Supplementary Information).

First, we used a glass syringe to aspirate the filtered Nile Red-methanol solution (0.45 μm, Jinteng, China) and placed 2–3 drops of the solution into the center of the filter membrane. Then, the filter membrane was fixed in the center of the slide using a coverslip and secured around it with tape. The coverslip should ensure both that the filter membrane does not slide and it does not interfere with the observation of the microplastics. The filter membranes were placed in an oven and dried at 60 °C for 30 min. Finally, the filter membranes were placed under a laser confocal microscope (Revolution XD, Andorra, UK) for quantitative analysis. After the magnification was adjusted to × 100, the light source was switched from the bright-field light source to a blue one (450–490 nm, B-2A) with the fluorescence intensity at the range of 8–16. The cross-shaped shooting method was used to take photographs, and five photographs were obtained at the five positions on the top, bottom, left, right, and center of the filter. Statistical analysis of the acquired photos was performed by counting the green blocks larger than 50 μm using Image J. The equations for calculating sediment abundance were as follows:

$$C_s = n_1 \times (A_t / A_s) \times (m / 1000) \quad (1)$$

where C_s is the abundance of sediment microplastics (items/kg), n_1 is the total number of microplastics counted by the five filters (items), A_s is the total area of the five filters, A_t is the total area of the filter, A_t/A_s is generally 8, and m is the mass of the sediment (g).

Selected microplastics were placed on a clean filter membrane and labeled with a stereomicroscope (XTL-165-LT, Phmias, China). The fluorescently labeled microplastics were then analyzed and identified by Fourier transform infrared spectroscopy (FTIR; Nicolet iS10, PE, USA), and the obtained spectra were compared with the infrared spectra of microplastic standard samples (Fig. S2 in Supplementary Information) to determine their polymer type. Standard samples included polyethylene (PE; 427772, Sigma, USA), polyvinyl chloride (PVC; 81388, Sigma, China), polystyrene (PS; 331651, Sigma, USA), polypropylene (PP; 428116, Sigma, USA), and polyamide (PA; 301497641, Sinopharm, China). Subsequently, the surface microstructure of the microplastics was analyzed by field emission scanning electron microscope (SEM)–energy disperse spectroscopy (EDS) (JEOL, JSM-7900F, Japan), and the magnification of the lens was adjusted from × 60 to × 10000. Energy spectroscopy was performed on the surface microregion with the acceleration voltage adjusted to 10 keV.

2.5. Quality control

In the field, a blank control was conducted at each sampling site in the Liangfeng River, which was used to assess the contaminated potential of microplastics from ultra-pure water and containers while collecting and transferring samples. Sampling tools used in the field are repeatedly rinsed with ultrapure water before use to reduce background contamination. In the laboratory, a cotton lab coat and disposable nitrile gloves were worn during the experiments to reduce microplastic contamination. The solution was filtered (0.45 μm, Jinteng, China) before use and the solutions were covered with aluminum paper immediately after use. Glass containers are rinsed repeatedly with ultrapure water before use, dried, and sealed. The average value of microplastics in the blank control was 310 items/kg, and the average value of microplastics in ultrapure water was 10 items/L.

2.6. Statistical analysis

Microsoft Office Excel 2007, Image J v1.8.0 (NIH, USA), and R (Team et al., 2006) were used for the statistical analysis and ArcGIS 10 (ESRI, USA) was used to map the geographic location and sampling site of the Liangfeng River sediment.

