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Microplastics in surface water and sediments of Chongming Island in the Yangtze Estuary, China

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Abstract

Background: The Yangtze Estuary acts as gateways where microplastics transport from freshwater into marine environments, with one of the largest discharge volumes in the world. The occurrence of microplastics in surface water and sediments of the Yangtze Estuary has been reported. However, little is known about microplastics in and around Chongming Island in the estuary. In this study, the distribution of microplastics in surface water and sediments of Chongming Island was investigated and compared in different environmental medium.

Results: Abundances of microplastics in surface water and sediments were in the ranges of 0–259 items m^{-3} and 10–60 items kg^{-1} dry weight, respectively. Microplastics were more abundant in the surface water of the Yangtze River shores than in the inland rivers ($p < 0.01$). Proportions in fiber form in surface water and sediment were 33% and 67%; and those in fragment form were 39% and 24%. Most particles ($> 72\%$) were < 1 mm in the longest dimension; 65% were white and 30% were transparent. Of the 11 compositions identified, polyethylene, polypropylene, and α -cellulose predominated in both phases.

Conclusion: This is the first study to focus on microplastics in inland watercourses on Chongming Island and along the Yangtze River's shores in both phases. There were differences between the island and estuary in composition and density due to the distinct vertical mixing processes. The in situ filtration of surface water (100 L) sampling method was well employed in various freshwater environments and free of plastic materials in front of the filter, analysis results of which provided an important baseline reference for evaluating microplastic pollution in the Yangtze Estuary.

Keywords: Microplastics, Yangtze Estuary, Chongming Island, Surface water, Sediment

Background

Plastics have become indispensable due to their lightness, flexibility, cheapness, and long service life, with global production reaching 360 million tons in 2018 [1]. The term 'microplastics' refers to plastic particles of < 5 mm in size [2]. Their presence in the environment has been reported since the early 1970s [3], and many studies since have shown that microplastics are now ubiquitous in the oceans at all depths [4, 5], from the Arctic [6] to the

Antarctic [7]. Most studies have focused on microplastics in marine systems, with $< 4\%$ of publications concerning freshwater systems [8]. Oceanic plastic debris mainly originates from the land, where innumerable plastic particles and fibers accumulate [9]. Microplastics enter freshwater environments through various routes including discharge of domestic wastewater [10], application of sludge from wastewater treatment plants in agriculture [11], landfill leachate [12], surface run-off (little is known about transport by run-off), and atmospheric deposition [13]. Previous studies have shown that once in the aquatic environment, microplastics are ingested by a range of organisms, with further impact due to the leaching of toxic plastic additives including bisphenols and

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phthalates [14, 15]. As for processes, there is insufficient understanding of appropriate sampling and analysis techniques for microplastics in freshwater [9], with variations in methodology hindering comparisons of study results. Sampling methods may involve either small-volume or bulk sampling, while analysis methods mainly include the use of spectroscopic instruments and identification by a microscope or the naked eye [16].

The Yangtze Estuary is considered to be the largest contributor of plastic to the ocean in global modeling studies [17], and thus it has raised the level of concern. Several studies have separately reported the occurrence of microplastics in surface water or sediment of the Yangtze Estuary, and different volumes of samples were collected and analyzed. A total of 43 water samples (5 L per sample) from the Yangtze River and the East China Sea were analyzed with average abundance around 900 items m^{-3} [18]. By using a Teflon pump and neuston trawls to sample 12–20 L water in the Yangtze Estuary, Zhao obtained a range of microplastic abundances from 500 to 10,200 items m^{-3} [19]. Zhao collected 100 L water samples during the ebb phase and reported the overall mean microplastic abundance was 157.2 ± 75.8 items m^{-3} [20]. After analyzing 100 g sediment, Peng reported that the mean concentration of microplastics in surface sediments of the Yangtze Estuary was 121 ± 9 items kg^{-1} dry weight [21]. Additionally, previous studies have assessed the environmental risk of microplastics and re-estimated the riverine plastic load of the Yangtze River [20, 22]. Chongming Island, with its densely distributed river network, is situated in the middle of the Yangtze Estuary, but it is still unclear whether there exists microplastic pollution, particularly how it compared to the Yangtze Estuary.

This study investigates the distributions of microplastics in surface water and sediments in the Yangtze River and inland watercourses of Chongming Island at the river's mouth. Surface water samples were collected using a modified bulk-sampling method. Microplastics were characterized by quantity, shape, color, and size using a stereoscopic microscope, and their compositions were determined by micro Fourier-transform infrared spectroscopy (μ -FTIR). Here, we present comparable data for microplastics in the rivers of estuarine island and nearshore waters of the Yangtze River's downstream.

Methods

Study area and sampling sites

The Yangtze River flows through 11 provinces and cities, entering the East China Sea at Shanghai. Its estuary divides into north and south branches around Chongming Island, the largest alluvial island in the world, located north of Shanghai city. Approximately 70 thousand people live on the largely flat island, whose the river

drainage system is controlled by culverts and sluice gates. During drainage periods, the influence of tides allows the river network to draw water from the Yangtze River through open sluice gates on the southern side of the island, then the gates on the northern side are opened to discharge water. The gates are closed during non-drainage periods, isolating the island's rivers from the Yangtze and forming an almost closed water system. The gate control system contributes directly to the lack of river hydrodynamics.

This study considers two E–W flowing rivers (the Nanhengyin and Beihengyin), six N–S rivers (the Gelong, Laoyao, Xinhe, Buzhen, Siyao, and Bayao) on Chongming Island, and both branches of the Yangtze River. Sampling was undertaken continually during June 21–23, 2019, when the gates were in the closed state. Fifteen sets of surface water and sediment samples were collected; nine from inland island rivers and six from the Yangtze River shores along the island during the ebb phase, representing the microplastic pollution situation of the Yangtze Estuary. Detailed information about the sampling sites is shown in Additional file 1: Table S1 and Fig. S1.

