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Abundance and characteristics of microplastics in the mangrove sediment of the semi-enclosed Maowei Sea of the south China sea: New implications for location, rhizosphere, and sediment compositions☆

Ruilong Li [a, b, c, d], Linlin Zhang [a, b, c, 1], Baoming Xue [a, b, c], Yinghui Wang [a, b, c, *]

[a] *School of Marine Sciences, Guangxi University, Nanning, 530004, PR China*
[b] *Guangxi Laboratory on the Study of Coral Reefs in the South China Sea, Guangxi University, Nanning, 530004, PR China*
[c] *Coral Reef Research Center of China, Guangxi University, Nanning, 530004, PR China*
[d] *State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen, 361000, PR China*

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ABSTRACT

Microplastic pollution of intertidal mangrove ecosystems is receiving growing attention, and scientists suspect that the microplastic pollution of semi-enclosed seas is significantly different from that of other coastal types because of their unique geographical features. However, data on the distributions and characteristics of microplastics in the mangrove sediment of semi-enclosed seas are very limited. This study selected the Maowei Sea, a typical semi-enclosed sea, as its representative study site. The analysis revealed that the microplastic abundances in the river estuaries were much lower than those at the oceanic entrance zones, with values ranging from 520 ± 8 to 940 ± 17 items/kg. Polyethylene (PE)/polypropylene (PP)/polystyrene (PS), white/transparent, and <1 mm were the dominant type, colour, and size of the microplastics, respectively, in the observed mangrove sediments. Moreover, some other factors, including the rhizosphere/non-rhizosphere and the proportion of organic matter, codetermined the distribution and characteristics of microplastics. Specifically: (1) the percentage of colorful microplastics were higher in the rhizosphere due to the microbial activities and (2) positive linear relationships were found between the pore volume (PV) values of the free particulate organic matter (FPOM), occluded particulate organic matter (OPOM) (1.6–2.0 g/cm^3 and >2.0 g/cm^3), and the abundance of very small microplastics (<1 mm).

1. Introduction

Plastic products have broad and widespread uses in almost all aspects of daily life. Total global production of plastics increased almost 200 times from 1.7 t in the 1950s to 299 t in 2013 (Galloway et al., 2017; Chae and An, 2018; Law and Thompson, 2014). Lambert reported that, once released into the environment, relatively large plastics might undergo a variety of biotic and abiotic processes through which they become smaller and smaller plastic particles instead of disappearing (Lambert and Wagner, 2016). Recently, these small plastic particles, particularly microplastics (<5 mm), have been confirmed to present a new series of problems, mainly: (1) they are small enough to be taken up by marine organisms and accumulated through the food chain and (2) they adsorb persistent organic pollutants and heavy metals on their surfaces and, thus, somewhat increase the bioavailability of these contaminants (Su et al., 2016; Steensgaard et al., 2017; Song et al., 2017; Huffer et al., 2017; Chubaenko and Stepanova, 2017). Barboza et al. confirmed in 2018 that reduced swimming velocity (80%–87%) and resistance time (52%–64%) of the juvenile European sea bass (*Dicentrarchus labrax*) were obvious after exposure to microplastic and mercury mixtures (Barboza et al., 2018).

To further our understanding of the environmental behaviours and potential hazards of microplastics, many studies have

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* Corresponding author. School of Marine Sciences, Guangxi University, Nanning, 530004, PR China.

E-mail address: wyh@gxu.edu.cn (Y. Wang).

[1] Co-first author: Linlin Zhang.

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investigated the sources, pathways, and distributions of microplastics in marine environments using data from coastal to deep-sea areas from the Arctic to the Antarctic and from freshwater to marine organisms (Lots et al., 2017; Browne et al., 2010; Cincinelli et al., 2017; Graca et al., 2017; Fork et al., 2017). All of these studies clearly confirmed that microplastics are dispersed throughout the world's oceans (water, sediment, and biota). For example, Zhu et al. demonstrated that the abundance of microplastics in the North Yellow Sea's surface seawater and sediment were 545 ± 282 items/m^3 and 37.1 ± 42.7 items/kg, respectively (Zhu et al., 2018). In the Northeast Pacific Region, plastic microfibers were found in the stomachs of approximately 1.5% of the sand lance (*Ammodytes personatus*) and 2.0% of the herring (*Clupea pallasii*) (Hipfner et al., 2018). However, the number of studies focused on microplastic pollution in unique marine ecosystems (coral reef, mangrove, sea grass, and so on) has been small compared to studies of the four major oceans (Pacific, Atlantic, Indian and Arctic). Due to their high productivity, the source/sink, decomposition and deposition fate of microplastics there were found to be significantly different from other marine environments (Jacotot et al., 2018; Komiyama et al., 2008).

Mangrove ecosystems always serve estuaries as buffers and are considered barriers to land-based inorganic/organic contaminants' delivery to the sea, which needs particular research attention. Ramdine et al. reported that the concentrations of polycyclic aromatic hydrocarbons (PAHs), a typical hydrophobic organic contaminant (HOC), in the mangrove sediment and associated oysters (*Crassostrea rhizophorae*) of Guadeloupe, France, might even range from 49 to 1065 ng/g dw and 66–961 ng/g dw, respectively, with a trend of annual escalation (Ramdine et al., 2012). However, limited information is available on the distributions of microplastics in mangrove ecosystems. To date, the only relevant study has focused on the microplastic pollution status of Singapore's coastal mangrove ecosystems, which found that the content might be as high as 62.8 items/kg dry sediment (Nor and Obbard, 2014).

The hydrodynamics of semi-enclosed seas (the usual mangrove vegetation habitat) are a dominant factor determining the content of the microplastics (Boelens et al., 2018), which significantly differed from that of the above study area of Singapore. Aside from the sedimentary locations (river estuaries, entrances and so on), the rhizosphere effects and sedimentary compositions have long been considered the two most important influences on the partition, transportation, and degradation of persistent organic pollutants (POPs) in sediment-water interfaces (Lu et al., 2011; Countway et al., 2003; Mustajarvi et al., 2017). However, no relevant studies were found about the abundances and characteristics of microplastics in semi-enclosed mangrove sediments or their possible implicating factors (locations, rhizosphere, and sediment compositions).