3. Results and discussion

3.1. Effects of temporal variation of microplastics between rainy and dry seasons

3.1.1. Morphology

Fibers, fragments, and films (Fig. 2) were detected in the sediment of the Liangfeng River (Yan et al., 2019). Microplastics on the filter membrane were selected for subsequent morphological analysis via stereomicroscope. The selected microplastics were mainly concentrated in the particle size range of 200–1000 μm since microplastics smaller than 200 μm looked similar in shape and were difficult to manually collect by tweezers. The smaller the particle size of microplastics, the more difficult and demanding it is to sample and analyze. This is the reason why the majority of microplastic investigations use a size range of 300–5000 μm (Hengstmann and Fischer, 2019; Lenz et al., 2015). In our study, the number of microplastics with particle sizes above 1000 μm is very limited. Existing studies rarely mention the difficulty of classifying microplastics of smaller sizes, as few studies have considered microplastic particles smaller than 300 μm. Therefore, microplastics in the range of 200–1000 μm were used as typical microplastics for subsequent morphological analyses. During the rainy season (Fig. 4A), microplastics were mainly fibers (47%), followed by fragments (31%) and films (22%). The microplastic morphology in the dry season (Fig. 4B) was predominantly fibers (41%), followed by fragments (33%) and films (26%), which is similar to the results of Zhao et al. (2020). The morphology of microplastics was similar during the rainy and dry seasons, indicating that seasonal variations have no significant effect on their morphology. The higher proportion of fibers may be due to agricultural equipment cracking and fiber-containing domestic wastewater (Ding et al., 2019). There is evidence to suggest that each piece of clothing will produce more than 1900 fibers during the washing process (Browne et al., 2011). The Liangfeng River basin is a transitional area from urban to rural areas with high agricultural activity. Wastewater treatment plants were an important and critical point in the transfer of microplastics from human life to the natural environment. There are two WWTPs in the upper stream of the Liangfeng River, which mainly receive domestic sewage from seven universities in the vicinity. Besides, shipping activities, fishing activities, and surface runoff are potential sources of fibrous microplastics. Besides, SEM images showed that there was breakage on the surface of microplastics in sediment, which was attributed to ageing caused chemical oxidation, pressure erosion, mechanical abrasion, and water flow shear (Ding et al., 2019; Luo et al., 2020).

Eighteen samples were chosen for element analysis of microplastic surface with EDS (Fig. S3 in Supplementary Information). Only one heavy metal Zn was detected on the surface of microplastics, except some common nonmetallic elements including C, O, Si, P, S, and Cl, and several other metallic elements K, Na, Fe, Mg, Al, Ca, Ti, Zr. It is an interesting phenomenon that only Zn was detected in this study, while no other heavy metals Cu, Ni, Cd, and Pb, even though all of them were detected from the sediment of Liangfeng River by other researchers (Xiao et al., 2021; Xu et al., 2016). It may be related to both the concentration difference of these heavy metals and the detection method used in this study. Xiao et al. (2019) reported that there were higher concentrations of Zn in the Liangfeng River sediments than Cu, Ni, Cd, and Pb. And, Deng et al. (2019) found that EDS could only detect Zn of a high concentration, but not for low concentrations of Cu, Ni, Cd, and Pb on the surface of microplastics, while all of them in the same samples were detected by ICP-MS. In addition, the content of heavy metals could be reduced during the digestion process of microplastic samples, which may also affect the detection of Cu, Ni, Cd, and Pb. Similar results were observed by Shruti et al. (2019), which reported that Cu, Ni, Cd, and Pb were didn't detected on the surface of microplastics in the sediment of the Atoyac River dominated by agricultural activities.

3.1.2. Abundance variation

Microplastics were observed at all sediment sampling sites with a 100% detection rate. During the rainy season, the abundance of microplastics in all sediments (Fig. 3A) ranged from (6.95–149.35) × 10^3 items/kg, with a mean value of (33.2 ± 11.99) × 10^3 items/kg. The maximum and minimum values of microplastics were found at sites S12 and S2, respectively. The dry season abundance ranged from (14.40–79.45) × 10^3 items/kg, and the mean value was (27.9 ± 15.05) × 10^3 items/kg. The maximum and minimum concentrations of microplastics were found at sites S2 and S12, respectively. The abundance values varied significantly from season to season at three of the sampling sites (S2, S4, and S12), and the three replicate sediment samples at these sites also varied considerably, which could be related to human activities and industrial pollution (McCormick et al., 2014). There are WWTPs located upstream of S2, S4, and S12, the discharge methods of these plants were intermittent drainage. Thus, the effluent from WWTPs may be one of the causes of the dramatic changes in microplastics abundance. Microplastics abundance in the dry season exceeded that in the wet season at 9 of the total 13 sampling sites, which may be related to runoff and water velocity. Also, it was found that the proportion of large-sized microplastics in the sediment was relatively high at sampling sites with finer sediment grain sizes (Fig. S4 in Supplementary Information), which may be related to the resuspension capacity of the sediment at each sampling site. Generally, a finer-sized sediment is likely to have more resuspension events than a coarser-sized one (Lecrivain et al., 2021). Resuspension events can facilitate the transfer of microplastics from the sediment to the overlying water, leading to a reduction in the number of microplastics in the sediment (Tang et al., 2020). The Liangfeng River is a typical rain-fed river, its runoff varies greatly with the seasons. Rainy season runoff is much larger than that of