Sample collection and processing

A modified surface-water sampling method was used as follows. An empty metal cylinder (volume, 575 mL; $\Phi=7$ cm, $H=15$ cm) was immersed in water with its exterior attached to floats to keep the top at a depth of 5 cm. The open top (water inlet) had a coarse screen with an average mesh size of ~ 1 cm, and a metal filter of 300 μm mesh size was placed across the middle of the cylinder. The cylinder bottom was connected to a centrifugal pump, which drew at least 100 L of surface water with a flow rate of 0.2 L s^{-1} through the cylinder at each sampling site. After sampling, the metal filter was transferred and stored in a sealed metal container pending analysis. Plastic components were avoided in front of the metal filter, and all components were thoroughly washed with distilled water before sampling. Sediment samples were collected at the same sampling site of 1 m² quadrats from the upper 5–10 cm of the riverbed, using a sediment core sampler. Replicate samples (600–800 g) were taken from three randomly chosen points at each sampling site, then placed in aluminum foil bags and homogenized. All sediment samples were stored at 4 °C pending analysis.

In the laboratory, samples were processed based on previous criteria, with little modifications [21]. Metal filters were oven-dried at 60 °C for 24 h and sediment samples were dried at 75 °C for 72 h to constant weight. 200 g of each dried sediment sample was placed in a 1 L glass beaker, and 500 mL of saturated NaCl solution (density 1.20 g cm^{-3}) was added. The mixture was manually stirred for 2 min, and after settlement for 2 h the

suspension was decanted in a 150 mL beaker. Organic matter in the suspension was degraded by treatment with 20 mL 30% H₂O₂ at 65 °C for 24 h, and the solution was filtered under vacuum through a 75 µm nylon filter. The filters were dried for further analysis. The metal filters were not subjected to digestion processes, as these could have negative impacts such as bleaching and the addition of organic materials [23]. However, it was necessary to treat the sediment samples with peroxide because floatation carries large amounts of impurities from the sediment, leading to difficulties in performing analyses on nylon filters compared with relatively 'clean' metal filters.

Sample analysis

The dried filters were studied using a Nikon SMZ25 Stereo Microscope (Nikon, Tokyo, Japan) coupled with imaging software (NIS-Elements 4.60.00; Nikon). Suspected microplastic particles were counted on the basis of structural integrity when touched or moved by tweezers, avoiding those with biological structures [23]. Each filter was scrutinized by two or three observers, with the quantity, shape, color, and size of items being recorded. Abundances were recorded as items m⁻³ water and items kg⁻¹ dry sediment, and shapes were categorized as fiber, fragment, film, or granule. Microplastics were measured using the imaging software and classified according to their longest dimensions as 75–300, 300–1000, 1000–2000, or 2000–5000 µm, in view of the ingestion of microplastics by aquatic organisms [24].

The µ-FTIR analyses involved a Nicolet TM iNTM10 FTIR system (Thermo Fisher Scientific, USA) equipped with a single-element mercury cadmium telluride detector. Transmittance mode was used, with each particle compressed in a diamond anvil compression cell. Spectrum acquisition involved 32 scans per replicate over a bandwidth of 4000–675 cm⁻¹ at a resolution of 4 cm⁻¹. Spectra were processed by OMNIC™ Specta™ software and compared with spectral libraries (including Aldrich Polymers, Hummel Polymer and Additives, Polymer Additives and Plasticizers, Sprouse Polymer Additives, and Synthetic Fibers by Microscope).

Quality assurance and quality control

Special precautions were given to prevent contamination during the whole procedures. Non-plastic components were used wherever possible. Contamination was prevented by rinsing all containers three times with distilled water and drying before their first use. All of the filters were rinsed and heated at 450 °C for 8 h to eliminate any organic materials. The measures for contamination prevention during transportation are specified in Additional file 1: Fig S2. The laboratory was sealed during sample handling and analyses to avoid airborne contamination,

and cotton lab coat and gloves were worn at all times. Filters and solutions were always covered by aluminum foil during drying and suspension process.

Blank experiments should be conducted to examine potential contamination by running parallel the same processing with the samples. 1 L of distilled water, 1 L of saturated NaCl solution, and 100 mL of 30% H₂O₂ were filtered, and laboratory air was pumped under vacuum for 1 h with two operators present. The filter used above was 75 µm nylon filter, which was left in covered containers and analyzed. If there were microplastics detected on the filter, then they should be deducted from the final values. In this study, two groups of blank experiments were conducted with no microplastics were found, but two natural fibers were identified on the filter (Additional file 1: Table S2).

Statistical analysis

Statistical analysis involved the IBM Statistic Package for Social Science (SPSS) 24. Pearson correlation coefficients (*r*) were calculated for the relationship between microplastic abundances in surface water and sediment, with the significance of differences between the groups being determined by the Mann–Whitney U test (significance level 0.05). Principal component analysis (PCA) was undertaken using a data matrix of polymer types found at each sampling site to evaluate the relationship between microplastic compositions and sampling sites.

Results

Abundance and distribution of microplastics

Totals of 51 and 105 microplastics were identified in surface water and sediments, with abundances range of 0.0–25.9 items per 100 L (0.0–258.9 m⁻³) and 2–12 items per 200 g dry weight (d.w., 10–60 items kg⁻¹ d.w.), respectively (Additional file 1: Table S1). Sampling sites on Chongming Island can be divided into two groups: group YRS (Yangtze River shores) including six sites along the island shorelines (sites Y1–Y6), and group ILR (inland rivers) including nine sites from six main inland rivers on Chongming Island (sites M1–M3 and C1–C6), representing microplastic pollution from land-based sources. Average microplastic abundances (mean ± standard deviation) in surface water and sediments of groups YRS and ILR were 67.5 ± 94.4 items m⁻³ and 28.3 ± 14.4 items kg⁻¹; and 9.8 ± 12.2 items m⁻³ and 39.4 ± 16.1 items kg⁻¹, respectively. An overview of the distribution of microplastics on Chongming island and in the Yangtze River Estuary is given in Fig. 1.