This study selected the semi-enclosed Maowei Sea in the northwestern South China Sea as the target area. The Maowei Sea receives discharges from three major rivers (Qin River, Maoling River and Dalan River) and covers an area of approximately 135 km^2. Consequently, the objectives of this study were to: (1) identify the differences between the microplastics in the mangrove sediment of the river estuaries and those in entrances of the semi-enclosed sea, (2) determine the abundances and characteristics of the microplastics in the rhizosphere/non-rhizosphere of the mangrove sediment, and (3) further explore the relationships of the physicochemical properties of the sediment and the microplastic content.

2. Materials and methods

2.1. Sample data collection

Sediment samples were collected from the several mangrove habitats classified as atypical semi-enclosed seas throughout the Maowei Sea of Guangxi Province in southern China. The sampling sites are shown in Fig. 1 (21°61′N–21°91′N, 108°47′E–108°80′E). The Kangxi Ling (KL), Madi Ao (MA), Kuizi Jiang (KJ) and Da Maoling (DM) were the river estuary sites; and the Qishier Jing (QJ), Longmen Harbor (LH) and Qinzhou Harbor (QH) were the semi-enclosed sea entrance sites. The Leshan Village (LV), Danshui Wan (DW) and Hai Wei (HW) were selected as the adjacent zones. The plastics under observation were polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET) and polystyrene (PS) because of their widespread daily use. Additionally, the mangrove sediment rhizosphere, as Berg et al. reported (Berg and Smalla, 2009), has been defined as the root center and the diameter of 10 cm circle. Some other detailed information about the sampling procedures and devices were presented in the Supporting Information.

2.2. Density separation and microplastic extraction

Similar to Wu et al. (Zhang et al., 2017), three experimental procedures were used to quantify the microplastics in the mangrove sediments: (1) oxidation digestion, (2) density separation/filtration, and (3) visual inspection/identification. The scheme of laboratory workflow was presented in Fig. S1. First, the sediment samples collected at the sampling sites were dried at 60 °C and sieving with 5 mm meshes. Then, to avoid the interference of sediment organic matter (SOM) in the quantification of the microplastics, the relatively small mangrove sediment samples that passed through the sieves were sequentially treated three times with 10 mL of 30% hydrogen peroxide (H_2O_2) and deionised water for about 24 h in 2-L Erlenmeyer flasks.

Second, 1.5 L of potassium formate aqueous solution with a 1.5-g/cm^3 density was prepared and poured into Erlenmeyer flasks. The samples were settled overnight and, then, the supernatant was filtered onto 1.2 μm GF/C glass microfiber filter membranes (Whatman, UK). After that, the filters were transferred to petri dishes and oven-dried for 30 min at 298.15 K. At that point, the numbers of particles on the filters were detected under the stereomicroscope (Olympus SZ53, Japan) with 3–4 × magnification. Meanwhile, the suspected and typical particles were captured using the charge coupled device (Andor Zyla 4.2 sCMOS) and carefully retrieved from the filters.

In the next step, all of the selected particles were placed on quartz glass slides and identified using a micro-Raman spectrometer (Renishaw inVia, UK). The parameters of the micro-Raman spectrometer were modified to reduce the effects of background fluorescent signals: Laser energy, 15 mW (5%); Laser wavelength, 785 nm; Exposure time, 2.0 s; and Emission wave number, 130–4000 cm^{-1}. The spectra of six distinct microzones were scanned to obtain a final estimate and assessment of the microplastic types. The Raman spectra of typical samples are presented in Fig. S2.

2.3. Quality assurances (QA) and quality controls (QC)

The following QA and QC measures described in previous studies were employed by this study (Lozoya et al., 2016).

1. Mangrove sediments were collected and stored in metal samplers and containers to avoid possible contamination.
2. All flasks and beakers were rinsed three times with distilled water before use.
3. Before identification and quantification of the microplastics, the sample holders of the stereomicroscope and micro-Raman spectroscope were carefully cleaned and inspected.

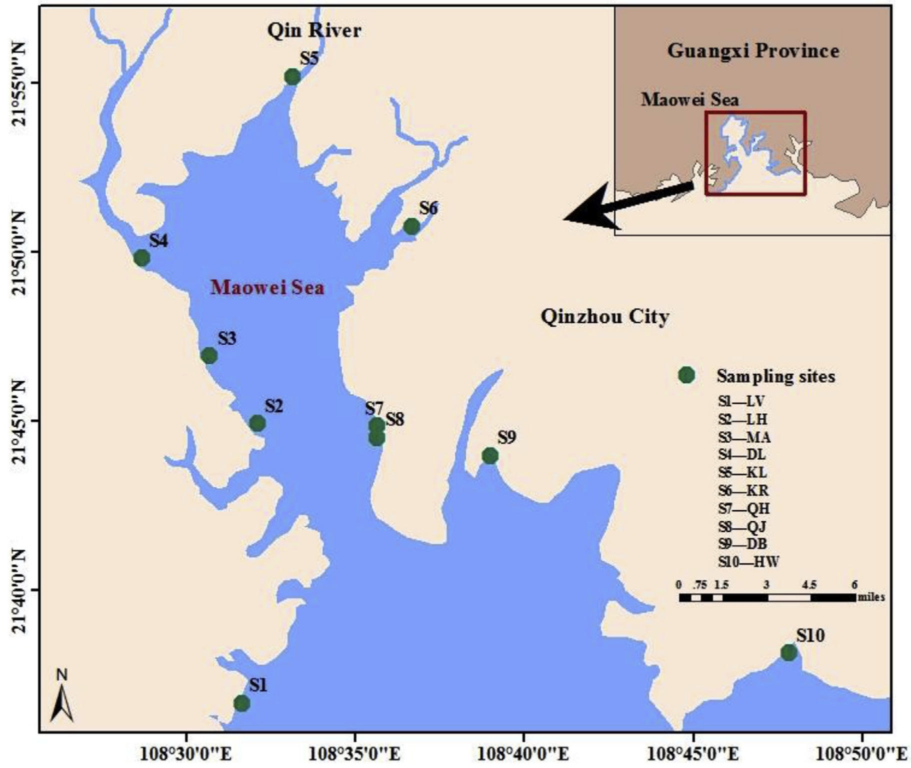

Fig. 1. Geographic location and sampling sites.