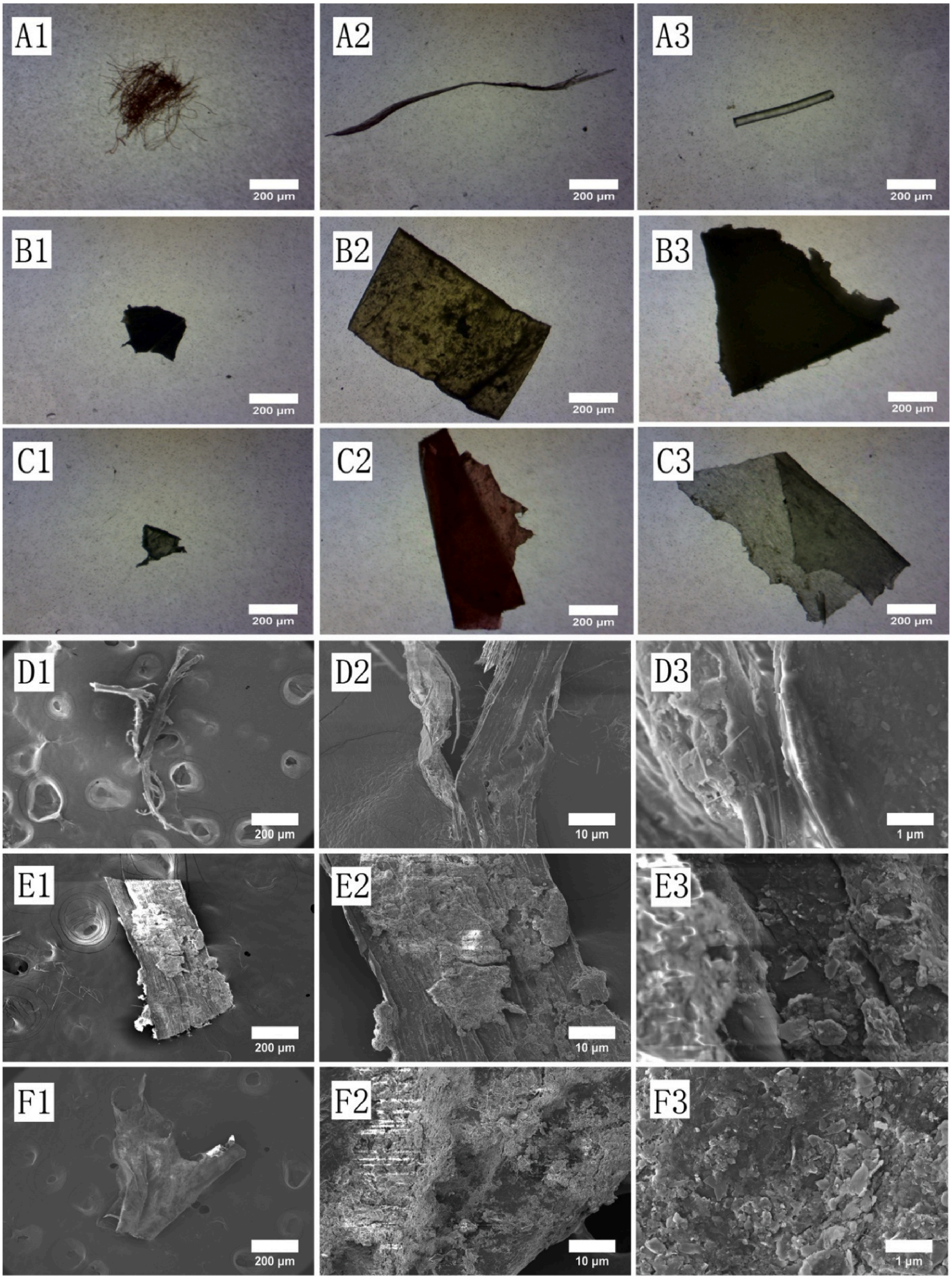

Fig. 2. Stereomicroscope image of the microplastics in sediment (A1–A3, fibers; B1–B3, fragments; C1–C3, films). SEM of the microplastics in the sediment (D1–D3, fiber; E1–E3, fragment; F1–F3, film), with the magnifications of (× 60, × 500, × 10000).

