frontiers in Environmental Science

ORIGINAL RESEARCH
published: 07 February 2022
doi: 10.3389/fenvs.2022.829942

Microplastic Distribution and Influence Factor Analysis of Seawater and Surface Sediments in a Typical Bay With Diverse Functional Areas: A Case Study in Xincun Lagoon, China

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Specialty section:
This article was submitted to Toxicology, Pollution and the Environment,
a section of the journal Frontiers in Environmental Science

Received: *06 December 2021*
Accepted: *19 January 2022*
Published: *07 February 2022*

Citation:
Wei Y, Ma W, Xu Q, Sun C, Wang X and Gao F (2022) Microplastic Distribution and Influence Factor Analysis of Seawater and Surface Sediments in a Typical Bay With Diverse Functional Areas: A Case Study in Xincun Lagoon, China. Front. Environ. Sci. 10:829942. doi: 10.3389/fenvs.2022.829942

Microplastics come directly or indirectly from human activities. The bay and coastal areas are constantly under pressure from human activities, including tourism, fishing, and aquaculture. Microplastic pollution is now recognized as a great threat to bay environments. In this study, we assessed microplastics in the Xincun Lagoon Bay, which had multiple human activities, to understand whether human activities could directly reflect the pollution level of microplastics. The results showed the dominant microplastics were small (100–500 µm, 45.2%) and transparent (57.0%), mainly consisting of fibers (95.7%), and cellophane (54.4%) was the dominant polymer. The color, type, and component indicated that wastes from aquaculture, laundry wastewater in the Tanka fishing raft area, and domestic wastes from tourism were the primary sources of microplastics in Xincun Bay. During the rainy season, microplastic abundances in surface water and surface sediment at the outer bay were found to be significantly higher (108.8 ± 37.1 item/L and 250.4 ± 92.0 item/kg, respectively) than those found at the inner bay (34.3 ± 12.9 item/L and 167.6 ± 71.7 item/kg, respectively), which presented a reverse trend in the dry season ($p < .01$). Although Xincun bay has a relatively closed environment and diverse human activities, concentrated rainfall and strong winds could cause microplastic abundance inside the bay during the rainy season to be lower than that outside the bay. Furthermore, the comparison of microplastic abundances in the areas with intensive human activities and non-human activity areas indicated that the intensity of human activities could not directly reflect the pollution of microplastics in the lagoon bay. It is also necessary to consider the geographical and seasonal characteristics in order to explain the pollution degree of microplastics in a bay.

Keywords: microplastics, lagoon bay, human activity, seasonal characteristics, source

1 INTRODUCTION

Plastic waste has become one of the most serious environmental issues (Shen et al., 2021). Plastics in the environment would slowly degrade into plastic particles under the action of sunlight, microbes, and mechanical abrasion. Plastic particles less than 5 mm in diameter are defined as microplastics (Thompson et al., 2004; Cole et al., 2011).

Marine and terrestrial activities are the two primary sources of microplastics in marine environments (Shao et al., 2020). Marine sources of microplastics include ship transport, oil and gas exploration, fishing, aquaculture, and other marine activities that release microplastics directly into marine environments (Sun et al., 2016). Terrestrial sources include agricultural activities and industrial and domestic wastes. Microplastics from land enter marine environments through groundwater runoff or tidal action (Luo et al., 2021). These particles either accumulate in the surface sediment or get suspended in the water and then migrate toward the deep sea following the current (Wang X. et al., 2021). Indeed, microplastics have been detected in various marine environments, including coastlines, seawater, sediments, and beaches, where they cause damage to the ecological systems. Specifically, they elicit harmful effects on organisms, including false satiation caused by microplastic ingestion, accumulation of toxic substances (harmful additives and heavy metal pollutants), negatively impacting organism survival, growth, metabolism, and reproduction (Derraik, 2002; Xu et al., 2019). Moreover, microplastics can also negatively impact humans (Borges-Ramírez et al., 2020) as they can induce oxidative stress in cells resulting in cytotoxic effects (Schirinzi et al., 2017). Additionally, if humans ingest a large amount of microplastics through their diet, reproductive cells can be affected with subsequent adverse effects on embryo formation, fetal development, and postnatal development (Qin et al., 2021).