4. Blank tests were performed to adjust the results obtained during sample collection and laboratory analysis; microplastics were not found in the blank samples.

2.4. *Characteristics of the sediment samples*

2.4.1. *Fractionation*

The density fraction method developed by John et al. (2005). was performed on all the mangrove sediments with little modification. Briefly, 10 g of sediment were mixed with 40 mL of 1.6-g/cm^3 sodium polytungstate solution in a thin glass tube and shaken five times at 120 rpm (about 30-min period). Then, the solutions were centrifuged at 5085×g for 1 h. The free particulate organic matter (FPOM) was collected on 0.45 μm glass fibres after being rinsed three times with deionised water. After that, the residues were again mixed with 40 mL of 2.0-g/cm^3 sodium polytungstate solution and shaken for 10 min at a frequency of 100 rpm. The occluded particulate organic matter (OPOM) with a density of 1.6–2.0 g/cm^3 was collected on 0.45 μm glass fibres, and the other organic proportions were classified as high density OPOM (>2.0 g/cm^3). All dried proportions were ground before analyses.

2.4.2. *Organic carbon content*

Along with the pores of the different proportions of sediment, organic carbon, which is another important compositional factor, was identified and characterized using the method described by Cerli et al. (2012). First, 0.5 g of the FPOM and OPOM (1.6–2.0 g/cm^3 and >2.0 g/cm^3) samples were digested with 10 mL 4 mol/L of trifluoroacetic acid for 4 h at 105 °C. Then, the residues on the 10-μm glass fibres were collected and dried at 30–40 °C for at least two hours. Last, the C, H, and N contents of these residues were measured using a Vario EL III elemental analyser (Elementar, Germany).

2.4.3. *Pore volume (PV)*

Seven randomly selected FPOM and OPOM (1.6–2.0 g/cm^3 and >2.0 g/cm^3) samples were used to evaluate PV using low-pressure nitrogen adsorption measurements. Before analysis, these samples were dried overnight in a vacuum oven at 110 °C to remove other gases. Then, the ASAP 2020 M instrument (Micromeritics Instruments, US) was operated at 77 K with relative pressures ranging from 0.005 to 0.995, and the PV values on the different types of POM were determined using the Barrett-Joyner-Halenda (BJH) equations.

3. Results and discussion

3.1. *Abundance and characteristics of microplastics in the river estuaries and entrances to the sea*

3.1.1. *Abundance*

Microplastics were identified and counted at all sites located on the river estuary of the semi-enclosed Maowei Sea, which yielded abundances ranging from 520 ± 8 items/kg to 940 ± 17 items/kg, were much lower than those in entrance zones (ranging from 1780 ± 18 to 2310 ± 29 items/kg) ($^*p < 0.05$). The typical microplastics from mangrove sediment are presented in Fig. 2. The levels were much higher than those found in the North Yellow Sea, China, at 37.1 ± 42.7 items/kg (Zhu et al., 2018). Therefore, the microplastic pollution of the mangrove sediment in the semi-enclosed Maowei Sea cannot be ignored, and further measurements must be taken in the near future.

Many reports have indicated that the microplastic content of estuary sediments was owing to multiple factors, including human activities, water flow rates, dissolved organic matter (DOM)/

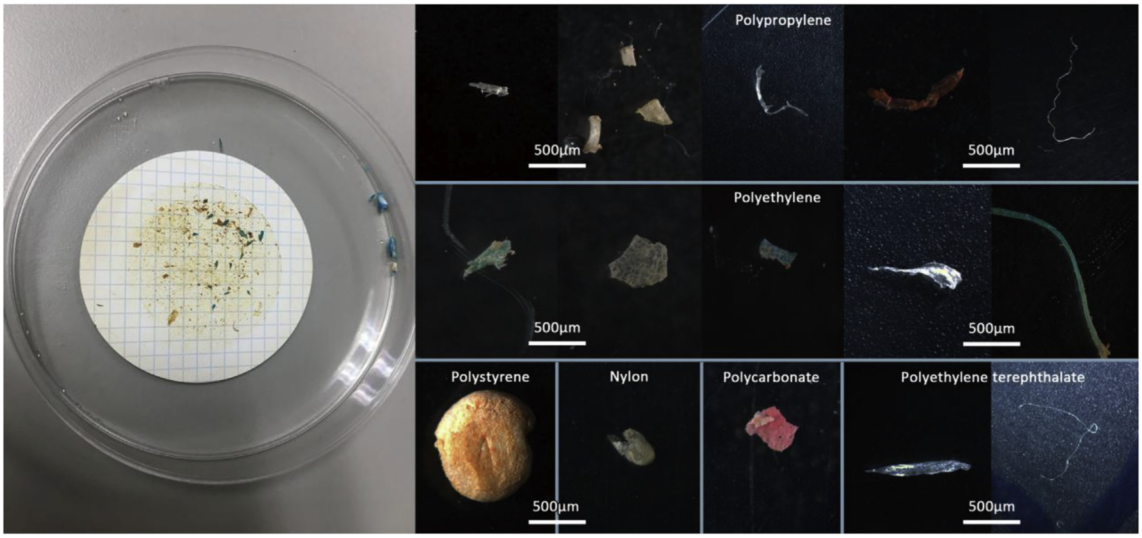

Fig. 2. Typical microplastic collected from the mangrove sediment located on the semi-enclosed Maowei Sea.

particulate organic matter (POM) content and so on (Chubarenko et al., 2018; Ma et al., 2016; Karami et al., 2018). Among these, Nor et al. found that waste matter generated at shorelines was the dominant factor determining the distribution of microplastics in Singapore's mangrove sediment (Nor and Obbard, 2014). However, the current study found that the total amounts of microplastics in the river estuary zones were 940 ± 17 items/kg, 520 ± 8 items/kg, 560 ± 9 items/kg and 640 ± 11 items/kg at the KL, MA, KJ and DM sites, respectively, and that the microplastic content at sites located almost at Qinzhou City (KL) was only slightly more than at the other sites (Fig. 1). The difference implies the existence of other factors influencing the distribution of microplastics in the mangrove sediment, which needs further investigation.