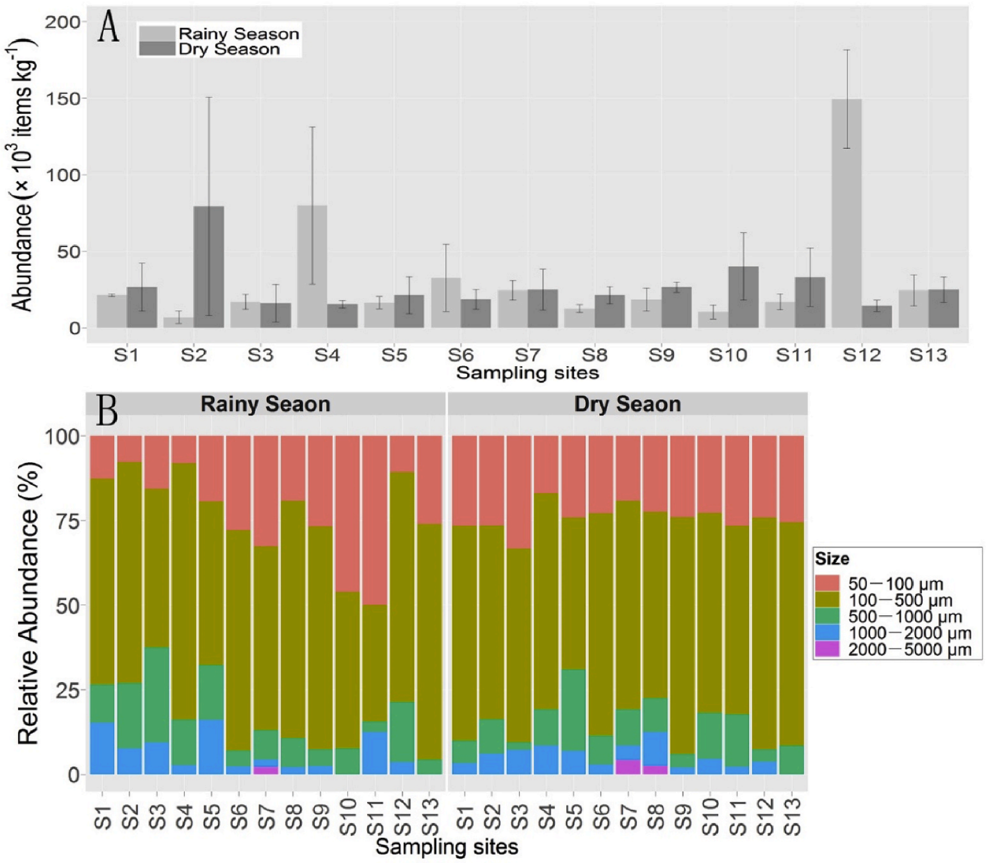

Fig. 3. Microplastic abundance distribution in sediment (A) and microplastic particle size distribution in sediment (B).

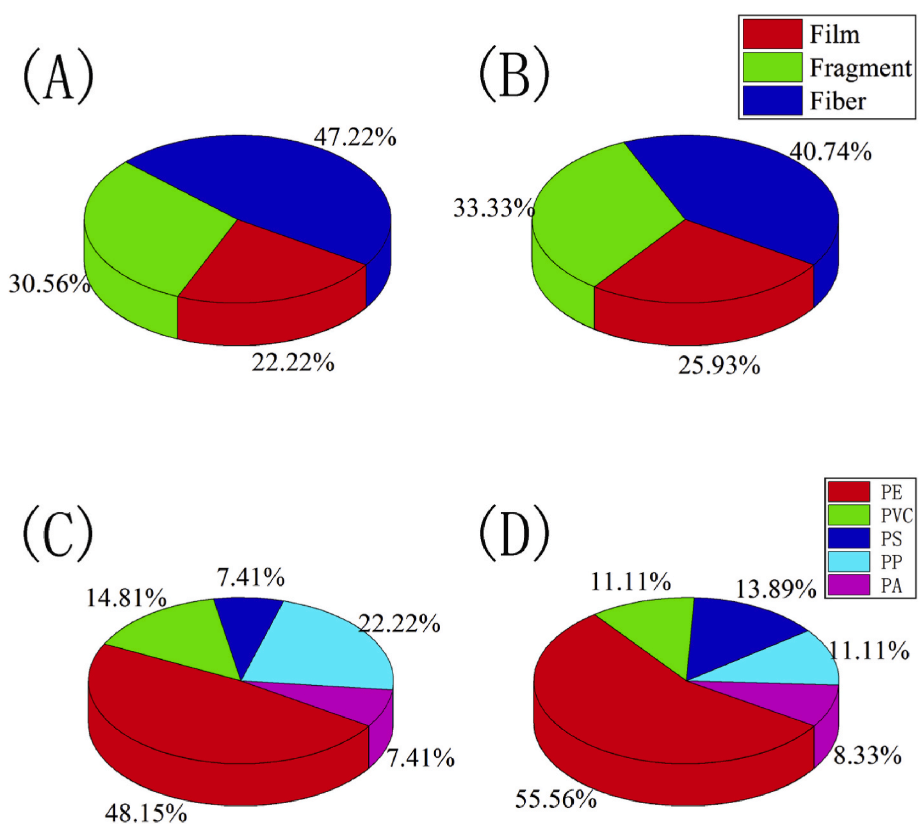

Fig. 4. Shape distribution of microplastics in rainy (A) and dry (B) seasons; distribution of polymer types in rainy (C) and dry (D) seasons.

