



Occurrence of Microplastic Pollution in the Beibu Gulf, the Northern South China Sea

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In this study, microplastics were sampled and analyzed from surface water and sediment samples from July to August in 2020, in the Beibu Gulf (the northern South China Sea [SCS]), a gulf with intensive fishery activities while the economy is less developed, compared with other coastal areas of China. The abundances of microplastics in seawater and sediment in the Beibu Gulf were 0.67 items/m³ and 4.33 items/kg of dry weight, respectively. In seawater, the fragments (92.38%) contributed the most, and polystyrene (PS) was the dominant polymer (53.23%). In sediment, the most abundant microplastics were fiber (82.93%) and rayon (RY; 39.54%). The abundances of remarkably higher microplastics were found in the seawater and sediment adjacent to the urban area. The abundances of microplastics in far coastal sediment were only slightly lower than that in the coastal sediment, indicating that microplastics are ready to transport and bury in open area sediment. Significant positive correlations between the microplastic abundance and population density and per capita gross domestic product (GDP) were found in Chinese coastal seawater, with low population density and less developed economy, and the microplastic pollution in the Beibu Gulf was at a low level. This study provides preliminary data of microplastics in the Beibu Gulf, supporting further investigation of transportation fate and management of this emerging pollutant from the coastal zone to the SCS.

Keywords: microplastics, distribution, Beibu Gulf, long distance transportation, socioeconomic correlations

INTRODUCTION

As an emerging marine pollutant, microplastics (defined as those plastics with size < 5 mm) can be derived from the degradation of larger plastics in the ocean by sunlight, microbes and mechanical abrasion (Cózar et al., 2014; Khan, 2020; Cordova et al., 2021), or from discharge of wastewater that contains microplastics (Jambeck et al., 2015; Liu et al., 2017; Rochman, 2018; Naji et al., 2020; Nurhasanah et al., 2021). Due to the low density and stable properties, microplastics can be transported to a long distance in the ocean. For example, microplastics have been found in polar waters, deep seawaters, and ocean central island waters and can stably exist in seawater, sediments, and organisms (Cauwenbergh et al., 2013; Isobe et al., 2017; Waller et al., 2017;

Li et al., 2019; Wu et al., 2020). Microplastics will produce harmful additives and monomers and also carry heavy metals and persistent organic pollutants in the marine environment (Boyle et al., 2020; Catarino et al., 2021; Chen et al., 2021). Microplastics may be ingested by marine organisms, which could cause various adverse effects. Thus, they are potentially incorporated into the marine food web through trophic transfer and ultimately endanger human health through the consumption of contaminated seafood (Lusher et al., 2017; Pannetier et al., 2020; Philipp et al., 2021). Thus, monitoring microplastics in the ocean (especially the coastal zone) and exploring its biogeochemical cycle are the hot science topics in recent years (Everaert et al., 2018; Li Y. et al., 2020).

The Beibu Gulf, a semi-enclosed bay where microplastics are more likely to accumulate (Sharma et al., 2021; Zhou et al., 2021), is located in the northern South China Sea (SCS), surrounded by three major cities, such as Beihai, Qinzhou, and Fangchenggang, with a total population of 6.2 million (2020). As one of the world's largest fishing grounds in the SCS, mariculture is highly crowded in the coastal zone of the Beibu Gulf compared with other coastal areas of China. Intensive anthropogenic activities, including fishery and mariculture, have contributed a large amount of microplastics in the adjacent sea (Zhang et al., 2017; Cheung L. T. O. et al., 2018; Wang et al., 2018; Li Y. et al., 2020; Li Z. et al., 2020; Xue et al., 2020). Few studies reported microplastics in the coastal zones of the Beibu Gulf. Zhu et al. (2019) reported high levels of microplastics in the Maowei Sea (a bay of the Beibu Gulf), a traditional oyster farm bay. Xue et al. (2020) discovered that a large amount of microplastics derived from fishery activities were buried in deep sediment, suggesting that the microplastic storage worldwide might be underestimated because most of the previous studies examined only surface sediment. To date, still less is known of the abundance and distribution of microplastics in the coastal and far coastal zones of the Beibu Gulf.

At the same time, though Beibu Gulf is experiencing the economic development and rapid urbanization of the surrounded human land, still it is one of the least developed regions among the coastal areas of China, with per capita gross domestic product (GDP) of USD 8.56k, while for whole China is USD 11.3k (2020). The microplastic pollution should be at a low level according to the positive relationships found between microplastic abundance and factors, such as land use percentages (Kataoka et al., 2019), population density (Yonkos et al., 2014), and GDP (Fan et al., 2019) in some water bodies. However, the Beibu Gulf is also a microcosm of the fishery industry of China and Southeast Asian countries and fishery is one of the pillar industries. Therefore, the Beibu Gulf is a typical area to study the co-influence of socioeconomic and fishery industry to the microplastic pollution, understanding the status of microplastics in Beibu Gulf is helpful in taking measures and policymaking to reduce microplastics in China and Southeast Asian countries (Xue et al., 2020).

In this study, the characteristics and distributions of microplastics in the coastal zones of the Beibu Gulf were investigated, and socioeconomic indices, such as population density and per capita GDP, were chosen to assess the microplastic pollution status in the Beibu Gulf. To obtain more

comparable data, a Manta net with a netmesh of 0.33 mm was used for surface seawater microplastic sampling (Yonkos et al., 2014; Chen et al., 2018; Xu et al., 2021). Sample preparation of microplastics in seawater and sediment was conducted according to the literature methods, i.e., wet oxidation (10% potassium hydroxide [KOH] for water; 30% hydrogen peroxide [H_2O_2] for sediment) and density separation (1.2 g/cm³ sodium chloride [NaCl]) were employed (NOAA Marine Debris Program, 2015; Rocha-Santos and Duarte, 2015; Wang et al., 2020; Wu et al., 2020). Stereo microscope and micro-Fourier transform infrared spectrometer (μ -FTIR) were used to identify microplastics.

The aims of this study were to: (1) determine the microplastic abundance, size, color, and polymer composition in the Beibu Gulf, (2) analyze the differences of the microplastic status between Beibu Gulf and other comparable Chinese sea areas, (3) confirm the relationships between microplastic abundances and socioeconomic indices, and (4) provide preliminary data for further study of the transportation fate and management of microplastics in the Beibu Gulf and the SCS. The result of this study may be useful for the cooperation actions taken by the departments of marine environment protection, marine fishery, waste treatment, and public organizations to handle the microplastic pollution in the Beibu Gulf and other ocean waters.

MATERIALS AND METHODS

Field Sampling

Study Area

Sampling was conducted in the Beibu Gulf by two cruises, one was L cruise (coastal area) in July 2020 by the R/V Yueke 1, during which 59 stations were sampled for seawater and 43 stations for sediment. The other was B cruise (far coastal area) in August 2020 by the R/V Yuexiyuzhi 20028, during which 16 stations were sampled for seawater and 23 stations for sediment. The study area and sampling station distribution are shown in **Figure 1**.

Sampling Methods

Seawater samples were collected using a Manta trawl (330 μm mesh nylon net), while surface sediment (>5 cm) was collected using a Van Veen sediment collector. Detailed sampling methods were described in the **Supplementary Materials**.