Because of the unique characteristics of the semi-enclosed sea and its relatively small area (approximately 135 km^2), the input of organic contaminants by the three major rivers was a main factor determining the distributions of microplastics in the mangrove sediment of the river estuaries. Based on this, we assumed that the loadings of microplastics from upstream might be a main source instead of local human activities. To test our assumption, the types of microplastic in the mangrove sediment of the river estuaries, the upstream river and the adjacent zones were compared to each other. From Table S1, it can be clearly concluded that no obvious differences were found between the percentages of nearly all kinds of microplastics in river upstream Sha Ping site and the river estuary KL site ($^*p < 0.05$). While such percentages were obviously different from the adjacent zones, especially to the PP microplastics with approximate 15.6% lower than the adjacent LV site (see Table 1).

Then, as Table 2 and Fig. 3 demonstrate, the total content of the microplastics in the entrances was about one order of magnitude higher than that at the river estuaries, with 2200 ± 27 items/kg, 1780 ± 18 items/kg and 2310 ± 29 items/kg for QJ, LH, and QH, respectively. Specifically, the proportions of PS microplastics were much higher than those at the river estuary with the values of 28.2%, 37.5% and 20.1% for QJ, LH and QH, respectively ($^*p < 0.05$). These phenomena were mainly caused by two characteristics. First, the widespread use of the above three types of plastics in the semi-enclosed Maowei Sea region increased the probability of their

Table 2
The relationships between the abundances of microplastics and the organic carbon content/compositions of mangrove sediment.

Site	Abundance (items/kg)		Coefficients (R^2)[c]	Coefficients (R^2)[d]
1	375 ± 18[a]/296 ± 14[b]	FPOM	0.3377/0.3869[c]	0.6645/0.8994[d]
		OPOM (L)	0.2145/0.3884	0.6320/0.8311
		OPOM (D)	0.3077/0.4169	0.6893/0.8129
2	449 ± 16/210 ± 22	FPOM	0.3325/0.5037	0.6331/0.9079
		OPOM (L)	0.4624/0.2845	0.7422/0.8632
		OPOM (D)	0.1987/0.3968	0.6859/0.8047
3	530 ± 13/337 ± 6	FPOM	0.5017/0.4765	0.7311/0.9312
		OPOM (L)	0.4826/0.1129	0.8126/0.8388
		OPOM (D)	0.6035/0.3826	0.7257/0.8960
4	417 ± 14/354 ± 9	FPOM	0.5287/0.4057	0.7882/0.8542
		OPOM (L)	0.2216/0.3361	0.7650/0.8128
		OPOM (D)	0.3035/0.1965	0.6984/0.7965

[a] The mean and standard deviation of six samples.
[b] The abundance of total and small size (<1 mm) microplastics in bulk sediment.
[c] The correlation between the abundances of total and small size (<1 mm) microplastics in bulk sediment and the organic carbon content. The organic carbon content of FPOM, OPOM (L) and OPOM (D) were 1.96 ± 0.7 g/kg, 4.65 ± 0.12 g/kg and 3.70 ± 0.16 g/kg, respectively.
[d] The correlation between the abundances of total and small size (<1 mm) microplastics in bulk sediment and the PV values. The PV of FPOM, OPOM (L) and OPOM (D) were 1.22 ± 0.02 g/kg, 0.97 ± 0.04 g/kg and 1.44 ± 0.06 g/kg, respectively.

Table 1
The total abundance of microplastic in mangrove sediment samples collected at sampling sites from or adjacent the semi-enclosed Maowei Sea.

Sites	River Estuary				Entrance		
	Kangxi Ling (KL)	Madi Ao (MA)	Kuizi Jiang (KJ)	Da Maoling (DM)	Qishier Jing (QJ)	Longmen Harbor (LH)	Qinzhou Harbor (QH)
Microplastic (items/kg)	940 ± 17 [a]	520 ± 8	560 ± 9	640 ± 11	2200 ± 27	1780 ± 18	2310 ± 29
Sites	Adjacent Zones						
	Leshan Village (LV)	Danshui Wan (DW)	Hai Wei (HW)				
Microplastic (items/kg)	370 ± 19	170 ± 6	990 ± 3				

[a] The mean and standard deviation of three replicates.