the dry season, with runoff in the rainy and dry seasons being 560 m^3/s and 0.463 m^3/s, respectively. For sediment samples from the rainy season, resuspension could have been induced by sediment mobilization, which resulted in a reduction of microplastic abundance in the sediment. Simultaneously, microplastics in the water are more likely to accumulate in the sediment during the dry season when the flow of the Liangfeng River slows down (Zhao et al., 2020).

3.1.3. Particle size variation

The particle size of the microplastics in the sediment was mainly concentrated in the range of 50–500 μm (Fig. 3B). The small-sized microplastics could be from the breakdown of larger plastics in the aquatic environment (Wang et al., 2020) or discharge from some point pollution source such as WWTPs. Smaller microplastics are more likely to pass through WWTPs without being filtered (Simon et al., 2018). The abundance of microplastics increases exponentially as the particle size of microplastics in the sediment decreases with the main inflection point at a particle size of 100 μm. In contrast, the number of microplastics with the smallest particle size of 50–100 μm is slightly lower than 100–500 μm. The environmental behavior of microplastics is dramatically altered at particles less than 100 μm in size. It was believed that considering 100–500 μm microplastics as a fine particle may help to explain the reason. It has been shown that hyporheic exchange and turbulent bursts can trigger transient particle entrainment, which is particularly important for particles smaller than 100 μm in size (Drummond et al., 2020; Jiang et al., 2020; Tang et al., 2020). This may result in microplastic particles of 50–100 μm being transferred to the overlying water through resuspension, as they are small enough to be more susceptible to disturbance by hydrodynamic processes. Therefore, smaller size microplastic particles may be more easily transferred to the water column, leading to a decrease in the number of small-sized microplastics in the surface sediment, especially for particles of 50–100 μm.

In the sediment samples from the rain season, the relative abundance of 50–100 μm microplastics generally increased along with the flow direction of Liangfeng River from S1 to S11, while almost uniform in the sediments from the dry season. The difference was due to the variance of the hydrodynamic process among sampling sites in each season. The hydrodynamic process is considered to be the most important factor for releasing suspended solids from the sediment to water (Pang et al., 2020). During the rainy season, the high flow enhances the hydrodynamics process in the upstream channel of narrower width, which accelerates the transfer of 50–100 μm microplastics from the sediment to the overlying water, which then tends to settle in the downstream of the wider channel and results to large partitions of small-sized microplastics in the corresponded sediments. In the dry season, the much low velocity of river flow weakens the hydrodynamic process, which causes a low-intensity transfer of microplastics from sediment to water and makes the particle size distribution of microplastics uniform along the whole channel in the river-flow direction.

The abundance of microplastics in this study was higher compared to the results from other rivers (Table 1). The difference in abundance may be related to different analytical methods. The results of particle size distribution show that more than 80% of microplastics are concentrated in 50–500 μm. For the smaller-size classes, the Nile Red staining scheme proved to be reliable as more than 90% of the particles were verified as microplastics (Hengstmann et al., 2019). Conversely, the somatic microscopy results produced unreliable data due to the low resolution of the filtered photographs (Martin et al., 2017). Although visual classification is a legitimate and effective method, it tends to miss or incorrectly count microplastics with particle sizes of less than 1000 μm especially for microplastics with particles size below 200–300 μm (Nizzetto et al., 2016; Song et al., 2015). Previous studies have shown that the visual classification error rate ranges from 20 to 70%, increasing with decreasing particle size (Shim et al., 2016; Burns et al., 2018). In addition, particles in the sediment can interfere with the identification of microplastics on the filter membrane due to incomplete separation (Shim et al., 2016). Biological material is not eliminated by digestion, which also has an impact on microscopic observation. For smaller size microplastic particles, particles of 300–500 μm in size are most frequently found in stereomicroscope, accounting for more than 40% of the particles (Li et al., 2020). This is the main reason why most microplastics investigations use the 300–5000 μm size range (Lenz et al., 2015). The evaluation of microplastic accumulation worldwide may be underestimated because most previous studies have focused on the larger microplastics (300–5000 μm). In this study, the used sieve (50 μm) was also smaller than those (330 μm) typically applied in some previous studies to achieve detection of smaller size fractions of microplastics. The increased amount in this study may be from microplastic particles between 50–300 μm which were neglected in previous studies.