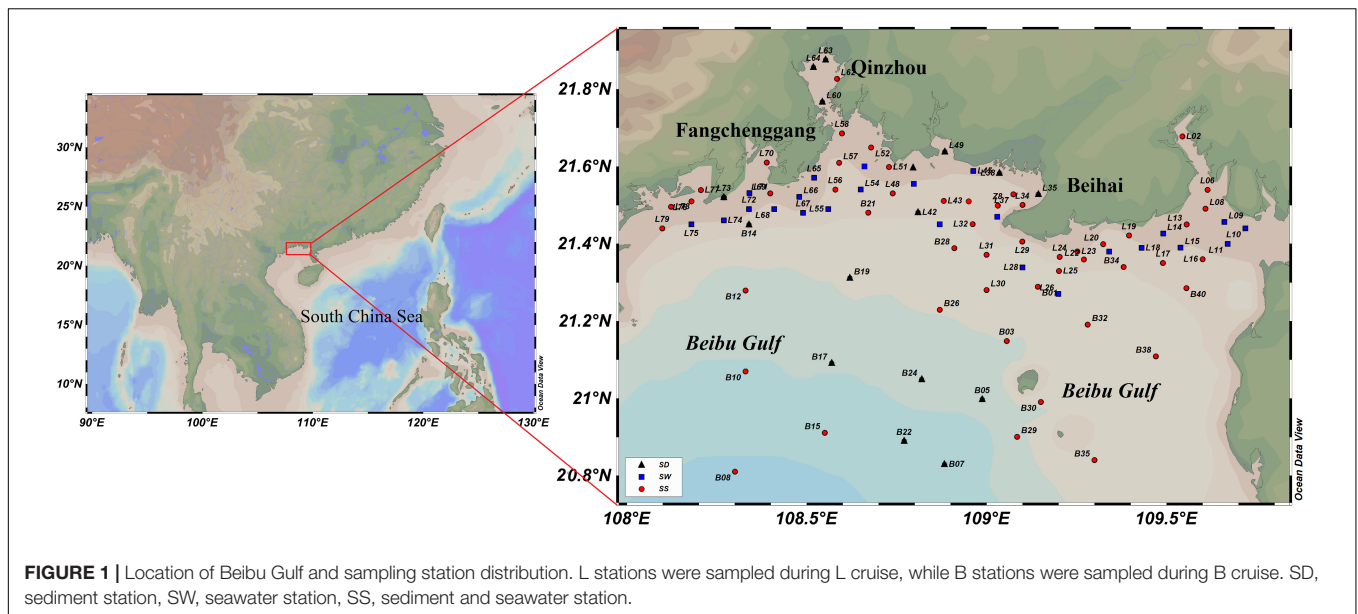
Sample Preparation

The sample treatment for seawater was slightly modified according to Wang et al. (2020), and the sediments were analyzed according to Wu et al. (2020). Notably, 10% KOH and 30% H_2O_2 were used for the wet oxidation of seawater and sediment, respectively. Saturated NaCl (1.2 g/cm³) was used for the density separation of microplastics in seawater and sediment. Sample pretreatment methods were detailed in the **Supplementary Materials**.

Characterization

The Shape, Color, and Size of Microplastics

A SteREO Discovery V8 microscope (Zeiss, Germany) equipped with a digital camera (C 33; OPLINIC, United States) and "ZEN lite" software was used to characterize the physical properties of



the microplastics. Guidelines from Zhao et al. (2018) were used to identify the microplastics: (1) the particle cannot be easily broken with tweezers, (2) the color of the particle is uniform, and (3) the particle is free of biological tissues and cell structures. The size of each particle was measured along its longest axis (Wang et al., 2020).

The Composition of Microplastics

A μ -FTIR (Nicolet iN10; Thermo Fisher, United States) was used to determine the chemical composition of inspected materials, all suspected microplastics were examined, and only materials with polymers were successfully determined as microplastics (Cai et al., 2018; Wang et al., 2020). The sample was measured in the transmittance mode. The spectral range ($650\text{--}4,000\text{ cm}^{-1}$) and aperture range (from $50 \times 50\text{ mm}$ to $150 \times 150\text{ mm}$) were selected according to particle size. The spectra obtained were matched with the OMNIC polymer spectral library (standard database) to identify the polymer types, and at least 70% similarity was assigned to the polymer conformation (Mecozzi et al., 2016).

Quality Control

All labware equipment used in the study were rinsed three times with Milli-Q water before use. All solutions and liquids used in the study were filtered by a glass fiber filter (GF/F Whatman, 47 mm diameter, and $0.7\text{ }\mu\text{m}$ pore size) before use. Procedural blank samples ($n = 3$) were analysed to correct the potential laboratory contamination in each batch sample treatment, and the recovery of the methods used was performed using standard reference materials (National Marine Environmental Monitoring Centre, China), with 95%. Other measures were taken in the lab to keep the contamination at the lowest level, such as using aluminum foil to cap the containers and wearing cotton clothes.

Data Analysis

Statistical analysis was carried out using the EXCEL 2010 (Microsoft Inc., United States) and SigmaPlot 12.5 (Systat

Software Inc., United States) software. Figures were drawn using the SigmaPlot 12.5 software, while distribution maps were drafted using the Ocean Data View 4 (Alfred Wegener, Germany) software.

RESULTS

Abundance of Microplastics Seawater Samples

A total of 75 stations of seawater samples were collected from the two (L + B) cruises. The mean abundance of microplastics in all seawater samples was $0.67 \pm 1.09\text{ items/m}^3$, while the mean abundances of 0.78 ± 1.20 and $0.26 \pm 0.32\text{ items/m}^3$ were obtained in seawater from L and B stations, respectively. These results were comparable with other studies, in which 0.3 mm trawl nets were used. The microplastic abundances reported in different Chinese sea areas are summarized in **Table 1**. The abundance observed in the Beibu Gulf was in the same order of magnitude as those in the Bohai Sea (0.79 items/m^3), Yellow Sea ($0.33 \pm 0.28\text{ items/m}^3$), East China Sea (0.31 items/m^3), and Hangzhou Bay ($0.14 \pm 0.12\text{ items/m}^3$) but much lower than those in Yangtze Estuary ($67.5 \pm 94.4\text{ items/m}^3$), Jiaozhou Bay ($46 \pm 28\text{ items/m}^3$), Xiangshan Bay ($8.91 \pm 4.7\text{ items/m}^3$), Haizhou Bay ($2.6 \pm 1.4\text{ items/m}^3$), Xiamen Bay ($514.3 \pm 520\text{ items/m}^3$), and Hong Kong waters ($3.973 \pm 1.777\text{ items/m}^3$). As expected, the mean abundance of microplastics in the Beibu Gulf was one order of magnitude higher than in the SCS ($0.045 \pm 0.093\text{ items/m}^3$).

Sediment Samples

A total of 66 stations of sediment samples were collected from the two (L + B) cruises. The mean abundance of microplastics in sediment samples was $13.87 \pm 9.9\text{ items/kg}$ of dry weight (d.w.), while mean abundances of $15.00 \pm 10.74\text{ items/kg d.w.}$ and $12.21 \pm 8.07\text{ items/kg d.w.}$ were obtained in sediment from L and B stations, respectively. The microplastic abundances in

TABLE 1 | Summary of microplastic abundances reported in surface water and sediment from various sea areas in China (data published within the last 3 years, revised from Wang et al., 2020).