Of all marine environments, bay serve as key routes for transporting microplastics from land to oceans (Xiong et al., 2020). As such, the occurrence, and pollution, of microplastics within bays have caused widespread global concern. At present, there are many studies on microplastics pollution in bays around the world. High degrees of urbanization and lack of supervision have caused serious microplastic pollution in Macajalar Bay, Philippines (Kalnasa et al., 2019). Moreover, Retama et al. (2016) attributed the amount of microplastics in Huatulco Bay (Mexico) to the sewage discharged by cruise vessels and tourist activities. Microplastic abundance in Guanabara Bay (Brazil) is higher than that in other marine ecosystems due to mussel farming and pollution on beaches (Figueiredo and Pintas-Vianna, 2018). Meanwhile, river discharge, plastic materials, and facilities from fishing and mariculture industries are also considered significant microplastic sources in bays (Castro et al., 2016).

To date, in China, studies on microplastics has been conducted in at least 15 bays that are primarily concentrated in marine areas near the Yellow Sea and Bohai Sea, including Laizhou Bay (Teng, 2021), Jiaozhou Bay (Zheng et al., 2019), Sishili Bay (Cheng et al., 2021), Sanggou Bay (Xia et al., 2021), Jinzhou Bay (Qu et al., 2021), and Bohai Bay (Wu, 2019). These studies have largely focused on the pollution characteristics and distribution of microplastics throughout the environment, the toxicological effect of microplastics, interactions and joint toxicity of microplastics with heavy metals, and migration processes of microplastics. In Hainan Island, the distribution and toxicological effect of microplastics in Haikou Bay (Qi, 2020), and Wanning Xiaohai Bay (Zhang Q. et al., 2020) have been explored. In addition, Huang Y. et al. (2020) investigated the seagrass bed area in Xincun Bay and Lian Bay, and found that the trap effect of seagrass was non-selective regarding microplastic shape, color and size of microplastics. High anthropogenic pollution and poor beach management could contribute to higher concentrations of microplastics in Lian Bay. It could be seen that it is of great significance to explore the microplastic pollution in Hainan Island.

Additionally, Chen and Chen (2020) observed high microplastic density on beaches with high levels of tourism activity. Meanwhile, Zhang Q. et al. (2020) and Liu et al. (2021) found that a substantial abundance of microplastics could be traced in surface water and sediments in most coastal environments of Hainan Province. Furthermore, plastic waste from coastal tourism and fishing activities has polluted many coastal waters in Hainan (Zhang Q. et al., 2020; Huang, 2020b). Hence, the main sources of microplastics in Hainan Province are tourism activities and aquaculture.

Xincun Bay, a lagoon bay in Lingshui County, Hainan Island, China, is a popular tourist attraction, accounting for more than 90% of the total number of tourists in Lingshui County (Yang, 2018). In most bays, human activities are primarily concentrated on beaches. However, in Xincun Bay, tourist activities are largely concentrated on the Tanka fishing boats (Guan and Huang, 2019). In addition, Xincun Bay is a closed natural lagoon bay with many functional areas, including the Tanka fishing raft area, aquaculture area, Xincun Port, seagrass bed area, and national mangrove wetland protection area, all of which, according to Wang S. et al. (2021), have placed Xincun Bay under considerable environmental pressure. Furthermore, Xincun Bay has no large rivers flowing into it, making its environment relatively stable. Thus, microplastic pollution originated from different functional areas of the bay. Consequently, Xincun Bay could serve as a typical representative lagoon bay for analyzing the impact of human activities on microplastic accumulations in bays. Therefore, we hypothesized that concentrated rainfall and strong wind might lead to the microplastics abundance in Xincun Bay being lower than that outside the bay in rainy season, while the microplastics abundance in Xincun Bay was higher than that outside the bay in dry season, because the calm bay and prevailing southwest wind made more microplastics enter the bay and stay in Xincun Bay. Also, we predicted that microplastics in Xincun Bay may originate from local farming activities and tourism activities. Tourism and aquaculture are the main human activities in Xincun Bay. We also hypothesized that human activities could not directly reflect the pollution of microplastics in the lagoon bay. Geographical and seasonal characteristics are also important factors affecting the abundance of microplastics. To test this hypothesis we collected samples of surface water and surface sediments in