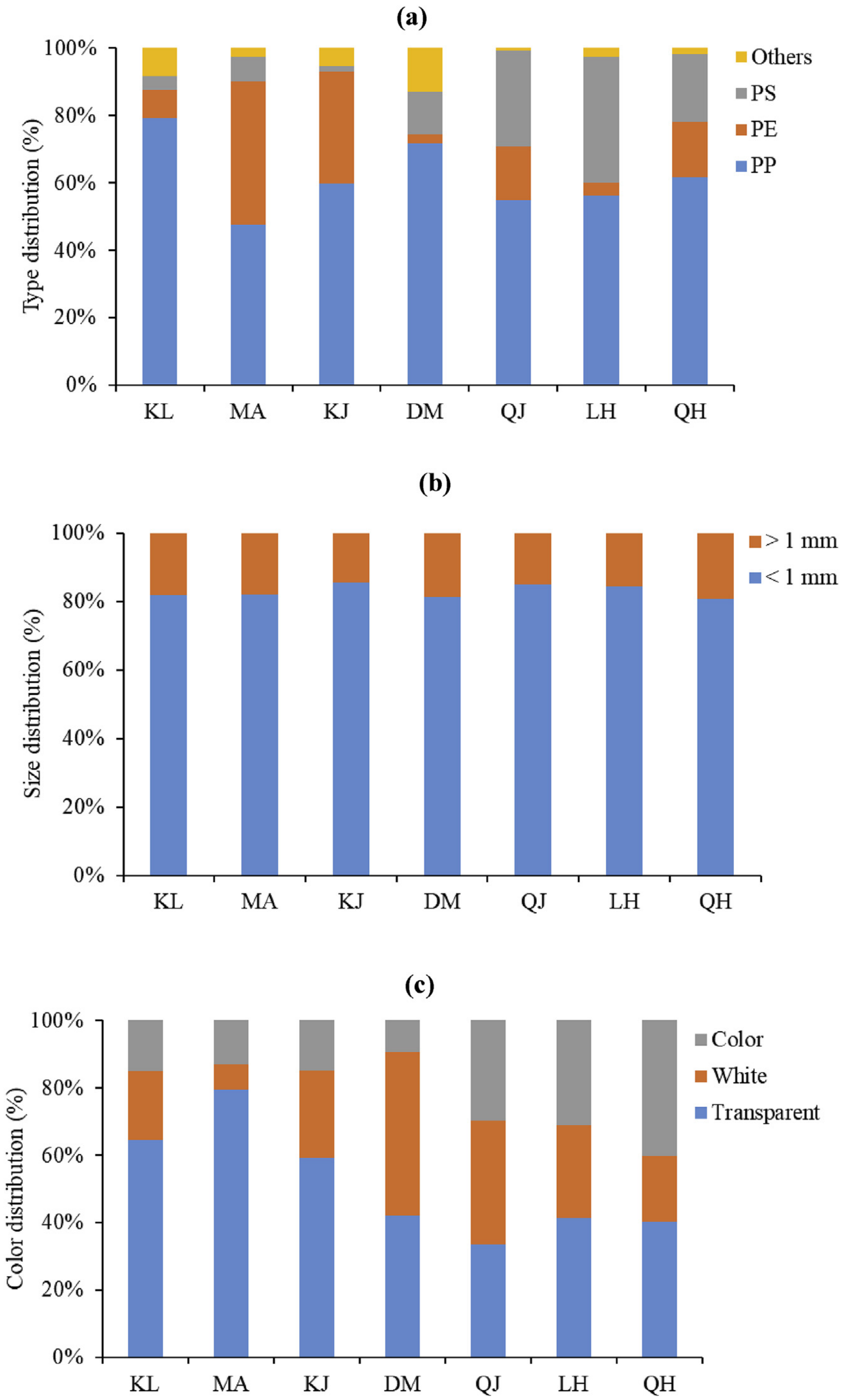

Fig. 3. The type (a), size (b) and colour (c) characteristics of microplastic in mangrove sediment located on the river estuary and entrances of the semi-enclosed Maowei Sea. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

presence in the mangrove sediments (some detailed discussion is presented in section 3.2). Second, the water flow rates at the entrances, as Ibrayev reported, were much low than the river estuary (Ibrayev, 2001), and such phenomenon (ie. low flow rates) may accelerate the vertical deposition of low-density plastics or microplastics from the water to the sediment.

3.1.2. *Type, size and colour characteristics*

Similar compositions of microplastics were observed in the sediment samples collected at the four river estuaries (KL, KM, KJ and DM), with PE, PP, PS, and five other types of plastics (PET, PC, nylon, POM and PVC) accounted for in the total, which ranged from 47.5% to 79.2%, from 2.5% to 42.5%, from 1.8% to 12.8% and from 2.5% to 12.8%, respectively (Fig. 3a). The PS shares significantly increased to 28.2%, 37.5% and 20.1% (*$p < 0.05$) at the LH, QH and QJ site entrances of the semi-enclosed Maowei Sea, respectively. A main reason for this phenomenon was the different sources of these two zones (see section 3.1.1). Moreover, Batel et al. (2018) reported that the small size of microplastics in soil/sediment might pose much stronger potential threats to the biota because of their strong adsorption by the POPs and their easy transportation to the tissues. Therefore, it also is necessary to determine the sizes of the microplastics separated from the mangrove sediment (Fig. 3b).

Fig. 3 also clearly shows that microplastics measuring <1 mm accounted for more than 80% of the microplastics in the river estuaries and the entrances. Obvious differences were obtained between our results and the other kinds of estuary sediment (Yangtze estuary, Bohai Sea and Yellow Sea) (Zhao et al., 2018; Zhou et al., 2018; Hu et al., 2018) with small size (<1 mm) accounted for not more than 70% ($^*p < 0.05$). Eerkes-Medrano et al. (2015) confirmed that, when PP, PE, or PS were the dominant type, most of the detected microplastic was fragmented from larger plastic items. The relatively high percentages of small microplastics indicated that mangrove ecosystems might accelerate plastic decomposition, and, thus, somewhat promote the negative effects of plastic particles on the mangrove benthos. However, to date, the reasons for such phenomena are largely unknown and need further investigation.

Except for the size and type of microplastics, some recent studies confirmed that the coloured microplastics are more easily mistaken ingested by marine organisms, especially the higher mammals, and thus the abundances of white and colorful microplastics should be investigated separately. In our study, the percentages of white and transparent microplastic can reach to 64.6% and 20.3% in the KL sites of river estuary (Fig. 3c). Similar results were obtained for the MA, KJ and DM sites. However, the colorful microplastics particles, including the blue, yellow and transparent, increased to about 29.6%, 31.0% and 40.3% in the QJ, LH and QH mangrove sediment located on the entrances of Maowei Sea due to the widely usage of the marine aquaculture industry.

Overall, the abundances of microplastics are more abundant in the entrances, while the colour, size and type of microplastics showed entirely different trends.