Location	Abundance		References
	In seawater (items/m ³)	In sediment (items/kg d.w.)	
Bohai Sea	0.79	48.88	Xu et al., 2021
Jiaozhou Bay	46 ± 28	15 ± 6	Zheng et al., 2019
Yellow Sea	0.33 ± 0.28	2580 ± 1140	Wang et al., 2018
North Yellow Sea	ND	37.1 ± 42.7	Zhu et al., 2018
Haizhou Bay	2.6 ± 1.4	330 ± 260	Li Z. et al., 2020
East China Sea	0.31	ND	Liu et al., 2018
East China Sea	ND	142 ± 38	Zhang et al., 2019
Yangtze Estuary	67.5 ± 94.4	28.3 ± 14.4	Li Y. et al., 2020; Li Z. et al., 2020
Hangzhou Bay	0.14 ± 0.12	84.3 ± 56.6	Wang et al., 2020
Xiangshan Bay	8.91 ± 4.7	1740 ± 2150	Chen et al., 2018
Xiamen Bay	514.3 ± 520	181	Tang et al., 2018
Hong Kong waters	3.973 ± 1.777	–	Cheung P. K. et al., 2018
Beibu Gulf	ND	405 ± 336 ^a	Xue et al., 2020
Qin River Estuary, Maowei Sea, Beibu Gulf	0.1–4.6	0–97	Zhang et al., 2020
Maowei Sea, Beibu Gulf	1200–10100	ND	Zhu et al., 2019
Beibu Gulf	0.67 ± 1.09	13.87 ± 9.9	This study
Coast area of Beibu Gulf (L)	0.78 ± 1.2	15 ± 10.74	
Far coast area of Beibu Gulf (B)	0.26 ± 0.32	12.21 ± 8.07	
South China Sea	0.045 ± 0.093	ND	Cai et al., 2018

ND, no data available.

^aFloating phase was potassium formate solution, with a density of 1.5 g/cm³.

sediments from other areas are also summarized in **Table 1**. The table shows that from the aspect of microplastics, the sediment quality in the Beibu Gulf was the best in China since the microplastic abundance was the lowest (13.87 ± 9.9 items/kg d.w.), while higher abundances (0–97 items/kg d.w.) were observed in the Qin River Estuary and Maowei Sea, which is a traditional oyster farm sea, indicating the contribution of

mariculture. A much higher abundance (405 ± 336 items/kg d.w.) was discovered in the Beibu Gulf by Xue et al. (2020), in which a potassium formate solution with a density of 1.5 g/cm³ was used as floating phase, yielding more microplastics from the sediments.

Microplastic Characteristics

Seawater Samples

Among all the seawater samples, the fragment was prevalent shape (91.0–92.6%), and no microplastic sphere was detected (**Figure 2A**). Only a small amount of fiber (4.9%), film (2.0%), and particle (0.8%) were found in L stations, whereas fiber (8.4%) and particle (0.6%) were found in the B station (**Figure 3**). Most of the microplastics were white (>50%), followed by transparent (33.0%) and green (6.4%) in L stations, whereas transparent (14.0%) and black (4.5%) in B stations (**Figure 2B**) were observed.

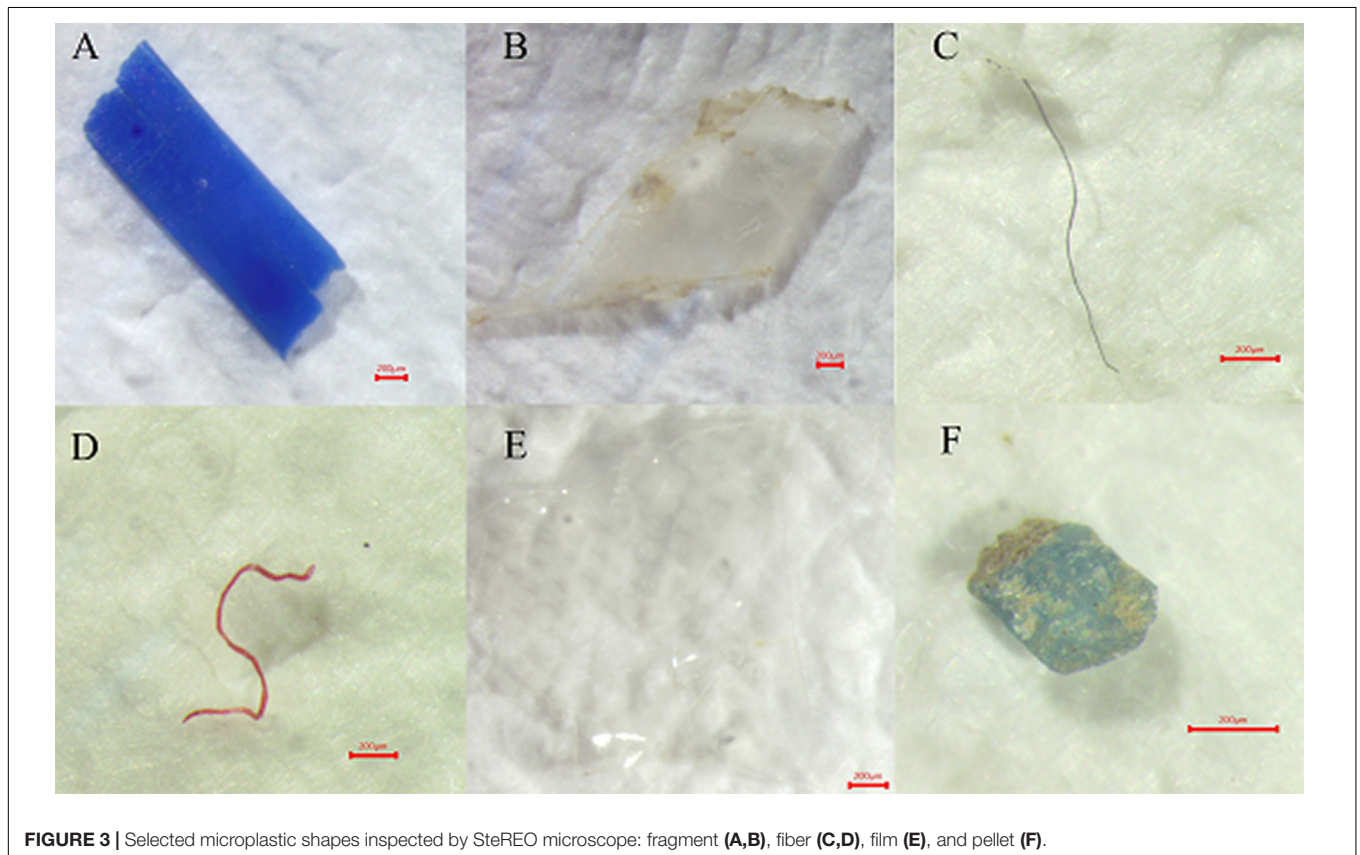
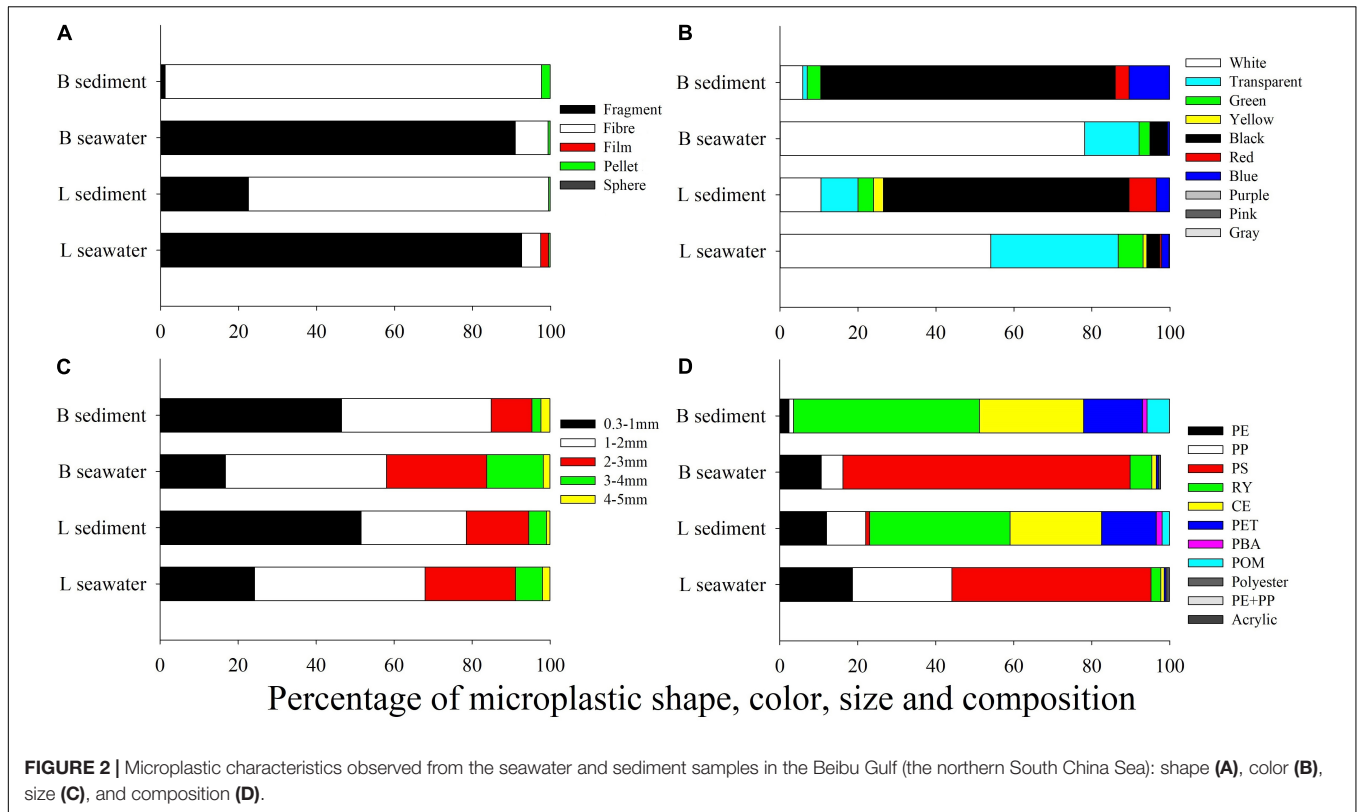
The size compositions of microplastics in seawater are shown in **Figure 2C**. In both L and B stations, microplastics with a diameter of 0.33–1 mm were the dominant polymers, accounting for 51.5 and 46.5%, respectively, followed by 1–2 mm (27.0 and 38.4%) and 2–3 mm (16 and 10.46%). Microplastics with a diameter of 3–5 mm were proportioned to less than 10% in the two sampling areas.