3.1.4. Type

The composition of the microplastics was identified by FTIR. Among the 70 selected microplastic samples, 63 were identified as microplastics, with a detection rate of 90%. PE, PVC, PS, PP, and PA were the main categories of plastic pellets in the Liangfeng River (Fig. 4C and 4D). Among them, PE made up the highest proportion, accounting for 48% and 55% in the rainy and dry seasons, respectively. Seasonally, the samples showed equal diversity in both the rainy and dry seasons, with all five types of microplastics being detected. PE and PP are widely used in daily life owing to their lightweight and stable characteristics, as packaging bags, fishing nets, and agricultural films (Wang et al., 2019). As the Liangfeng River basin is a suburban area dominated by agricultural production activities, PE and PP are frequently used, thereby gradually becoming the main sources of microplastics. PVC has been widely used in construction materials, probably mainly from construction sites along the Liangfeng River. PS is mainly used in packaging, transportation, and decoration, whereas PA is an important engineering plastic that replaces steel (Auta et al., 2017).

3.2. Effects of resuspension

3.2.1. Effect of resuspension on the overlying water

In general, the number of suspended particles in the overlying water increases significantly with the gradual increase of the disturbance intensity (Orlins and Gulliver, 2003). However, the abundance of microplastics in the overlying water did not increase linearly along with the disturbance level (Fig. 5A). During re-suspension, relatively high

Table 1
Abundance of microplastics in sediment from different study areas.

Project	Size (μm)	Microscope	River	Abundance (items/kg)	Literature
Sediment	45–5000	High-speed camera	Rivers in Shanghai	5274 ± 3812	Zhao et al. (2020)
	20–5000	Stereomicroscope	Tunisian Rivers	2340–6920	Toumi et al. (2019)
	63–5000	Binocular microscope	Rhine-Main River	Rhine:3763; Main: 1368	Klein et al. (2015)
	20–5000	Stereo optical microscope	Pearl River	80–9597	Lin et al. (2018)
	0–5000	Stereomicroscope	Atoyac River	833–1633	Shruti et al. (2019)
	10–5000	Stereomicroscope	Maozhou River	560 ± 70	Wu et al. (2020a)
	50–5000	Laser scanning confocal microscope	Liangfeng River	6950–149350	This study