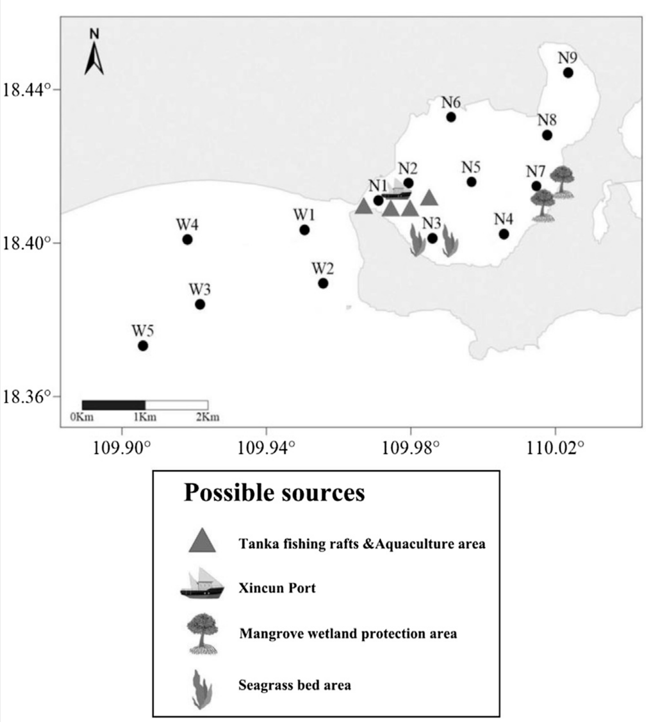

FIGURE 1 | Map showing the study area around Xincun Bay. The black dots are the surface water and sediment sampling stations. N and W represent the sampling stations inside and outside Xincun Bay, respectively.

Xincun Bay during the dry (March 2021) and rainy seasons (October 2020). In the present work, microplastics were isolated from surface water and sediment samples. Isolated microplastics were then quantified and observed for color, particle size, and type. Subsequent determination of the composition of microplastics and analysis of their sources (Sunitha et al., 2021).

This study attempted to comprehensively evaluate the distribution of microplastics inside and outside Xincun Bay for the first time. The main objective of this study was to determine whether human activities could directly reflect the degree of microplastic pollution in Xincun Bay. Furthermore, we focused on microplastic characterization to better understand the different sources of pollution, thereby, addressing a current gap in knowledge regarding microplastic pollution in Xincun Bay. Collectively, the findings of this study advance the current understanding regarding microplastic pollution in lagoon bays, while enabling Xincun Bay to further improve the microplastic pollution risk assessment standard system.

2 MATERIALS AND METHODS

2.1 Study Area and Station Layout

Xincun Bay (18.38°–18.45°N, 109.97°–110.03°E) is a lagoon bay with a single narrow channel connecting to the open waters and no large rivers flowing into it. It is located in the southeast region of Lingshui County, Hainan Island, China, covering approximately 22.6 km^2, with an approximately 28.5 km coastline (Yang et al., 2016). Xincun Bay belongs to Xincun Town, which spans about 60.97 km^2, with 15.28 km^2 of planned urban area (Liu, 2020). By the end of 2018, the registered population of Xincun Town was 34,529 (National Bureau of Statistics, 2020). Xincun Bay has a tropical monsoon climate with dry and rainy seasons. The dry season begins in November and ends in April of the following year. Most rainfall occurs between May and October, and the study area often experiences typhoons (Yang et al., 2016).

According to statistics from Hainan Plastics Industry Association (2020), it is estimated that about sixty thousand tons of plastic waste entered into the ocean around the Hainan Island each year. Hainan Province has introduced multiple policies to reduce plastic pollution in the environment, such as "Provisions on Prohibition of Disposable Non-degradable Plastic Products in Hainan Special Economic Zone," "Joint Law Enforcement Action Plan for the Prohibition of Plastics in Hainan Province in 2021," and "Implementation Plan for Hainan Province to Prohibit the Production, Sale and Use of Disposable Non-degradable Plastic Products" (Zai, 2020). To implement relevant management systems, the government set up multiple plastic recycling points in Xincun Town, and significantly suppressed the sale and storage of non-degradable plastics in accordance with the law (http://lingshui.hainan.gov.cn/). Nonetheless, the current state of plastic pollution remains severe.