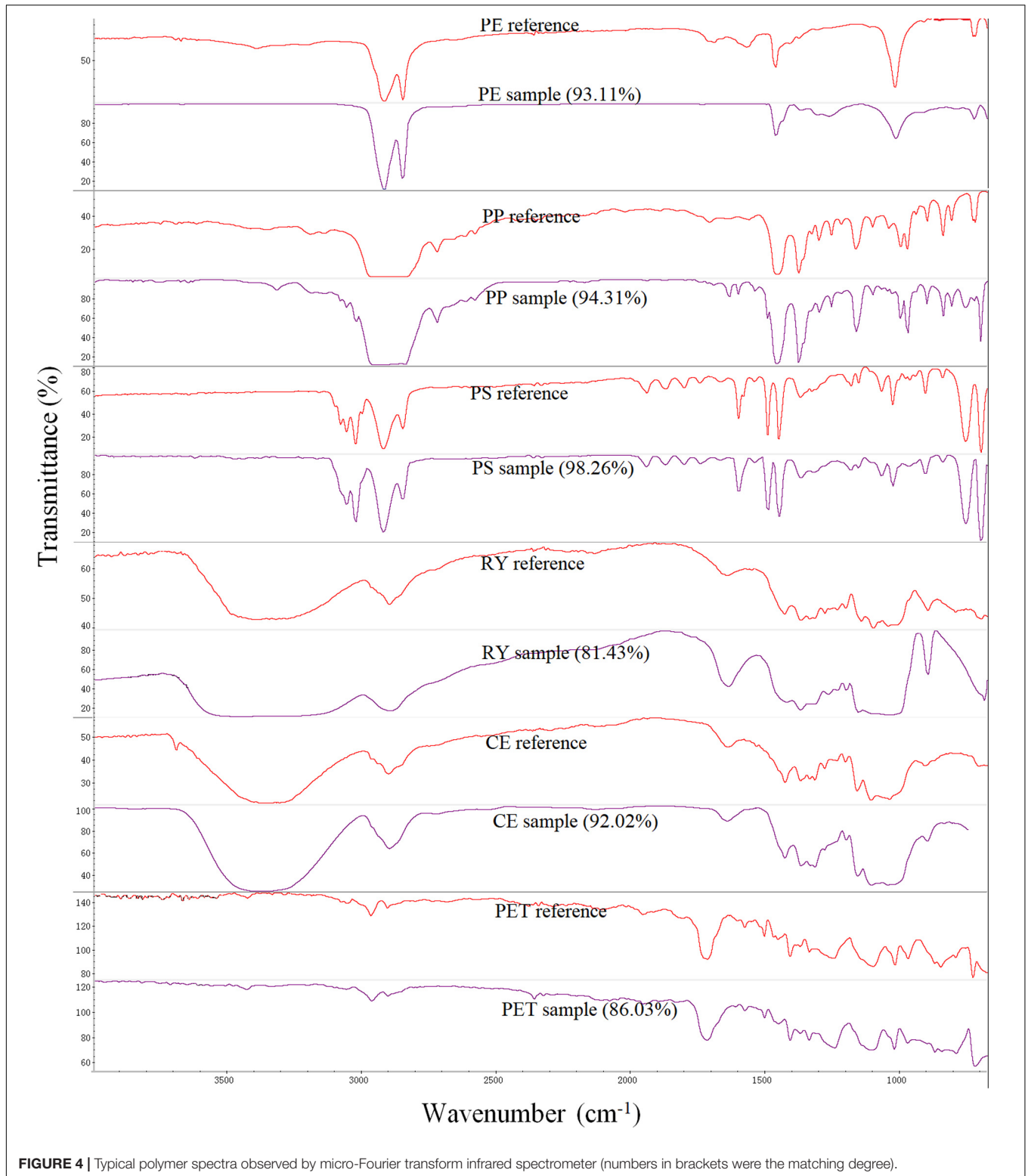
Typical polymer μ -FTIR spectra are shown in **Figure 4**. To identify the synthetic polymer, a relatively higher matching degree (>75%) was set to provide more accurate results. There was little shift of the main polymer absorption band according to the comparisons (Chen et al., 2018; Li Y. et al., 2020). Eleven polymers were detected in seawater samples, including polyethylene (PE), polypropylene (PP), PS, rayon (RY), cellulose (CE), polyethylene terephthalate (PET), polyester, polybutylene adipate glycol (PBA), polyoxymethylene (POM), and acrylic. The proportion of each polymer type in seawater is shown in **Figure 2D**. The main polymers in coastal seawater (L stations) were PS (51.1%), PP (25%), PE (18.6%), and RY (2.5%), while in far coastal areas (B stations), they were PS (73.7%), PE (10.6%), PP and RY (5.6%), and CE (1.1%).