Microplastics were found in the sediment at every sampling site, and there were no statistically significant differences in microplastic abundances between the two groups (Mann–Whitney U test, *p* = 0.224). The highest

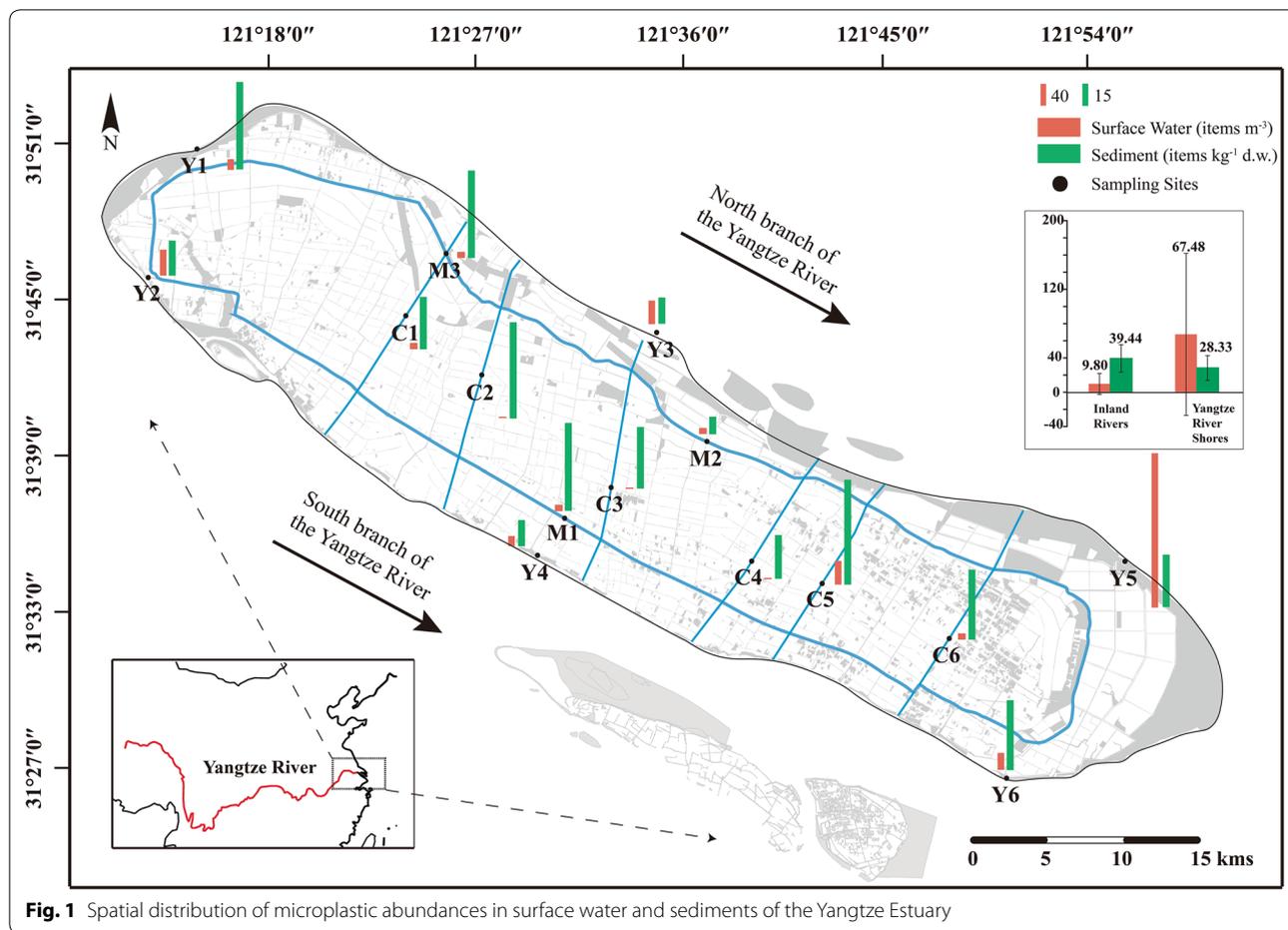


Fig. 1 Spatial distribution of microplastic abundances in surface water and sediments of the Yangtze Estuary

abundance of microplastics in sediments was found at site C5 (60.0 items kg⁻¹ d.w.). There is an aquaculture market near C5, and therefore the long-term use and unintentional disposal of plastic products may result in accumulation of microplastics within this area. Other higher abundances in group ILR (50–60 items kg⁻¹) were collected at site M1 and M3, which were characterized by increasing human activities.

In surface water, however, microplastics were more abundant in group YRS, with the difference being significant (Mann–Whitney U test, $p=0.005$). The highest abundance of microplastics in surface water (258.9 items m⁻³) was found on northeastern Chongming Island at site Y5, which may partly be explained by the special topography near the north branch and tide interact in the Yangtze Estuary [25]. The second highest abundance (43.4 items m⁻³) was at site Y2, near the Chongxi sluice gate in the western Chongming Island. There the external and internal gates are linked to the Yangtze River and intake channel, respectively, with the potential to influence microplastics transportation in the surrounding waters. No microplastics were found in surface water at

three sampling sites (C2, C3, and C4), possibly due to the low level of human activity in the middle part of Chongming Island. Correlations of microplastic abundances in both phases of all sites were not statistically significant (Pearson’s correlation, $p>0.05$).

Shape, color, and size of microplastics

The morphological characteristics of the observed microplastics are summarized in Fig. 2. Fragments were the predominant shape in surface water with an average proportion of 39.2%, dropping to 23.8% in sediments. Fiber proportions were higher in sediments (average 66.7%) than those in surface water (33.3%). The proportion of films decreased from 19.6% in surface water to 9.5% in sediments. Granules were the least frequent shape, accounting for 7.8% and 0.0% in surface water and sediment, respectively (Fig. 2a). Typical shapes of microplastics from all samples are summarized in Fig. 3.