3.2. Abundance and characteristics of microplastics in the rhizospheres and non-rhizospheres of mangrove sediments

The abundance and characteristics of microplastics in the rhizosphere and non-rhizosphere of the mangrove sediments were compared across the sites and the results are presented in Fig. 4. Regarding the river estuary sites (KL, MA, KJ and DM), obvious differences were obtained in the microplastic abundances in the rhizospheres and non-rhizospheres, with values ranging from 1190 ± 7 items/kg to 1860 ± 21 items/kg and from 520 ± 8 items/kg to 940 ± 17 items/kg, respectively. Under flood conditions, plastic and microplastic might translocate from the surface water of the mangrove ecosystems to the seawater or the mixing zones, and the mangrove vegetation somewhat inhibited such translocation processes.

At the oceanic entrance sites (QJ, LH and QH), the contribution of

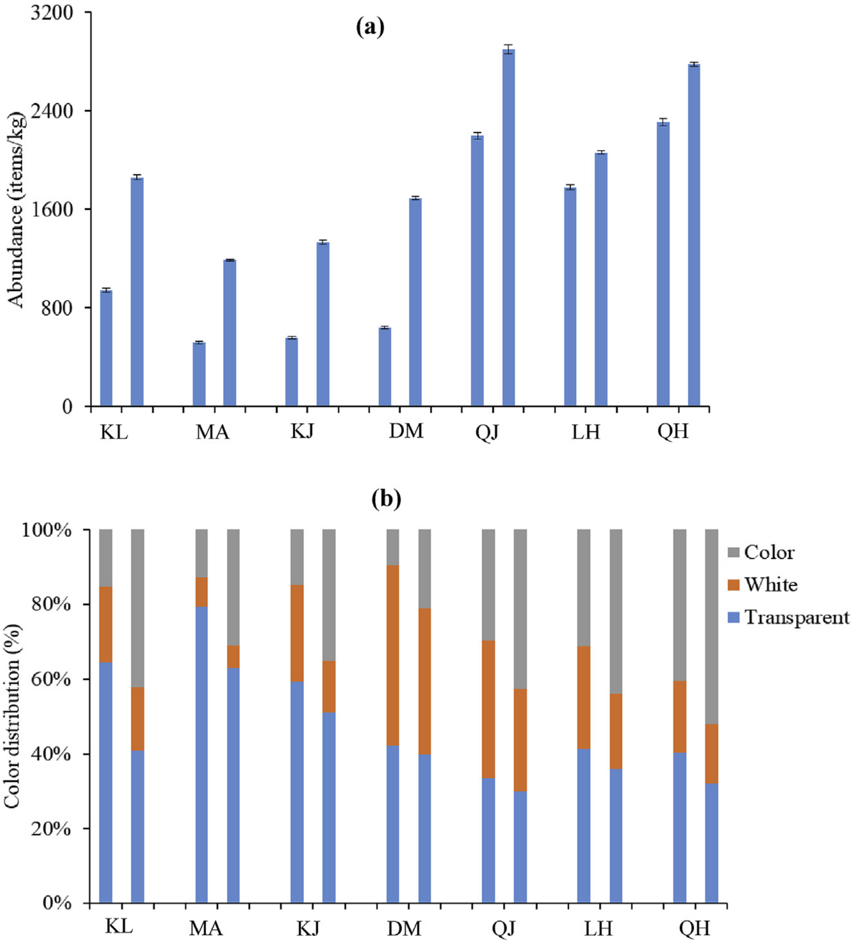

Fig. 4. The abundance (a) and colour (b) of microplastics in the rhizosphere (right bar of one sample site) and non-rhizosphere (left bar of one sample site) of semi-enclosed mangrove sediment. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

this inhibition was relatively small compared to the deposition of microplastic in the sediments, with values ranging from 2060 ± 14 items/kg to 2900 ± 35 items/kg and from 1780 ± 18 items/kg to 2310 ± 29 items/kg in the rhizosphere and non-rhizosphere, respectively. However, as Fig. 4b displays, the percentage of coloured microplastics in the rhizosphere were significantly higher than in the non-rhizosphere of the river estuaries and oceanic entrance zones. The weathering of plastics, including both the biotic (bacterium, fungi and so on) and abiotic (ultraviolet radiation, flooding and so on) processes, was somewhat related to the higher extents of coloured microplastics in the rhizosphere zones of mangrove plant (Andrady, 2017).

Additionally, the particle sizes and types of microplastic in the river estuary were identified. The results are shown in Fig. S3, from which it clearly can be concluded that almost no difference existed in microplastic sizes or types in the rhizospheres and non-rhizospheres of the mangrove sediment sampled from the river estuaries ($p > 0.05$). Similar results were obtained on the samples taken at the entrances of the semi-enclosed Maowei Sea.

3.3. *Abundance of microplastics in mangrove sediments with different proportions of organic matter*

Almost all of the previous reports attributed the abundance and distribution of microplastics in soils/sediments to their sources, extents of self-aggregation and/or deposition rates (Waller et al., 2017; Cheung et al., 2018). However, the spatial variation of microplastic abundance in sediment samples from river estuaries (Datang Ling sites, 21°60′ N, 108°80′ E) of the semi-enclosed Maowei Sea with similar environmental conditions (see discussion in sections 3.1 and 3.2) were high, as indicated by the standard deviation with the values of 375 ± 8 items/kg, 449 ± 6 items/kg, 530 ± 10 items/kg and 417 ± 14 items/kg at sites 1, 2, 3 and 4, respectively. On the other hand, no observable differences were found regarding the type, size or colour of the microplastics at the four sites ($p > 0.05$, Table 2).

Rillig recently demonstrated that microplastic particles were likely to incorporate and integrate into the aggregated matter along with pieces of other organic matter before accumulating in soil/sediment (Rillig, 2018). Therefore, we inferred that the composition, structure, and stability of the organic matter's proportions in the sediments (FPOM, OPOM (1.6–2.0 g/cm^3, and >2.0 g/cm^3)), as well as other factors, might contribute to the distribution of microplastics in mangrove sediments (Table 2). In our study, no definitive correlation was found between the microplastic abundance (items/kg) in sediments at the Longmen estuary and the organic carbon content of FPOM, OPOM (1.6–2.0 g/cm^3) or OPOM (>2.0 g/cm^3) ($n = 30$, $p > 0.05$) (Table 2). These divergent findings reveal a need for further probing of the structure of sediment organic matter fractions and the distributions of microplastics.