Sediment Samples

As for microplastics in sediment (**Figure 2A**), the fiber was the prevalent shape (96.5 and 77.0% for L and B stations, respectively), and no microplastic film and sphere were detected. Only a small amount of fragment (22.5%) and particle (0.5%) were found in L stations, while fragment (1.2%) and particle (2.3%) were found in the B station. The microplastic color in sediment was dominated by black (both > 60.0%) (**Figure 2B**).

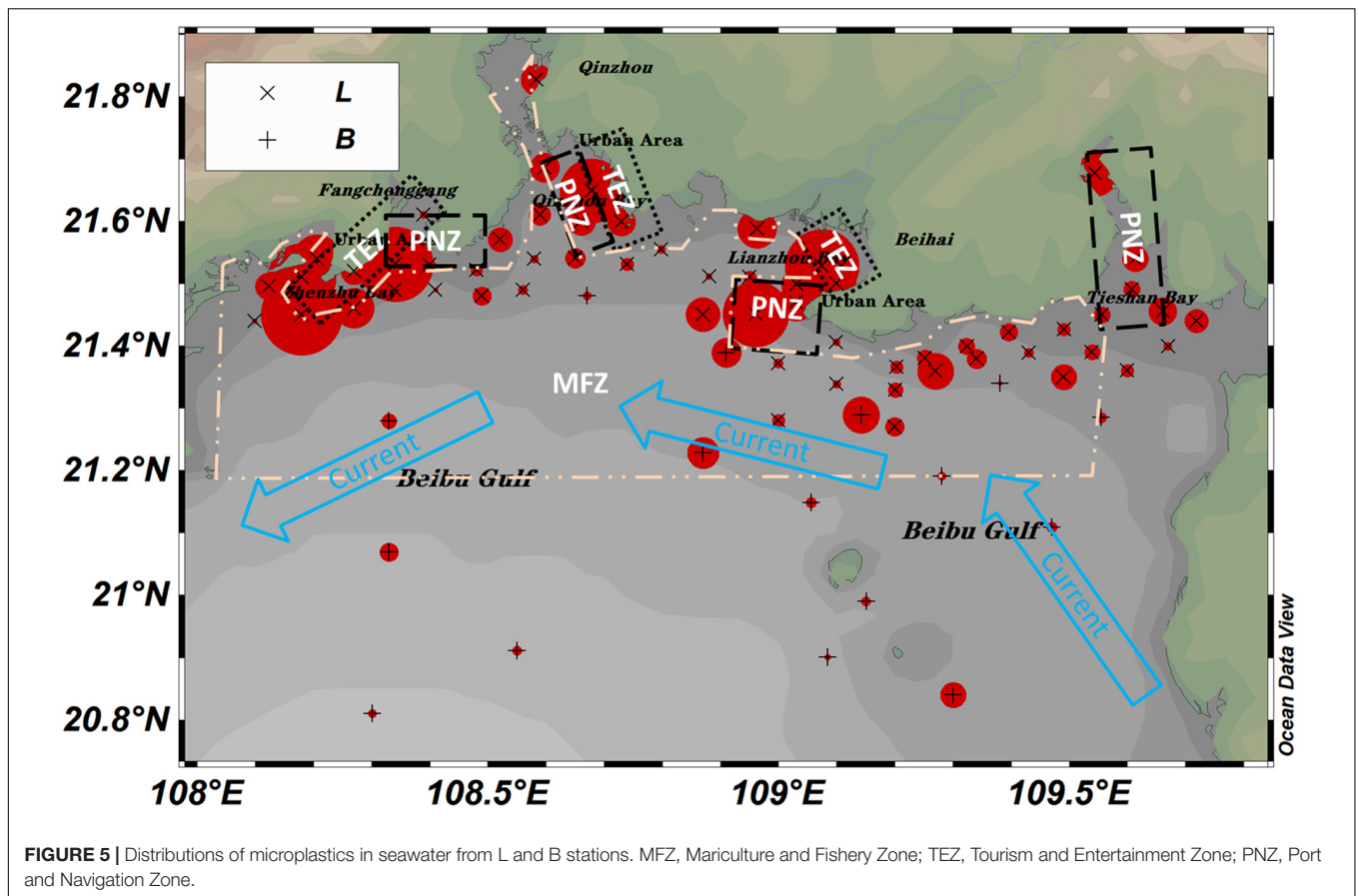
The size compositions of microplastics in sediment are shown in **Figure 2C**. In both L and B stations, microplastics with a diameter of 1–2 mm were the dominant, accounted for 43.8 and 41.3%, respectively, followed by 0–1 mm (24.2%), 2–3 mm (23.2%), 3–4 mm (6.9%), and 4–5 mm (2.2%) in L stations, and 2–3 mm (25.7%), 0–1 mm (16.7%), 3–4 mm (14.5%), and 4–5 mm (2.8%) in B stations.





Eight polymers were detected in sediment samples, including PE, PP, PS, RY, CE, polyester, PET, and acrylic. The proportion of each polymer types in sediment is shown in **Figure 2D**. The main polymers in coastal sediment (L stations) were RY (36.0%),

CE (23.5%), polyester (14.0%), PE (12.0%), PP (10%), acrylic (2.0%), PET (1.5%), and PS (1.0%), while in far coastal sediment (B stations) they were RY (47.6%), CE (26.7%), polyester (15.1%), acrylic (5.8%), PE (2.3%), and PP and PET (1.2%).



DISCUSSION

Distribution Characteristics of Microplastics in Seawater

The distribution of microplastics in seawater demonstrated the significant contributions of anthropogenic activities to the coastal seawater, especially the strong influence of fishery activities, such as oyster farming and fish culture occurred in the coastal area of the Beibu Gulf (Xue et al., 2020). As shown in **Figure 5**, the abundances of microplastics in L stations were remarkably higher than those in B stations, with an average abundance of 0.78 ± 1.20 and 0.26 ± 0.32 items/m³, respectively. A large amount of microplastics were found in seawater close to urban areas, such as Zhenzhu Bay, Qinzhou Bay, and Lianzhou Bay, compared with other seawaters like Tieshan Bay. The stations in these bays with relatively higher microplastic abundances were coincidentally located in the Port and Navigation Zone (PNZ) and Tourism and Entertainment Zone (TEZ), according to the official marine functional zoning of Guangxi (2011–2020) (The People's Government of Guangxi, 2012). Seawaters adjacent to urban areas (especially PNZ and TEZ) receive a large amount of plastic litters and domestic sewage discharge, resulting in high abundant microplastics in these seawaters, as evident in **Figure 5**. However, the PNZ may not control the

abundance of microplastics in seawater. For example, Tieshan Bay is the largest PNZ in the Beibu Gulf, while the abundances of microplastics in seawater were the lowest among the bays. One of the reasons was that Tieshan Bay is surrounded by rural area with a population density of 418 persons/km², presented the remarkably low microplastic abundance (0.39 ± 0.44 items/m³), while Lianzhou Bay is surrounded by urban area with a population density of 4,272 persons/km², presented the highest microplastic abundance (2.49 ± 1.6 items/m³). The other reason was that there is no TEZ in Tieshan Bay but the other three bays have, while the plastic litters produced by tourists were one of the main sources of microplastics in the seawater. Compared with the microplastic abundances in Zhenzhu Bay, Qinzhou Bay, and Lianzhou Bay with PNZ and TEZ, the microplastic abundances in the mariculture and fishery zone were quite small. These findings further confirmed that the relatively higher microplastic abundances found in seawater adjacent to the urban areas than the rural areas, and anthropogenic activities (i.e., domestic and industrial littering and sewage discharge) domain the microplastic distribution in seawater, rather than mariculture and fishery zone (Naidoo et al., 2015; Zhao et al., 2015; Tang et al., 2018).