Eight colors (white, blue, transparent, yellow, black, red, brown, and green) were observed in microplastics in surface water and sediment (Fig. 2b), with white being the most common in surface water (64.7%; cf. 11.4% in

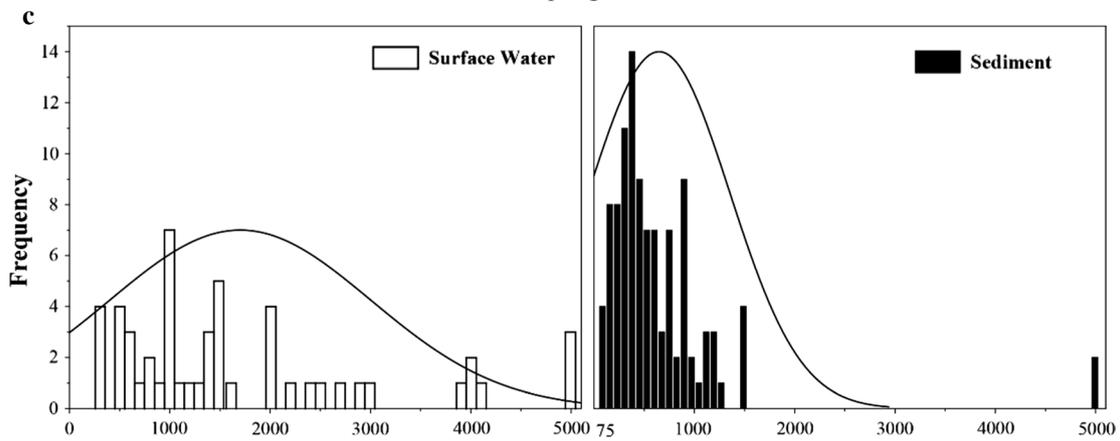
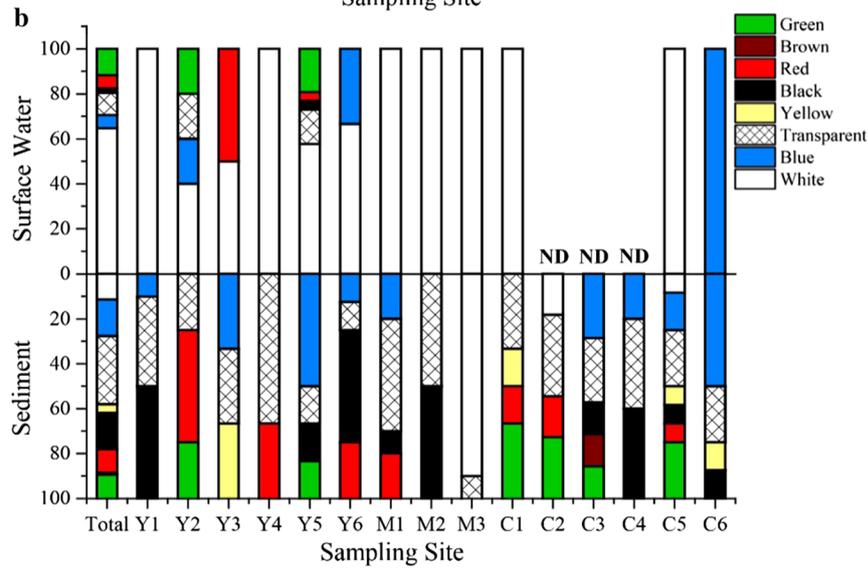
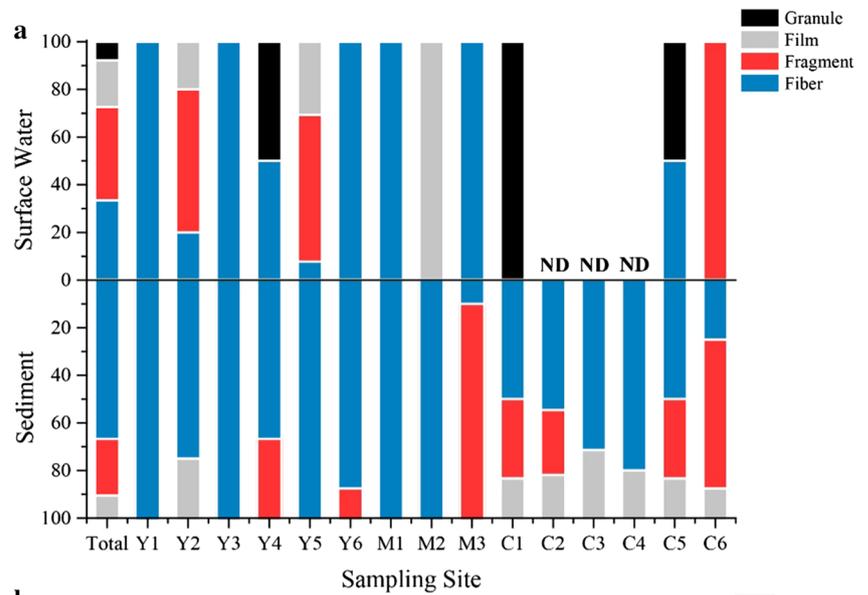


Fig. 2 Cumulative percentages of microplastics colors (a), microplastics shapes (b) and normal frequency distribution across different size categories (c) of total microplastics in two phases. *ND* means not detectable