Still no linear relationships were observed between the abundances of microplastics (items/kg) and PV values of these fractions ($^*p > 0.05$). However, to the smaller sizes microplastics (<1 mm), it is interesting to note that these phenomenon almost disappeared, and the correlations become positive linear relationships ($^*p < 0.05$). These data suggest that the PV values of FPOM and OPOM (1.6–2.0 g/cm^3, or > 2.0 g/cm^3) played a relatively more important role in blocking the release of small microplastics from the sediment aggregates, which is considered another dominant factor determining the distribution of small microplastics. Different organic matter-mineral interaction was responsible for the pore composition and structures of micro-/nano-sizes, and our study demonstrated that the pore-space or different spatial pore-domains were more likely to match the detectable small size microplastics (<1 mm).

4. Conclusions

In this study, the features of microplastics in mangrove sediment collected at the semi-enclosed Maowei Sea were relatively large quantities (ranging from 520 ± 8 to 2310 ± 29 items/kg), variety types (PP, PE, PS and so on) and large percentages of particles with size less than 1 mm (>75%). Except for the sources, further studies demonstrated that the abundances and characteristics of microplastic also determined by the hydrodynamic factors in the river estuary/entrance of the semi-enclosed sea and the interception/weathering processes of microplastics in the rhizosphere of mangrove plant. Additionally, the PV/SSF of OPOM fractions (>2.0 g/cm^3) rather than their compositions showed linear relationships with the smaller size microplastics (<1 mm) content. The findings of this work provided new insight into the distribution, transportation and transformation of microplastics in mangrove ecosystems located on the semi-enclosed sea.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2018.10.089.

References

Andrady, A.L., 2017. The plastic in microplastic: a review. Mar. Pollut. Bull. 119 (1), 12–22.

Barboza, L.G.A., Vieira, L.R., Guilhermino, L., 2018. Single and combined effects of microplastics and mercury on juveniles of the European seabass (*Dicentrarchus labrax*): changes in behavioural responses and reduction of swimming velocity and resistance time. Environ. Pollut. 236, 1014–1019.

Batel, A., Borchert, F., Reinwald, H., Erdinger, L., Braunbeck, T., 2018. Microplastic accumulation patterns and transfer of benzo[a]pyrene to adult zebrafish (*Danio rerio*) gills and zebrafish embryos. Environ. Pollut. 235, 918–930.

Berg, G., Smalla, K., 2009. Plant species and soil type cooperatively shape the structure and function of microbial communities in the rhizosphere. FEMS Microbiol. Ecol. 68, 1–13.

Boelens, T., Schuttelaars, H., Schramkowski, G., Mulder, T.D., 2018. The effect of geometry and tidal forcing on hydrodynamics and net sediment transport in semi-enclosed tidal basins. Ocean Dynam. https://doi.org/10.1007/s10236-018-1198-9.

Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial patterns plastic debris along estuarine shorelines. Environ. Sci. Technol. 44 (9), 3404–3409.

Cerli, C., Celi, L., Kalbitz, K., Guggenberger, G., Kaiser, K., 2012. Separation of light and heavy organic matter fractions in soil-Testing for proper density cut-off and dispersion level. Geoderma 170, 403–416.

Chae, Y., An, Y.J., 2018. Current research trends on plastic pollution and ecological impacts on the soil ecosystem: a review. Environ. Pollut. 240, 387–395.

Cheung, P.K., Fok, L., Hung, P.L., Cheung, L.T.O., 2018. Spatio-temporal comparison of neustonic microplastic density in Hong Kong waters under the influence of the Pearl River Estuary. Sci. Total Environ. 628–629, 731–739.

Chubaenko, I., Stepanova, N., 2017. Microplastics in sea coastal zone: lessons learned from the Baltic amber. Environ. Pollut 224, 243–254.

Chubarenko, I.P., Esiukova, E.E., Bagaev, A.V., Bagaeva, M.A., Grave, A.N., 2018. Three-dimensional distribution of anthropogenic microparticles in the body of sandy beaches. Sci. Total Environ. 628–629, 1340–1351.

Cincinelli, A., Scopetani, C., Chelazzi, D., Lombardini, E., Martellini, T., Katsoyiannis, A., Fossi, M.C., Corsolini, S., 2017. Microplastic in the surface waters of the ross sea (Antarctica): occurrence, distribution and characterization by FTIR. Chemosphere 175, 391–400.

Countway, R.E., Dickhut, R.M., Canuel, E.A., 2003. Polycyclic aromatic hydrocarbon (PAH) distributions and associations with organic matter in surface waters of the York River, VA Estuary. Org. Geochem. 34 (2), 209–224.

Eerkes-Medrano, D., Thompson, R.C., Aldridge, D.C., 2015. Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritization of research needs. Water Res. 75, 63–82.

Fork, L., Cheung, P.K., Tang, G., Li, W.C., 2017. Size distribution of stranded small plastic debris on the coastal of Guangdong, South China. Environ. Pollut. 220, 407–412.

Galloway, T.S., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecology Evolution 1, 0116.

Graca, B., Szewc, K., Zakrzewska, D., Dolega, A., Szczerbowska-Boruchowska, M., 2017. Source and fate of microplastics in marine and beach sediments of the Southern Baltic Sea-a preliminary study. Envion. Sci. Pollut. Res. 24 (8), 7650–7661.

Hipfner, J.M., Galbraith, M., Tucker, S., Studholme, K.R., Domailk, A.D., Pearson, S.F., Good, T.P., Ross, P.S., Hodum, P., 2018. Two forage fishes as potential conduits for the vertical transfer of microfibers in Northeastern Pacific Ocean food webs. Environ. Pollut. 239, 215–222.