It is known that current can influence microplastic distribution in the ocean (Eriksen et al., 2013; Pan et al., 2019); a case study in the Jiaozhou Bay reported by Zheng et al. (2019)

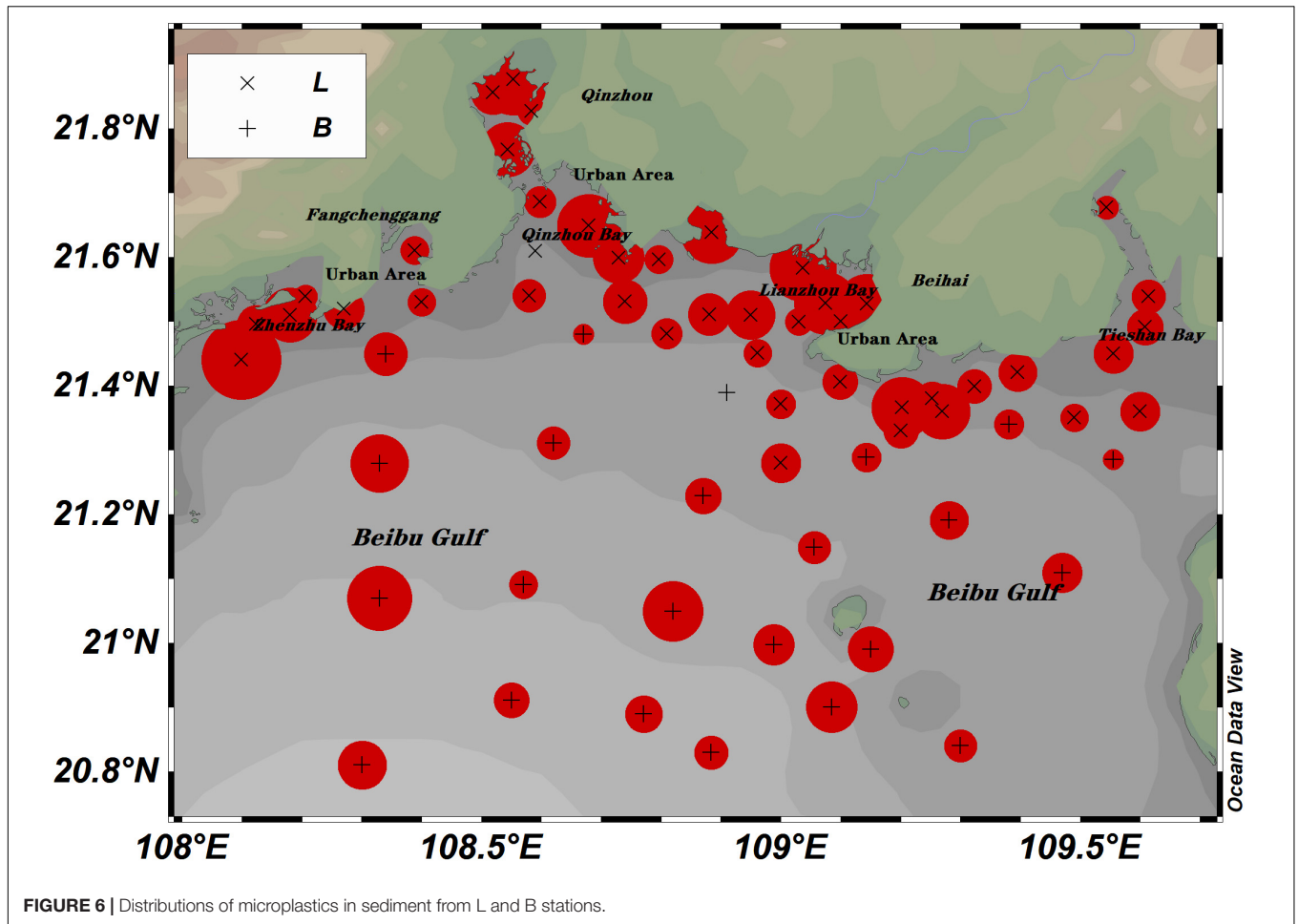


FIGURE 6 | Distributions of microplastics in sediment from L and B stations.

showed that residual currents seem to have a significant impact on the distribution and composition of microplastics. In this study, the abundance of microplastics in seawater increased from the east to the west (Figure 5), which was consistent with the current existed in the coastal areas of Beibu Gulf (Gao et al., 2014; Chen et al., 2019), showing that the current in the Beibu Gulf may have influence on the transportation of microplastics in the seawater.

Sediment

Similar to the distribution of microplastics in seawater, microplastic abundances in sediment samples from Zhenzhu Bay, Qinzhou Bay, and Lianzhou Bay were higher than those from Tieshan Bay and other stations, far away from urban areas (Figure 6; Vaughan et al., 2017). In addition, the intensive

traditional oyster farm (floating row or pile) distributed in Zhenzhu Bay, Qinzhou Bay (Maowei sea), and Lianzhou Bay contributed a large proportion of microplastics in the sediment (Zhu et al., 2019, 2021; Xue et al., 2020). However, the average abundance of microplastics in L sediment stations (15.00 ± 10.74 items/kg d.w.) was only slightly higher than that of B sediment stations (12.21 ± 8.07 items/kg d.w.), indicating that a large amount of microplastics are readily transported to long distance, and sink down and bury in the sediment (Näkki et al., 2019).

Correlation Between Seawater and Sediment

Previous studies have shown that the abundance of microplastics in the seawater and sediment was positively correlated (Zheng et al., 2019; Li Z. et al., 2020; Wang et al., 2020); however, no significant correlations were observed between seawater and sediment in this study, probably related to mismatch in spatiotemporal distributions and variations in the characteristics, fate, and behavior of microplastics in the surface water and sediment (Xu et al., 2021). The average microplastic abundance ratio of sediment to seawater in L (19.23) and B (46.96) stations was obviously different, as shown in Table 2. Interestingly, it

TABLE 2 | Average microplastic abundances in seawater and sediment sample in this study.

	L	B
Seawater (items/m ³)	0.78	0.26
Sediment (items/kg d.w.)	15	12.21
Sediment/Seawater	19.23	46.96

TABLE 3 | Main microplastic characteristics observed in surface water and sediment in Chinese coastal seas and selected similar bays in other country with comparable data (data published within the last 3 years, revised from Xu et al., 2021).