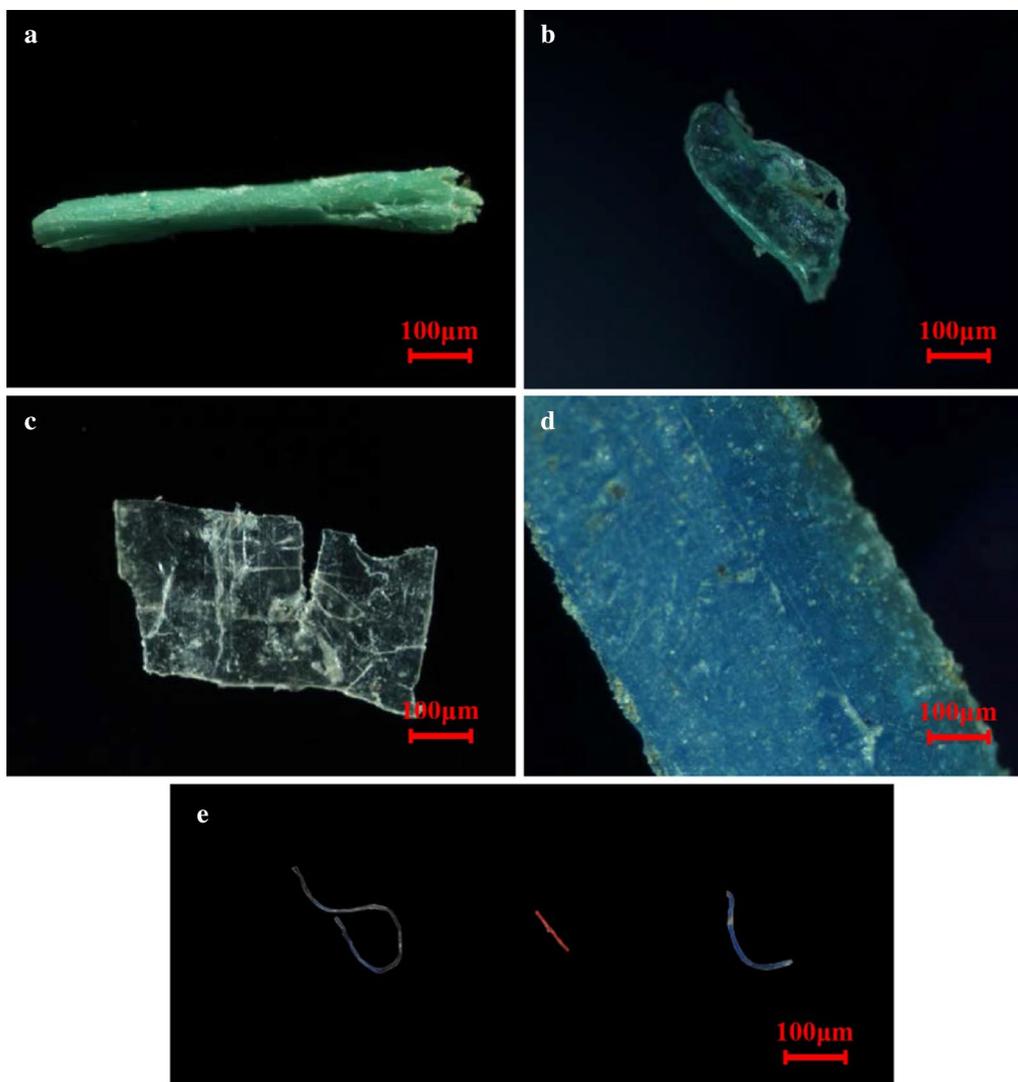


Fig. 3 Microscope images of typical microplastics. Fragment (a, b); film (c, d); fibers (e)

sediment). Transparent particles were most common in sediments (16.2%; cf. 9.8% in water). A large number of transparent plastics are commonly used in fishing nets and lines for the frequent fishery activities in Shanghai [21], and transparent microplastics in sediment samples may be attributed to the bleaching caused by digests.

The lower limit of microplastics size was 300 μm in surface water and 75 μm in sediments, as dictated by different filters. Most microplastics in both phases were <2000 μm in size, whereas the large microparticles (2000–5000 μm) were seldom observed (Fig. 2c). In surface water, microplastics possessed the wide size distribution from 300 μm to 4000 μm (Fig. 2c), meanwhile the size of most microplastics valued less than 1000 μm (Fig. 2d). A possible explanation is that large plastics are

prone to forces of flow and wind leading to floating on water, while smaller plastics tend to migrate into sediments and deep water [26, 27]. Size distribution of group YRS and ILR in both phases is shown in Additional file 1: Table S3.

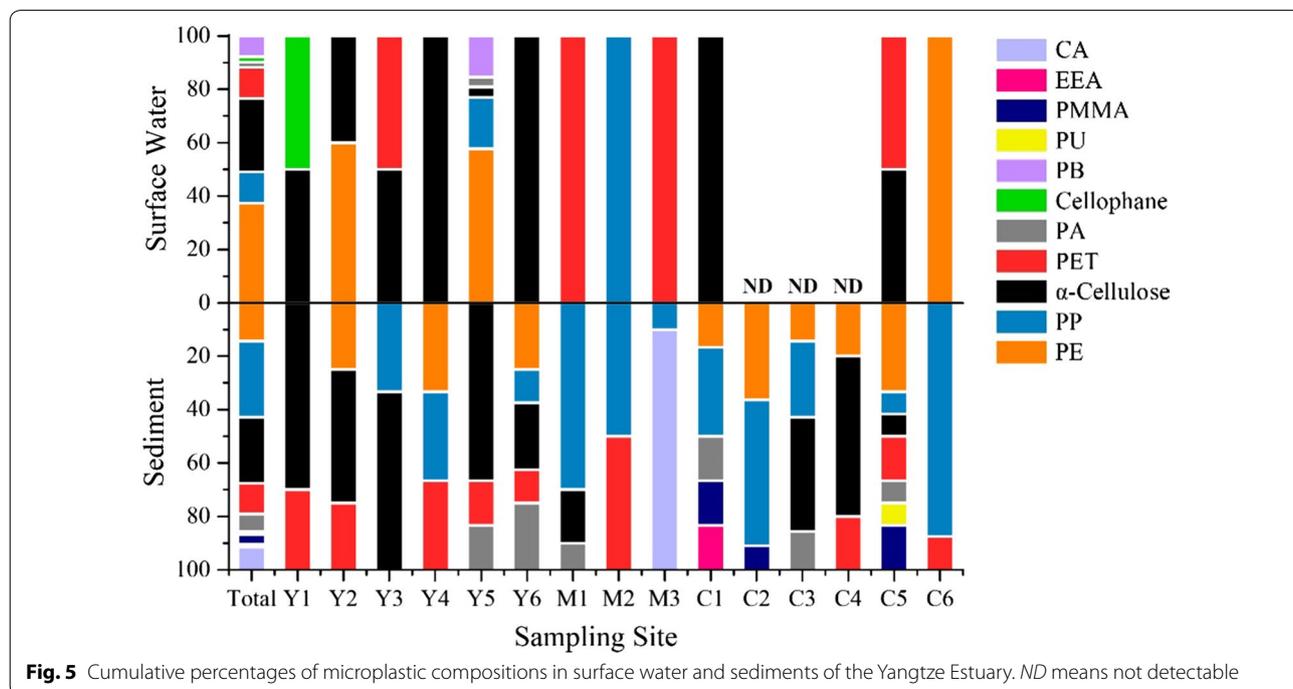
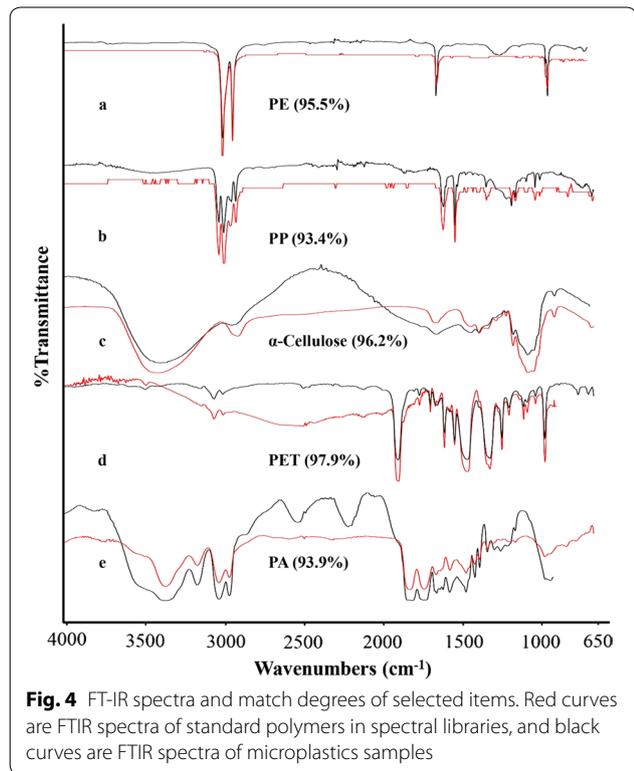
Identification of microplastics