Hu, L., Chernick, M., Hinton, D.E., Shi, H., 2018. Microplastics in small waterbodies and tadpoles from Yangtze river delta, China. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.8b02279.

Huffer, T., Praetorius, A., Wagner, S., Kammer, F.V.D., Hofmann, T., 2017. Microplastic exposure assessment in aquatic environments: learning from similarities and differences to engineered nanoparticles. Environ. Sci. Technol. 51 (5), 2499–2507.

Ibrayev, R.A., 2001. Model of enclosed and semi-enclosed sea hydrodynamic. Russ. J. Numer. Anal. Math. Model. 16 (4), 291–304.

Jacotot, A., Marchand, C., Rosenheim, B.E., Domack, E.W., Allenbach, M., 2018. Mangrove sediment carbon stocks along an elevation gradient: influence of the late Holocene marine regression (New Caledonia). Mar. Geol. 404, 60–70.

John, B., Yamashita, T., Ludwig, B., Flessa, H., 2005. Storage of organic carbon in aggregate and density fractions of silty soils under different types of land use. Geoderma 128 (1–2), 63–79.

Karami, A., Golieskardi, A., Choo, C.K., Larat, V., Karbalaei, S., Salamatinia, B., 2018. Microplastic and mesoplastic contamination in canned sardines and sprats. Sci. Total Environ. 612, 1380–1386.

Komiyama, A., Ong, J.E., Poungparn, S., 2008. Allometry, biomass, and productivity of mangrove forests: a review. Aquat. Bot. 89 (2), 128–137.

Lambert, S., Wagner, M., 2016. Characterisation of nanoplastics during the degradation of polystyrene. Chemosphere 145, 265–268.

Law, K.L., Thompson, R.C., 2014. Microplastics in the seas. Science 345 (6193), 144–145.

Lots, F.A.E., Behrens, P., Vijver, M.G., Horton, A.A., Bosker, T., 2017. A large-scale investigation of microplastic contamination: abundance and characteristics of microplastics in European beach sediment. Mar. Pollut. Bull. 123 (1–2), 219–226.

Lozoya, J.P., Teixeira de Mello, F., Carrizo, D., Weinstein, F., Olivera, Y., Cedres, F., Pereira, M., Fossati, M., 2016. Plastics and microplastics on recreational beaches in Punta del Este (Uruguay): unseen critical residents. Environ. Pollut. 218, 931–941.

Lu, H.L., Zhang, Y., Liu, B.B., Liu, J.C., Ye, J., Yan, C.L., 2011. Rhizodegradation gradients of phenanthrene and pyrene in sediment of mangrove (*Kandelia candel* (L.) Druce). J. Hazard Mater. 196, 263–269.

Ma, Y., Huang, A., Cao, S., Sun, F., Wang, L., Guo, H., Ji, R., 2016. Effects of nanoplastics and microplastics on toxicity, bioaccumulation, and environmental fate of phenanthrene in fresh water. Environ. Pollut. 219, 166–173.

Mustajarvi, L., Eek, E., Cornelissen, G., Eriksson-Wiklund, A.K., Undeman, E., Sobek, A., 2017. *In situ* benthic flow-through chambers to determine sediment-to-water fluxes of legacy hydrophobic organic contaminants. Environ. Pollut. 231, 854–862.

Nor, N.H.M., Obbard, J.P., 2014. Microplastics in Singapore's coastal mangrove ecosystems. Mar. Pollut. Bull. 79 (1–2), 278–283.

Ramdine, G., Fichet, D., Louis, M., Lemoine, S., 2012. Polycyclic aromatic hydrocarbons (PAHs) in surface sediment and oysters (*Crassostrea rhizophorae*) from mangrove of Guadeloupe: levels, bioavailability, and effects. Ecotoxicol. Environ. Saf. 79, 80–89.

Rillig, M.C., 2018. Microplastic disguising as soil carbon storage. Environ. Sci. Technol. 52 (11), 6079–6080.

Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Jung, S.W., Shim, W.J., 2017. Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type. Environ. Sci. Technol. 51 (8), 4368–4376.

Steensgaard, I.M., Syberg, K., Rist, S., Hartmann, N.B., Boldrin, A., Hansen, S.F., 2017. From macro- to microplastics- Analysis of EU regulation along the life cycle of plastic bags. Environ. Pollut. 224, 289–299.

Su, L., Xue, Y., Li, L., Yang, D., Kolandhasamy, P., Li, D., Shi, H., 2016. Microplastics in Taihu lake, China. Environ. Pollut. 216, 711–719.

Waller, C.L., Griffiths, H.J., Waluda, C.M., Thorpe, S.E., Loaiza, I., Moreno, B., Pacherres, C.O., Hughes, K.A., 2017. Microplastics in the Antarctic marine system: an emerging area of research. Sci. Total Environ. 598, 220–227.

Zhang, K., Xiong, X., Hu, H., Wu, C., Bi, Y., Wu, Y., Zhou, B., Lam, P.K.S., Liu, J., 2017. Occurrence and characteristics of microplastic pollution in Xiangxi Bay of three Gorges reservoir, China. Environ. Sci. Technol. 51 (7), 3794–3801.

Zhao, J., Ran, W., Teng, J., Liu, Y., Liu, H., Yin, X., Cao, R., Wang, Q., 2018. Microplastic pollution in sediments from the Bohai Sea and the Yellow Sea. China. *Sci. Total Environ.* 640–641, 637–645.

Zhou, Q., Zhang, H., Fu, C., Zhou, Y., Dai, Z., Li, Y., Tu, C., Luo, Y., 2018. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and Yellow Sea. Geoderma 322, 201–208.

Zhu, L., Bai, H., Chen, B., Sun, X., Qu, K., Xia, B., 2018. Microplastic pollution in North Yellow sea, China: observations on occurrence, distribution and identification. Sci. Total Environ. 636, 20–29.