	Sample	Shape	Color	Size	Composition	
Bohai Sea	Seawater	Fragment (67.4%)	Transparent (>24.9%)	0.4–2 mm (64.2%)	Alkyd resin	Xu et al., 2021
	Sediment	Fiber (54.9%)	Blue (>18.5%)	0–1 mm (69.3%)	RY	
Jiaozhou Bay	Seawater	Fiber (~85%)	Black (~40%)	1–2 mm (~40%)	PET (~55%)	Zheng et al., 2019
	Sediment	Fiber (~88%)	Black (~30%)	0–1 mm (55%)	PET (~50%)	
Yellow Sea offshore	Seawater	Fiber (75.4%)	Black (~40%)	1–3 mm (~30%)	–	Wang et al., 2018
	Sediment	Fiber (68.7%)	Transparent (~30%)	1–3 mm (~30%)	–	
North Yellow Sea	Seawater	Film (58.1%)	Transparent (~80%)	0.03–1 mm (~80%)	PE (77.8%)	Zhu et al., 2018
	Sediment	Film (61.4%)	Transparent (~70%)	0–1 mm (~80%)	PP (44.5%)	
Haizhou Bay	Seawater	Fiber (91.12%)	Blue (50.9%)	0.16–1 mm (~47%)	PET (41.71%)	Li Z. et al., 2020
	Sediment	Fiber (93.21%)	Blue (33.25%)	0.16–1 mm (~40%)	RY (~41.98%)	
East China Sea	Seawater	Foam (54.8%)	White (71.9%)	0.5–5 mm (88.6%)	PE (45.5%)	Liu et al., 2018
	Sediment	–	–	–	–	
East China Sea	Seawater	–	–	–	–	Zhang et al., 2019
	Sediment	Fiber (77%)	Blue (35%)	0.06–1 mm (89%)	Cellophane (37.2%)	
Yangtze Estuary	Seawater	Fragment (39.2%)	White (64.7%)	0–1 mm (~48.05%)	PE (37.3%)	Li Y. et al., 2020
	Sediment	Fiber (66.7%)	Transparent (16.2%)	0–1 mm (88.5%)	PP (28.6%)	
Hangzhou Bay	Seawater	Pellet (46.4%)	–	0–1 mm (36.4%)	PE (52.3%)	Wang et al., 2020
	Sediment	Fiber (59.8%)	–	0–1 mm (38%)	RY (49.7%)	
Xiangshan Bay	Seawater	Foam	–	0.25–2 mm	PE (38.6%)	Chen et al., 2018
	Sediment	–	–	0.25–2 mm	RY (56.3%)	
Xiamen Bay	Seawater	Granule (~30%)	White (50%)	–	PE (50.4%)	Tang et al., 2018
	Sediment	Fiber (70%)	Black (26%)	–	PP	
Hong Kong waters	Seawater	Foam	–	0.3–0.7 mm	PS	Cheung P. K. et al., 2018
	Sediment	–	–	–	–	
Beibu Gulf	Seawater	–	–	–	–	Xue et al., 2020
	Sediment	Fiber (69.6%)	–	1–5 mm (~50%)	PP (68.7%)	
Qin River Estuary, Maowei Sea, Beibu Gulf	Seawater	Fiber (38.2%)	White (~28.5%)	1–5 mm (88.9%)	PP (39%)	Zhang et al., 2020
	Sediment	Film (62.8)	White (30%)	1–5 mm (76%)	PP (55.3%)	
Maowei Sea, Beibu Gulf	Seawater	Fiber (~80%)	White (~80%)	1–5 mm (4~0%)	PES (~40%)	Zhu et al., 2019
	Sediment	–	–	–	–	
In total (except Beibu Gulf)	Seawater	Fiber	White	0–1 mm	PE	
	Sediment	Fiber	Transparent	0–1 mm	RY	
Beibu Gulf	Seawater	Fragment (92.38%)	White (56.20%)	1–2 mm (44%)	PS (53.23%)	This study
	Sediment	Fiber (82.93%)	Black (66.83%)	0–1 mm (50.04%)	RY (39.54%)	

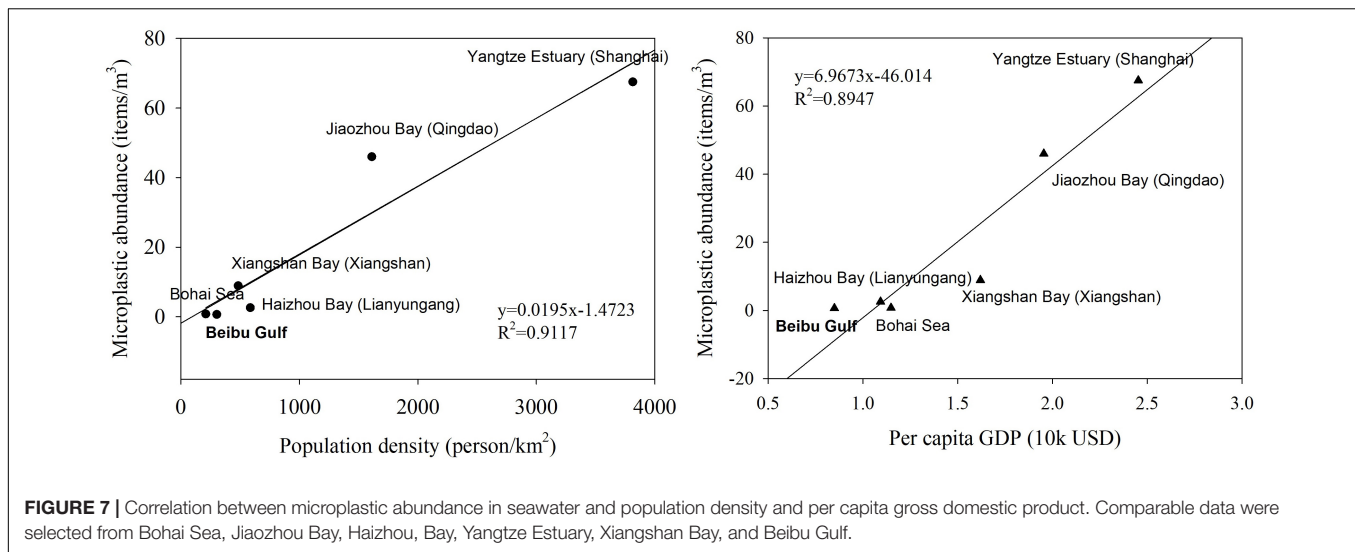
seems that the microplastic sedimentation in far coast area (B station) was much stronger than that in coastal area (L station); evidently, most of the microplastics were retained in the sediment of B stations while only a minimal amount in coastal area sediment. Furthermore, higher abundances of microplastics were found in coastal seawater, and a substantial part of them were sequestered into the far coast sediment, further confirming that the sediment is the sink of microplastics (Long et al., 2015; Martin et al., 2017; Zheng et al., 2019).

Dai et al. (2018) reported that the microplastic abundances were inversely correlated with the chlorophyll-*a* in surface water in the Bohai Sea; therefore, the algae aggregation might have an effect on the sinking of the microplastics into the sediment. In this study, no significant correlations were obtained between microplastics and chlorophyll-*a* or suspended particles, showing that the sedimentation of microplastics in the study area was controlled by multiple processes that remain further exploration,

e.g., benthos might promote the burial of microplastics in the sediments (Gebhardt and Forster, 2018).

Comparison of Microplastic Characteristics

The main microplastic characteristics determined in the seawater and sediment samples in the sea areas of China are summarized in **Table 3**. Most identified microplastics existed were fragments (92.38%) in seawater, which is of great difference from other areas, e.g., fibers were the dominant components in most sea areas of China, such as Jiaozhou Bay, Haizhou Bay, and Yellow Sea offshore. The dominant polymer in seawater was PS, which is widely used to produce plastic foam applied in the mariculture and other packing materials, and usually, it is white. The dominant color of microplastics in seawater was found to be white (56.20%), inconsistent with the microplastic color



discovered in most seawaters reported in China. In addition, most colored microplastics are subjected to be decolorized by sunlight (ultraviolet radiation), resulting in transformation to white. Since white microplastics are not as attractable as other colored microplastics, when missed to be eaten by marine organisms, they were likely to be retained in the water. The PS foam has more porous structures and then might be easily broken down into small plastics by sunlight, wind, and current, bringing much more fragments into the sea (Song et al., 2017), inconsistent with the dominant foams and fragments observed in the seawater in Hong Kong (Cheung P. K. et al., 2018), the north coast of Surabaya (Cordova et al., 2019), and this study, also inconsistent with the dominant PS foams (macroplastics), found in the beach and sediment of tourist spots in the coastal of Beihai, Qinzhou, and Fangchenggang according to the Marine Environment Bulletin (2017; Department of Ocean and Fishery of Guangxi). These findings provided clues for the mitigation of PS microplastic pollution such as the recycling of the PS foams used in mariculture.