Figure 1 shows the areas prone to microplastic pollution in Xincun Bay, including the Tanka fishing raft area, aquaculture area, and Xincun Port. The Tanka fishing raft area in Xincun Bay serves as the living area for fishermen, as well as a prominent tourist destination, both of which contribute to the generation of plastic waste (Gao et al., 2021). In the aquaculture area of Xincun Bay, most fishing gear, including fishing nets, ropes, floating balls, buckets, are either made of plastic or contain plastic components. Additionally, artificial fish feed contains large quantities of microplastics (Zhou et al., 2017). Xincun Port is an important fishing port on the southeastern coastline of Hainan Island with ship transportation estimated to have a comprehensive pollution index of >10 in Xincun Bay, which is considered to be relatively severe (Gong et al., 2018). **Figure 1** also shows the 14 sampling sites, including 9 sites in the inner bay (N1–N9), and 5 sites in the outer bay (W1–W5). Among these stations, N1 and N2 were located at the intersection of the Tanka fishing raft area, the aquaculture area, and Xincun Port; N3 was located in the seagrass bed area; N7 was positioned near the national mangrove wetland protection area; and the remaining stations had limited human activities.

2.2 Sample Collection

Surface water and surface sediment samples were collected from 14 stations (N1–N9 and W1–W5, respectively). Of these, surface water and surface sediments were collected at the same station. Seasonal sampling was carried out in Xincun Bay using a glass water collector (WB-PM, Beijing Purity Instrument Co., Ltd., China) and sediment sampler (Van Veen, Qingdao Haohai

Instrument Co., Ltd., China) during the rainy (October 2020) and dry seasons (March 2021).

Surface water was collected using a glass water collector. The water samples (3-L) were collected at a depth of about 10 cm the surface of each station using pre-cleaned containers, which were rinsed three times with sample water prior to the actual filling. Each water sample was then placed in a 1L amber wide-mouth jar (with a screw cap) that was pre-rinsed with ultrapure water. Water samples were stored in an incubator with ice packs for transportation (Chen C.-F. et al., 2021). The time from sample collection to sample analysis and processing did not exceed 6 h.

Surface sediment samples from each sampling site were collected using a sediment sampler. Approximately 1 kg of wet sediment from the top 5-cm layer of each station was collected and immediately placed in aluminum foil bags. Sediment samples were stored in the dark and at −20°C after being transporting to the laboratory.

2.3 Sample Extraction and Analysis

2.3.1 Microplastic Extraction From Water Samples

The surface water (1L) was transferred from the amber wide-mouthed jar to a glass beaker, and a graduated cylinder was used to measure 200 ml of surface water for sampling ($N = 5$). Each parallel water sample (200 ml) was digested with 5 ml of 30% H_2O_2 (Analytical pure, Xilong Science Co., Ltd., China) for 24 h. The supernatant was filtered through filter paper with a 0.8-μm pore size (Q/IEFJ01-1997) (Cai et al., 2021) (Jinjing, Shanghai Xingya, China) using a glass vacuum filtration unit (Solvent filter, Jinteng Technology, China). The filter membranes were placed in clean petri dishes and covered with lids.

2.3.2 Microplastic Extraction From Sediment Samples

According to the local standard of Shandong Province (DB37/T 4323-202), sediment samples were stored at 60°C in an oven until completely dried (Chen C.-F. et al., 2021). The dried samples were sieved through a 5-mm mesh steel sieve to remove large rocks (Ouyang et al., 2020). Weighed-out dried sediment (50 g) was placed in a 500-ml clean glass beaker (washed with ultrapure water). Saturated NaCl (200 ml, 1.2 g/cm^3) (Analytical pure, Xilong Science Co., Ltd., China) was added to the dried sediments (50 g) for flotation. The beaker was subsequently capped with aluminum foil, and then stirred vigorously for 2 min using a magnetic stirrer (Karlsson et al., 2017). The slurry mix was left to settle for 8 h. The supernatant was then transferred to a new beaker (1,000 ml). The flotation process was repeated three times for each sediment sample. Five milliliter of 30% H_2O_2 was added to the final supernatant of each sample and left at room temperature for 24 h (to remove the natural organic matter) and then the supernatant was filtered through a 50-mm glass fiber filter membrane (.8-μm pore size, Q/IEFJ01-1997) using a vacuum system. There were five parallel sediments at each station.