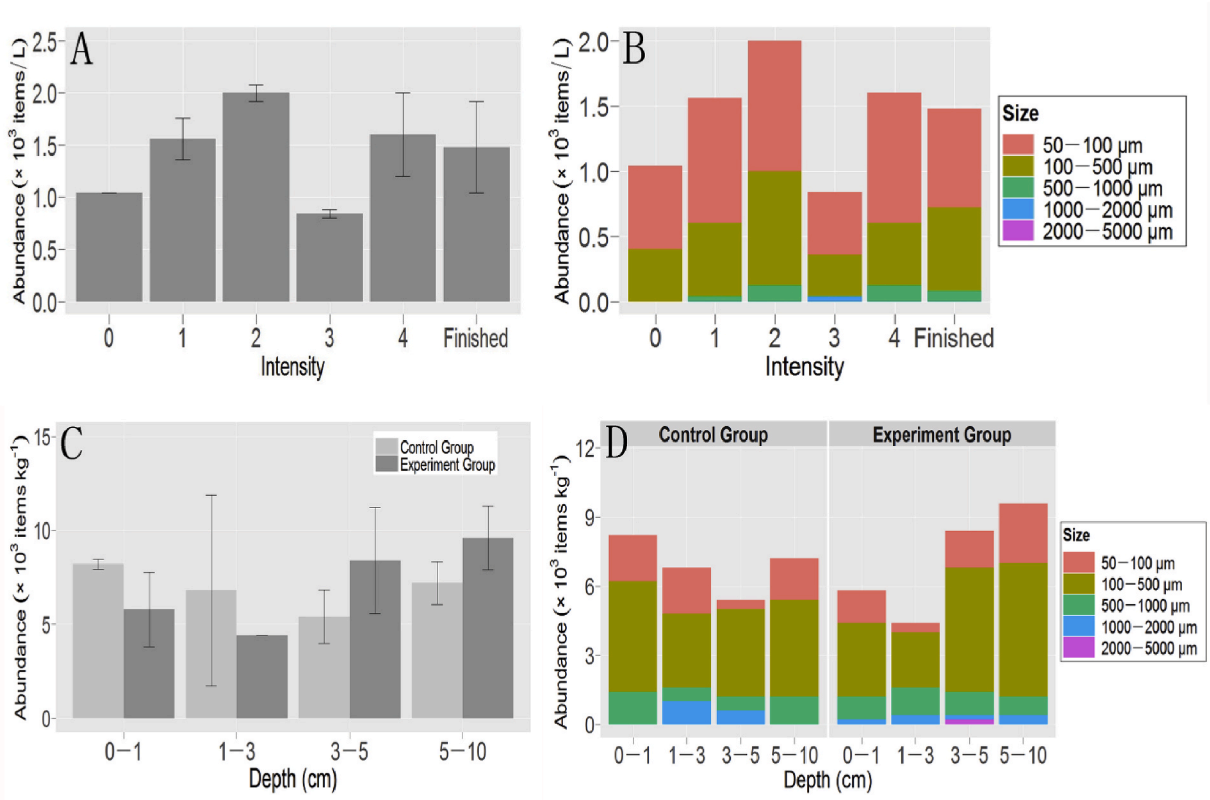

Fig. 5. Variation of the abundance of microplastics in the overlying water (A); Variation in particle size of microplastics in the overlying water (B); Vertical variation in the abundance of microplastics in sediment (C); Variation in particle size of microplastics in sediment (D).

intensity of up-down vibration in level 3 could cause turbulent eddies (Pang et al., 2020), which can carry suspended microplastics vertically upward to a higher elevation of the overlying water and result in a low concentration of microplastics in the near-bed region. An increase of microplastics in overlying water during resuspension means that sediment are not only the final sink but also a potential source for microplastics. More importantly, microplastics that were previously thought to be immobilized may be reactivated. This can lead to potential environmental threats, as "old microplastics" might often carry more toxic chemicals than "fresh microplastics".

The particle size of microplastics in the overlying water is mainly concentrated in the range of 50–500 μm, accounting for more than 90% of the total (Fig. 5B). So, microplastics in the sediment could be transferred to overlying water through resuspension, especially for smaller size microplastics (50–500 μm), and there are much more microplastics in the range of 50–100 μm than in the range of 100–500 μm. This is also consistent with our previous speculation that smaller-sized microplastic particles may be more easily transferred into the water column, especially for particles of 50–100 μm. A resuspension event happens when sediment particles are removed from a sediment to the overlying water (Lecrivain et al., 2021), which is likely to occur for microplastic particles of a similar size with the sediment particles. Moreover, small-sized microplastic particles could have more resuspension event as well as the fine-sized grain sediment, since smaller particles are easily subject to a disturbance of less strength. Of course, larger size microplastics are more likely to settle into the sediment (Auta et al., 2017), which may be one of the reasons for the predominance of small-sized microplastics in the overlying water. Furthermore, sediment resuspension is a frequent and continuous process in the field, caused by complex hydrodynamics. Therefore, small-sized microplastics are more likely to undergo multiple migrations and distribution through resuspension.

Besides disturbance intensity and microplastic size, several factors also could affect the transfer of microplastics from the sediment to overlying water, which include: microplastic density, biofouling, electrostatic-bind network, sediment cohesion, and turbulent eddy. It is widely believed that microplastics of higher density are more easily settle into the sediment (Wu et al., 2020b), such as PS and PVC. However, biofouling can neutralize the effect caused by the density difference between microplastics and water (Tu et al., 2020). The fine particles in the sediment can inhibit turbulence via electrostatic-bond network to alleviate the resuspension intensity of microplastics (Baas et al., 2002), while the sediment cohesion caused by Fe, Al also can be beneficial to reduce the resuspension intensity of microplastics (Bernatek-Jakiel et al., 2020). However, how those factors affect the microplastic resuspension is still unknown and needed to explore.