The dominant size (1–2 mm) of microplastics measured in seawater in this study is larger than those (0–1 mm) in the other sea areas, possibly because that smaller microplastics tend to sink down to the sediment, and PS fragments need to be in relatively larger size to keep floating on the surface seawater. This further confirms that a large amount of microplastics are white PS foams (macro fragment) in samples collected in this field study, especially in the coastal area.

Similar to the most study areas, fibers were the dominant microplastics in the sediment in this study (Table 3). It is known that fibers were originated mainly from fabrics and were difficult to remove during sewage treatment. The Beibu Gulf is a semi-enclosed bay receiving all the sewage from the river and coastal cities, which supports the findings. This finding is also consistent with the high relative abundance of RY in the sediment in this study, a synthetic polymer largely used in the textile industry (Kauffman, 1993; De Falco et al., 2018). The density of RY is usually less than PS, but still acts as a high-density polymer. Furthermore, the RY detected in this study existed

as very small size (0–1 mm), having large specific surface area for the microplastics, leading to more fiber microplastics settled and buried in the sediment. In addition, small microplastics tend not to retain in the water column and are likely to be deposited in sediments (Enders and Lenz, 2015; Wu et al., 2019; Xu et al., 2021), which was supported by the finding in this study that dominant microplastics were much smaller (0–1 mm, 50.04%) in sediments than in the surface water (1–2mm, 44%). These features were also discovered in Bohai and Yellow Seas (Dai et al., 2018; Zhao et al., 2018; Xu et al., 2021), Haizhou Bay, Hangzhou Bay, and Xiangshan Bay, indicating that more effective wastewater treatment technology should be adopted to remove the fibrous microplastic RY from domestic and industrial wastewater. Interestingly, the dominant color of fibers in the sediment in this study was black, and the same dominant color of microplastics discovered in Xiamen Bay (Tang et al., 2018) was quite different from the transparent in other sea area sediment, which need more exploration.

Comparison of Microplastic Abundances in Semi-Enclosed Bays

A semi-enclosed bay is likely to accumulate microplastics due to intensive anthropogenic activities and restricted water exchange (Li et al., 2018; Zhou et al., 2021). For example, up to 27.7 items/L of microplastic abundances were found in seawater of Bohai Sea (Dai et al., 2018), Maowei Sea (an inner bay of Beibu Gulf; Zhu et al., 2019, 2021), and Baltic Sea (Zhou et al., 2021), in which studies bulk water sampling was employed. However, significant lower microplastic abundance in seawater of Bohai Sea was reported using trawl net sampling by Xu et al. (2021), since much smaller filter pore size was used in the former method, theoretically resulted more microplastics were collected, and higher abundances were revealed than the trawl net sampling. Still, significantly higher microplastic abundances (>0.33 mm) in seawater were reported using bulk water sampling in those semi-enclosed bays than the Beibu Gulf. As a typical semi-enclosed bay, the Bohai Sea is surrounded by highly developed

regions in China compared with the Beibu Gulf. However, the microplastic abundance in seawater of Bohai Sea (0.79 items/m^3) and Beibu Gulf (0.67 items/m^3) was almost the same mainly because of the comparable population density, per capita GDP, and more relevantly, roughly the same water exchange time (406 days vs. 509 days; Cai, 2013; Fang, 2014). In contrast, the microplastic abundance in sediment of Bohai Sea ($48.88 \text{ items/kg d.w.}$) was larger than Beibu Gulf ($13.87 \text{ items/kg d.w.}$), indicating that the sediment in Bohai Sea accumulated more microplastics than Beibu Gulf since the Bohai Sea region was suffering much longer time economic development than the Beibu Gulf (Dai et al., 2018). Compared with the microplastics in Benoa Bay with similar ecosystems (i.e., mangroves and estuaries) (Suteja et al., 2021), the microplastic abundance (0.62 items/m^3) was nearly equal to the Beibu Gulf, suggesting that the indices influencing microplastic pollution, including population, GDP, and fishery between Beibu Gulf and Benoa Bay, were comparable, which provided clues for the applications of the microplastic pollution management in both waters.

Microplastic Abundance Links to Socioeconomics in China

Report showed that the plastic consumption was correlated with socioeconomic indices (Hossain et al., 2021). Therefore, the population density and other socioeconomic parameters are important when interpreting the occurrence of the microplastics (Lebreton et al., 2017; Wang, 2018; Mai et al., 2019; Chen B. et al., 2020; Wu et al., 2021). In this study, population density and per capita GDP were selected from districts with comparable microplastic data from **Table 1**; subsequently, we found positive correlations between microplastic abundance in seawater and population density and per capita GDP, respectively (**Figure 7**). Similarly, Yonkos et al. (2014) and Fan et al. (2019) found significant positive correlations between microplastic abundance in water and population density in four estuarine rivers in the Chesapeake Bay and the Pearl River catchment, indicating that large population areas released more microplastics. And Chen H. et al. (2020) reported a positive correlation between microplastic concentration in the global waterbodies and per capita GDP, indicating that increasing human living standards would accelerate the demand for plastic products, leading to the increase in the degree of microplastic pollution. However, Tang et al. (2018) and Chen H. et al. (2020) reported a positive correlation between microplastic abundance and population number (not population density), and Tang et al. (2018) reported a poor negative correlation between microplastic abundance and per capita GDP, which were contrary to the results of this study. These findings would play important roles in the first step of developing policy and regulations to mitigate the microplastic pollution risk (Xu et al., 2020).

CONCLUSION

In this study, microplastic distributions in seawaters and sediments in the Beibu Gulf were firstly investigated. Fiber and PE were the dominant microplastics in Chinese coastal seawater, while fragment and PS were the dominant microplastics in

the seawater of Beibu Gulf. The abundances of microplastics in coastal seawater were much greater than that in far coastal seawater, indicating important contribution of human activities. In addition, a large amount of microplastics can be transported for long distance, and then sink down and bury in the sediment, since the microplastic abundances were comparable between coastal and far coastal sediments. Significant correlations between the microplastics abundance and population density and per capita GDP were found in Chinese coastal seawater, indicating that microplastics in the Beibu Gulf were at a low level. This study presented microplastics abundances and distributions in a semi-enclosed bay with increasing anthropogenic activities, which may provide reference methods and data for the microplastic research in the other ocean. Further studies need to be carried out to explain the transport and sink processes of microplastics in the water column of Beibu Gulf and SCS.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

ZZ contributed for conceptualization, sampling, and writing – original draft preparation. HW contributed for sample preparation, characterization, and data management. WH contributed for characterization and draft modification. XW contributed for sample preparation and characterization. YG contributed for data management and editing. QZ contributed for conceptualization. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2021.821008/full#supplementary-material>

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Conflict of Interest: XW is employed by Central Cycle Ecological Technology Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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