2.3.3 Visual Inspection of Microplastics

The sample filters were investigated under a dissecting stereomicroscope (YYL-880E, China; Khan and Prezant, 2018). The suspected microplastics were visually inspected (Gu et al., 2020). In order to improve the accuracy of visual inspection, we determined whether it was microplastic by testing the flexibility and fragility of plastic particle. As microplastics exhibit a certain degree of toughness, they are not readily ruptured when handled with tweezer (Hidalgo-Ruz et al., 2012; Ran et al., 2018). Hence, those that were fragmented during this process were not counted as microplastics. Among them, the fibers thickness should be uniform, and there could be no bifurcation or thinning at the end (Ran et al., 2018). Also, no gloss on the surface of pellet microplastics (Mohamed Nor and Obbard, 2014). The shape, color, size, and abundance of all microplastics were recorded. Based on their shapes, microplastics were classified into fibers, films, fragments, foams, and pellets. Transparent and seven visual colors, including black, blue, green, red, yellow, white, and purple, were recorded. The size of microplastics was measured with built-in measuring software, and photographs were taken with a digital camera (YYL-880D, Nikon, Japan) installed on the stereomicroscope.

To analyze the composition of microplastics and explore their possible sources, micro-Fourier transform infrared (FTIR; Shimadzu, IR Affinity-1S, Japan) and Raman spectroscopy (HORIBA, LabRAM HR Evolution, France) were used (Hidalgo-Ruz et al., 2012; Tang et al., 2021). The FTIR spectra were recorded in reflectance mode and 64 scans per particle were analyzed to obtain a resolution of 8 cm^{-1}, with spectra ranging from 650 to 4,000 cm^{-1}. The spectra were produced through OMNIC software and compared with databases from the OMNIC polymer spectruma library (Yu et al., 2016). The polymer types of microplastics were verified when the match degree was >70% (Lusher et al., 2013). In addition, the microplastic on the silicon plate was exposed to light with a wavelength of 785 nm, 25 mW of power, with integration time varying from 20 to 45 s. The observed wave numbers are from 1,000 to 3,500 cm^{-1}. The obtained Raman spectra were compared to the reference polymer plastic spectrum in Wizard Library (Was-Gubala and Machnowski, 2014).

2.4 Prevention of Microplastic Contamination

To avoid microplastic contamination, non-plastic instruments were used during field sampling. Moreover, during sample handling, cotton lab coats and polymer-free gloves were used (Xue and Huang, 2020). During the laboratory experiments, all containers and glass instruments were rinsed with ultrapure water. To avoid microplastic cross-contamination, all solutions, including ultrapure water, 30% hydrogen peroxide (H_2O_2), and saturated NaCl (1.2 g/cm^3) solutions, were filtered through a 50 mm glass microfiber membrane (Q/IEFJ01-1997; .8-μm pore size) and stored in glassware covered with aluminum foil to avoid airborne contamination. To account for any environmental contamination, we completed laboratory procedural blanks and field blanks. Before collecting samples in the field, we put ultrapure water into 1-L amber wide-mouth jar (with a screw cap). These field blank samples were run through the vacuum filtration system after transport to the laboratory. In the laboratory, we used ultrapure water and completed all listed

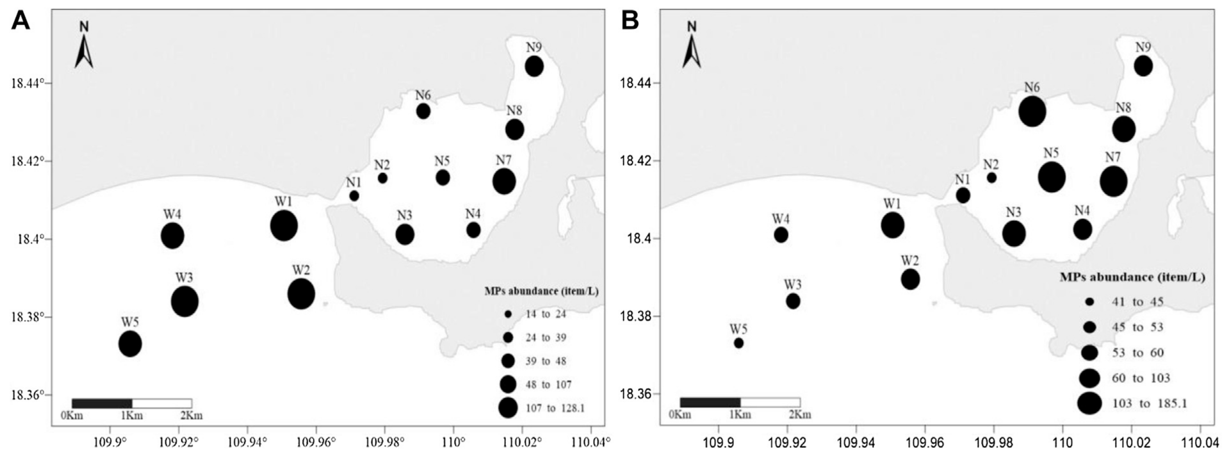

FIGURE 2 | Microplastic abundance in surface water during the rainy season **(A)** and dry season **(B)** (W1-W5 located outside Xincun Bay, N1-N9 located inside Xincun Bay).