Suspected microplastic particles were analyzed by $\mu\text{-FTIR}$, which has been widely employed in identifying microplastic polymers due to its high reliability in determining chemical compositions of unknown plastic fragments [16, 28]. Composition–library comparisons were difficult to achieve with high similarities due to the weathering and contamination of plastics [29], with the lower limit being set relatively high here (>75%) to

provide more accurate results (compared with 60%–80% in previous studies). Eleven polymer types were identified: polyethylene (PE), polypropylene (PP), α -cellulose,

polyethylene terephthalate (PET), cellulose acetate (CA), polyamide (PA), polybutene (PB), polymethyl methacrylate (PMMA), cellophane, polyurethane (PU), and ethylene/ethyl acrylate (EEA). FTIR spectra of the five most common types are shown in Fig. 4, and relative compositions are given in Fig. 5. The predominant polymer type in surface water was PE (37.3%), and that in sediment was PP (28.6%). PE and PP were the most abundant polymer types in both phases, and these are also the leading polymers in plastics production. In 2018, PP (19.3%), low-density PE (17.5%), and high-density PE (12.2%) were the predominant resin types used widely in packaging and construction [1]. Another common microplastic, α -cellulose, used mostly in clothing, had proportions of 27.5% in surface water and 24.8% in sediments, but such semi-synthetic fibers had lower search scores (most < 80%) and were difficult to accurately recognize. The characteristic spectral band at 1105 cm^{-1} was used to distinguish semi-synthetic and natural fibers [30]. Color uniformity and average shape were also considered when it was otherwise difficult to identify the composition of fibers.

PCA results indicate that 11 variables (i.e., 11 polymer types) described the spatial distribution of sampling sites in three-dimensional coordinates. Figure 6a shows the PCA of the 7 variables in surface water, with PC1, PC2, and PC3 explaining > 92.66% of the total variance (Component matrix and component plot are shown in Additional file 1: Table S4 and Fig. S3). PC1, explaining



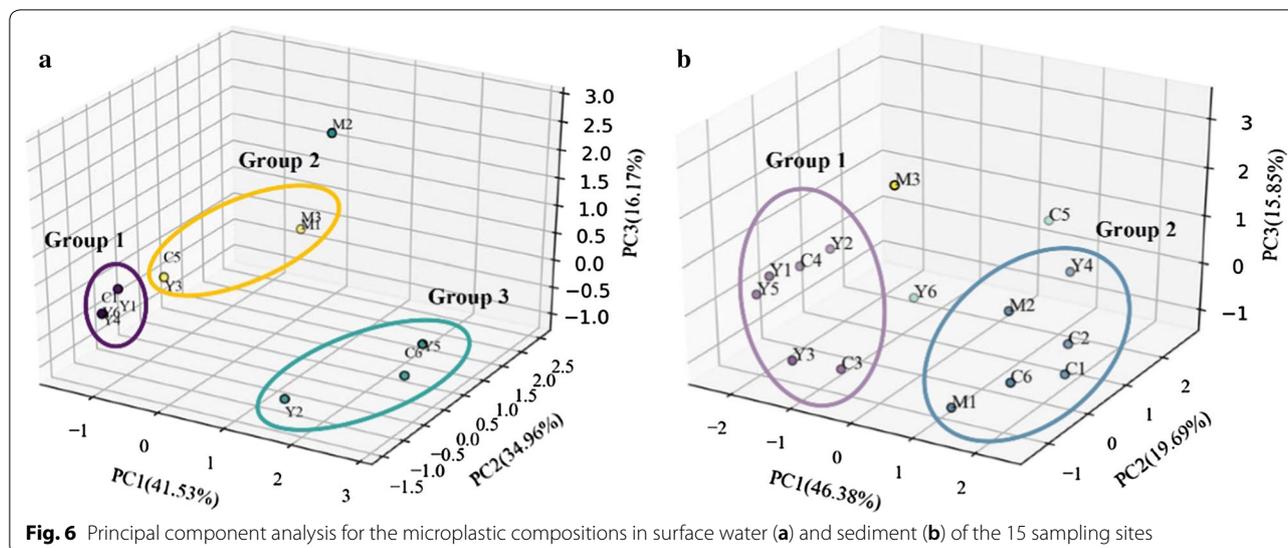


Fig. 6 Principal component analysis for the microplastic compositions in surface water (a) and sediment (b) of the 15 sampling sites

41.53% of total variance, had high loadings of PP, PE, PA, and PB; PC2 indicated strong contributions of PET and α -cellulose; and PC3 was dominated by cellophane. In terms of spatial distribution, some sampling sites overlapped others, with microplastic abundance there being lower and with single polymer types causing high similarities in the same component. Figure 6b shows the PCA of the 9 variables in sediment, with PC1, PC2, and PC3 explaining >81.92% of the total variance (component matrix and component plot are shown in Additional file 1: Table S5 and Fig. S4). PC1, explaining 41.53% of total variance, displayed strong correlations between PE, PU, and PMMA, while PC2 was mainly contributed by PP, α -cellulose, and PET, and PC3 with PA, EEA, and CA. Sediment analyses indicate that the sampling sites were divided into two main groups: group 1 comprising sites Y1, Y2, Y3, Y5, C3, and C4; and group two comprising sites M1, M2, C1, C2, C6, and Y4, consistent with the assignment of groups ILR and YRS, reflecting compositional differences between the island and estuary.