3.2.2. *Effect of resuspension on sediment*

The sediment samples were divided into four layers (0–1, 1–3, 3–5, and 5–10 cm) after the resuspension process. The results showed that the total abundance of microplastics in the 0–5 cm sediment layer does not differ much from the abundance at site S5. However, microplastics were still detected in the 5–10 cm sediment layer, indicating that a large number of microplastics may be "hidden" in the deeper sediment layer. Therefore, the global quantity of microplastics in sediment may have been underestimated, since most previous surveys only considered microplastics in surface sediment but excluded that in deep sediment (Li et al., 2020). The abundance of microplastics in the 0–3 cm layer of the experimental group was significantly lower than that of the untreated control group (Fig. 5C), whereas the microplastics abundance in the 3–10 cm layer was significantly higher than that of the control group. The main inflection point at 3 cm, which may be determined by the sediment compaction. Compaction of river sediment is a long-term uninterrupted process, which leads to the consolidation of deep sediment and can potentially increase the stability of the sediment (Liu et al., 2021). The disturbance had a significant effect on the sediment in the 0–3 cm layer, which is the main sediment resuspension area. However, this variability in abundance is more likely to be closely related to disturbance-induced resuspension and vertical transport. For example, microplastics in the 0–3 cm sediment layer may have been transferred to the overlying water, resulting in a decrease in the number of microplastics in the sediment. Simultaneously, microplastics in the 0–3 cm layer may have migrated into the deep sediment through gravitational settling and disturbance-induced vertical transport. This might also be the main reason for the higher abundance of microplastics in the 3–10 cm layer in the experimental group compared to the control group. Studies have shown that bioturbation and gravity deposition can facilitate the unidirectional transport of microplastics from surface sediment to deeper sediment (Xue et al., 2020). Bioturbation and gravitational settling are the results of prolonged action. In this study, the resuspension process was short enough to ignore the effects of bioturbation and gravitational settling. Thus, microplastics can be transferred from surface sediment to deep sediment by disturbance-induced vertical transport, especially for small-sized microplastics of 50–500 μm.

Unlike large-size microplastics, small-sized microplastics (50–500 μm) are significantly altered by disturbances (Fig. 5D). There was a decrease in the abundance of small-sized microplastics in the surface sediment, along with an increase in the deep sediment and the overlying water. In contrast, the abundance of 500–5000 μm microplastics did not change significantly either in the control group or in the experimental group. Microplastics in the surface sediment can move both to the overlying water and deeper sediment. This demonstrated that disturbance-induced vertical transport has a significant effect on small-sized microplastics (50–500 μm).

Interestingly, the disturbance-induced vertical transport does not change linearly with decreasing microplastics particle size, while the main inflection point at a particle size of 100 μm. Disturbance-induced vertical transport was most effective for 100–500 μm microplastics, followed by 50–100 μm microplastics. For microplastics with particle sizes less than 100 μm, the environmental behavior in different environmental media is slightly different. Microplastics with smaller particle sizes are more easily disturbed and more likely to be suspended in the water column. Furthermore, studies have shown that the microplastics content of the water-sediment interface is comparable to that of the surface sediment (Martin et al., 2017). In this study, the content of microplastics in the overlying water was in the same order of magnitude as that in the surface sediment. Therefore, microplastics exchange at the water-sediment interface should receive attention because it is likely to act as microplastic storage and carrying system. The adsorption of microplastics to heavy metals and organic pollutants, combined with their tiny special size, greatly increases the ecological risk in coastal areas. What is even more frightening is that this system is not static and fixed, it is variable and mobile, which is very favorable for the diffusion of pollutants.

4. Conclusions

In this study, the items of microplastic in the river sediments were in the range of (6.95–149.35) $\times$ 10^3 items/kg, which is higher about a magnitude than the reported values, and the majority of microplastic was with the size range of 50–500 μm. The abundance of sediment microplastics in the dry season were slightly higher than those from the rainy season, and the rainy season caused smaller microplastics to gradually accumulate in the sediment along with the river flow but not for the rainy season. A higher temporal-resolution study could be necessary to clarify the precise temporal variation of microplastics in the river sediment. During the resuspension process, only smaller microplastics (50–500 μm) could be transferred from the sediment to the overlying water but the bigger almost not. The initial results showed that these microplastics in surface sediment could be transferred to both overlying water and deeper sediment through disturbance-induced vertical transport, although more proof is needed. To better understand the environmental behavior of microplastics in the water-sediment, future studies are suggested to focus on the following aspects: hyporheic exchange, the effect of water quality, turbulent eddies, and the aging process.

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.

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Appendix A. Supplementary data

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Credit author statement

Feiyang Xia: Investigation, Writing – original draft, Formal analysis. Quanwei Yao: Investigation, Data curation, Methodology. Jun Zhang: Conceptualization, Writing – review & editing, Supervision. Dunqiu Wang: Writing – review & editing, Resources.

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