Discussion

Distribution characteristics of microplastics around the Yangtze Estuary

Chongming Island plays an important role in wildlife migration, providing spawning and feeding grounds for millions of fish and bird species, with physical and toxicological effects of ingested microplastics posing a threat to the coastal ecosystem [31–33]. The abundances of microplastics in surface water at the mouth of the Yangtze River were higher on the east and west corner of Chongming Island (Fig. 1). The highest abundance of all surface water samples ($258.9 \text{ items m}^{-3}$) was at site Y5, next to

the East China Sea, on the eastern shore of Chongming Island, where formed an accumulation zone under the effect of tide and topography. However, this abundance here did not exceed $10.9 \times 10^3 \text{ items m}^{-3}$, which is the highest record in the Yangtze Estuary by Zhao [19].

Table 1 compares microplastic pollution levels in surface water of estuaries in different countries. The average microplastic abundance ($67.5 \pm 94.4 \text{ items m}^{-3}$) in the Yangtze Estuary exceeds that of the Tamar Estuary ($0.028 \text{ items m}^{-3}$), Goiana Estuary ($0.14 \text{ items m}^{-3}$), and five estuaries in South Africa ($1.0\text{--}7.0 \text{ items m}^{-3}$), but is far less than that recorded in polluted estuaries in the USA, Germany, and China ($>157.2 \text{ items m}^{-3}$). Table 1 is sequenced according to the values of sampling volume and mesh size of different methods. There is an obvious trend that abundance values sharply decreased with the increment of volume and size. Many studies used small-sized sieve in the sampler to further investigate smaller microplastics ($<300 \mu\text{m}$), while it also means less sampling volume (1 to 20 L) was taken due to a large quantity of tiny particles. Researchers, however, should be cautious that insufficient sampling volume may lead to skeptical results [34], especially when the result is used to represent regional pollution level and compare with others. Inconsistency of units, including items L^{-1} and items m^{-3} , also makes comparison questionable. For example, there is two orders of magnitude between results in 1 L water samples ($0.94 \text{ items L}^{-1}$) through a $1.2 \mu\text{m}$ pore size filter and about ten thousands of liters $330 \mu\text{m}$ net samples (4.5 items m^{-3}) in results of the Tampa Bay [35]. Given all this, it seems advisable to take sufficiently bulk samples with the use of smaller mesh size, considering

Table 1 Comparison of floating microplastic abundance and sampling method used in estuaries worldwide

Study estuaries	Location	Sampling method and mesh size (μm)	Sampling volume (L)	Abundance (items m^{-3})	References
Tampa Bay	Southeast USA, North America	Water sampler-1.2	1	940.0	[35]
Charleston Harbor and Winyah Bay	Southeast USA, North America	Water Sampler-63	4	6 600.0 30 800.0	[36]
Charleston Harbor	Southeast USA, North America	Water Sampler-63	4	2 750.0–36 500.0	[37]
German Baltic coast	Germany, Europe	Water sampler-55	5–10	0.0–5000.0	[38]
Pearl River Estuary	South China, Asia	Water sampler-50	20	8902.0	[39]
Yangtze Estuary	East China, Asia	Pump-300	100	67.5	This study
Mdloti Estuary	South Africa, Africa	Net-300	10 000	1.1	[40]
uMgeni Estuary				2.5	
Durban Harbour				7.0	
Isipingo Estuary				3.1	
iLovu Estuary				1.0	
Goiana Estuary	Northeast Brazil, South America	Net-300	100 000	0.1	[41]
Tampa Bay	Southeast USA, North America	Net-330	/	4.5	[35]
The UK Channel, North, and Celtic Sea area	Northwest Europe	Net-333	/	0–1.5	[42]
Tamar Estuary	England, Europe	Net-300	/	0.028	[43]

Abundances are expressed as items per cubic meter. The upper parts are small-volume sampling methods, while the lower parts are bulk volume sampling methods. "/" means the sampling volume is unknown, nets are often towed at ~ 2 knots for a certain time

that results should be accurate and broadly comparable with others.

This is the first study to report microplastic abundances in nearshore waters of the north branch of the Yangtze River. Both branches of the Yangtze Estuary have relatively high abundances of microplastics in surface water due to the Yangtze River's large discharge and plastic flux [44]. It is estimated that 16–20 trillion microplastic particles (i.e., 537.6–905.9 tons) enter the East China Sea via the Yangtze River each year [20]. In the estuaries, the distribution of microplastics is affected by hydrodynamic forces (waves, tides, and currents) in aquatic systems [45, 46]. Plastic particles repeatedly transport offshore and onshore, with some being trapped in enclosed waters [47, 48]. An experiment was conducted on Wadahama Beach to study backwash process of plastics floats. The results showed that the backwashed floats tend to concentrate in the convergence zone under the effect of offshore currents and alongshore currents around the tidal flat [49]. At six estuarine sampling sites (Y1–Y6) on the shores of the Yangtze River, we found various mismanaged plastic waste, including plastic bottles, packaging materials and fishing nets, which may be due to the backwash of the Yangtze River. Inland rivers had a low microplastic abundance (9.8 ± 12.2 items m^{-3}) in surface water, with three sampling sites having no detectable microplastics. This is consistent with results of a previous study, which indicated that some sections of urban creeks in Shanghai have low microplastic abundances (80 items m^{-3}) [18]. The movement of microplastics may be subject to flow conditions, vegetation patterns, and water levels in

particular rivers, which have a significant impact on their transport [50].

Resembling natural colloids and suspended solids, microplastics are subject to turbulent transport, settling, aggregation, biofouling, resuspension and burial, with movement between the water column and sediments [8]. Density is an important factor in vertical transport of microplastics. There were four types of detected polymers, including PE, PP, PB and EEA, whose densities were less than that of water, while the others (α -cellulose, PMMA, PA, PET, PU, Cellophane and CA) were dense than water. Density information is shown in Additional file 1: Table S6. Interestingly, high-density microplastics in surface water of the Yangtze River shores (25.0 ± 8.4 items m^{-3}) were significantly more than (Mann–Whitney U test, $p=0.008$) that of inland rivers (7.8 ± 13.0 items m^{-3}), while low-density microplastics in sediment of inland rivers (21.7 ± 16.0 items kg^{-1}) were significantly more than (Mann–Whitney U test, $p=0.036$) that of the Yangtze River shores (5.8 ± 5.8 items kg^{-1}). A possible explanation is that high-density particles can reenter the water column by resuspension of bottom sediments [8]. Influenced by nearshore circulation and offshore tides, the sediment resuspension in tidal estuaries contributes to redistribution and exchange of substances between water and sediment phases [51]. By contrast, the rivers on Chongming Island have a low river flow velocity ($0.2\text{--}0.5$ m s^{-1} during drainage periods and more slowly during non-drainage periods), which is conducive to the sedimentation of plastic particles. Many low-density microplastics were found in inland sediments.

This discrepancy could be attributed to change of densities with weathering and biofouling in the environment [52, 53]. Our results indicate that microplastics are widely distributed in sediments of both groups (overall average abundance 35.0 ± 15.9 items kg^{-1}), and sediment is regarded as the sink for abundant microplastics in the aquatic environment [54, 55]. Here we have only discussed the influence of density on the sinking of microplastics. Consequently, further research should be undertaken to investigate the sinking behavior more comprehensively.

Uncertainties in alternative methods

Appropriate sampling and analysis methods are of critical importance in obtaining reliable results. The advantages of our optimized sampling and analysis method are as follows. (1) Sampling and filtration components were made of metal to prevent contamination by plastic materials. (2) At least 100 L water was sampled at each site, as bulk volumes were considered to provide reliable and representative results. (3) Microplastics usually float on the surface of water, so suction from the surface allows collection of surrounding particles, with pumping improving in situ filtration efficiency. (4) All suspected microplastic particles were identified by μ -FTIR, with potential errors arising if a limited number of randomly selected particles are analyzed.

Compositional errors can be significant if a limited number of particles were randomly selected to identify their composition [28, 29]. For example, fiber is a common type of microplastics, accounting for 33% in surface water and 67% in sediments from Chongming Island. This prevalent shape is matched with various polymer compositions including α -cellulose, PA, PET, PMMA, PP and PE (the latter two only in sediment). However, there are many natural materials such as chipboard, cotton, and natural cellulose with fiber shapes, and it is difficult to distinguish between polymer and natural fibers, even spectroscopically, because some polymer fibers are cellulose-based and their FTIR spectra are almost identical to those of natural fibers [56]. Here, 137 fibers were selected using the microscope, but only 87 (63.5%) were identified as microplastics according to their spectral characteristics, color, and shape. Further analysis is therefore required to determine whether or not fibers should be recorded as microplastics.

Density separation and digestion are common processes of sample processing in many studies [9, 16], but can lead to incomplete sample transfer. Some particles and fibers are easily stuck to the beaker wall and glass rod when stirring solutions, however, these tiny items are often neglected by operators. Peroxide digestion causes bleaching of particles and may produce different organic

materials in some cases [23, 57]. We therefore applied visual sorting directly on the metal filters, without involving density separation and digestion steps. In order to withstand hydraulic pressure by suction of the pump, metal filters were woven from wires with diameter of 100 μm and designed as the multi-layer structure. Because of this structure, here we used the mesh size of 300 μm , which is larger than that used by other studies (< 100 μm). In the future, we hope to reduce the mesh size of metal filters, and thus further improve the performance of the microplastic sampler and decrease the lower limit for sampling.

Conclusions

Microplastics are ubiquitous in freshwater environments but, compared to marine environments, few reliable bulk-sampling methods are available for their study. This study aims to assess microplastic pollution in surface water and sediments of the Yangtze Estuary, including inland rivers on Chongming Island and the lower reaches of the Yangtze River. A modified bulk water-sampling method, having advantages of low-cost, high efficiency and anti-contamination, was employed and well applicable to various freshwater environments. Results indicate that microplastics are much more abundant in surface water in the Yangtze Estuary than in the inland rivers, while sediment contamination levels were similar. Compositional differences of microplastics between the island and estuary exist especially in sediments; in addition, significant density differences between surface water and sediments verifies the diverse vertical transport of microplastics in inland rivers and the estuary, where resuspension of sediments directly influenced redistribution in both phases. We suggest that microplastics monitoring of both phases should be conducted by suitable means, with further studies of the sinking behavior in the Yangtze Estuary being required.

Supplementary information

Supplementary information accompanies this paper at <https://doi.org/10.1186/s12302-020-0297-7>.

Additional file 1: Table S1. Sampling information and analysis results of all sampling sites in the Yangtze Estuary. **Table S2.** Detailed information of non-plastic particles found on the filter. **Table S3.** Comparison of different sized MPs. **Table S4.** Component matrix of surface water data. **Table S5.** Component matrix of sediment data. **Table S6.** Density information of identified polymers in this study. **Figure S1.** Map of sampling sites. **Figure S2.** Flow diagram of sample's transportation. **Figure S3.** Component plot of surface water data. **Figure S4.** Component plot of sediment data

Abbreviations

μ -FTIR: Micro-Fourier-transform infrared spectroscopy; PCA: Principal component analysis; SPSS: Statistic package for social science; YRS: Yangtze River shores; ILR: Inland rivers; PE: Polyethylene; PP: Polypropylene; PET: Polyethylene terephthalate; PA: Polyamide; PB: Polybutene; PU: Polyurethane; PMMA: Polymethyl methacrylate; EEA: Ethylene/ethyl acrylate; CA: Cellulose acetate.

Acknowledgements

Not applicable.

Authors' contributions

YL, JW, CC and HZ were involved in the sampling and experiments. YL and ZL wrote the manuscript. YL, ZL and HZ designed the study. All authors read and approved the final manuscript.

Funding

This work was supported by the Norwegian Research council program INT-PART (PLASTPOLL 275172).

Availability of data and materials

The datasets obtained and analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 19 November 2019 Accepted: 24 January 2020

Published online: 07 February 2020

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