laboratory isolation and extraction techniques alongside field samples for each day of analysis. In addition, the pretreatment process was conducted in a sterilized fume hood. The results all confirmed that the background contamination was negligible.

2.5 Statistical Analysis

Microplastic abundance in the surface water and sediments was expressed as the number of microplastics per 1-L of water (item/L) and per 1 kg of dry sediment (item/kg dry weight), respectively. All values were reported as mean ± standard deviation. Analyses of microplastic abundance, size, shape, and color were performed using Microsoft Office (Excel 2019). Statistical analyses were performed using IBM SPSS® Statistics 23.0., and Surfer 12.0 was used to create the abundance and station distribution maps.

3 RESULTS

3.1 Abundance and Correlation of Microplastics in Surface Water and Surface Sediments

During the rainy season, microplastic abundance in the surface water samples ranged from 14.0 to 128.0 item/L, with an average of 60.9 ± 21.5 item/L (**Figure 2**). The average abundance of microplastics at outer bay stations (108.8 ± 37.1 item/L) was significantly higher than that at the inner bay stations (34.3 ± 12.9 item/L; $p < .01$). Among them, the N2 station had the lowest microplastic abundance (14.0 item/L), and the W1 station had the highest microplastic abundance (128.0 item/L). Microplastic abundances at stations N1 and N2 in Xincun Bay were significantly lower than the overall average (t-test, $p < .05$).

During the dry season, microplastic abundance in the surface water samples ranged from 41.0 to 185.0 item/L, with an average value of 72.6 ± 23.7 item/L (**Figure 2**). The average abundance of microplastics at the inner bay stations (81.6 ± 27.4 item/L) was higher than those at the outer bay stations (56.4 ± 16.9 item/L). However, no significant differences were observed between inside and outside the bay. The N7 station had the highest microplastic abundance (185.0 item/L), and station W5 showed the lowest abundance value (41.0 item/L). Microplastic abundance at station N7 was significantly higher than the average (t-test, $p < .05$).

During the rainy season, microplastic abundance in sediment samples varied from 40.0 to 420.0 item/kg, with an average value of 197.1 ± 79.0 item/kg (**Figure 3**). The average abundance at the outer bay stations (250.4 ± 92.0 item/kg) was significantly higher than that at the inner bay stations (167.6 ± 71.7 item/kg). The highest value was observed at the W1 station (420.0 item/kg), and. microplastic abundance at station W1 was significantly higher than the overall average (t-test, $p < .05$), while at stationsN7 and W5, it was significantly lower than the overall average (t-test, $p < .05$).

During the dry season, microplastic abundance in sediment samples ranged from 116.0 to 492.0 item/kg, with an average value of 240.6 ± 94.5 item/kg (**Figure 3**). The average abundance of microplastics at inner bay stations (288.4 ± 96.8 item/kg) was significantly higher than that at outer bay stations (154.4 ± 90.5 item/kg; $p < .01$). The highest abundance was observed at station N1 (492.0 item/kg). Microplastic abundance at station N2 was significantly higher than the overall average (t-test, $p < .05$), while that at W5 stations was significantly lower than the overall average (t-test, $p < .05$). During the rainy season, the average microplastic abundance in surface water and sediment samples at the outer Xincun Bay stations (108.8 ± 37.1 item/L and 250.4 ± 92.0 item/kg, respectively) was higher than the corresponding values at the inner bay stations (34.3 ± 12.9 item/L; 167.6 ± 71.7 item/kg). However, in the dry season, the average microplastic abundances in surface water and sediment samples (81.6 ± 27.4 item/L and 288.4 ± 96.8 item/kg, respectively) at the inner bay stations were higher than those at the outer bay stations (56.4 ± 16.9 item/L; 154.4 ± 90.5 item/kg, respectively). Correlation analysis showed that there was no significant correlation

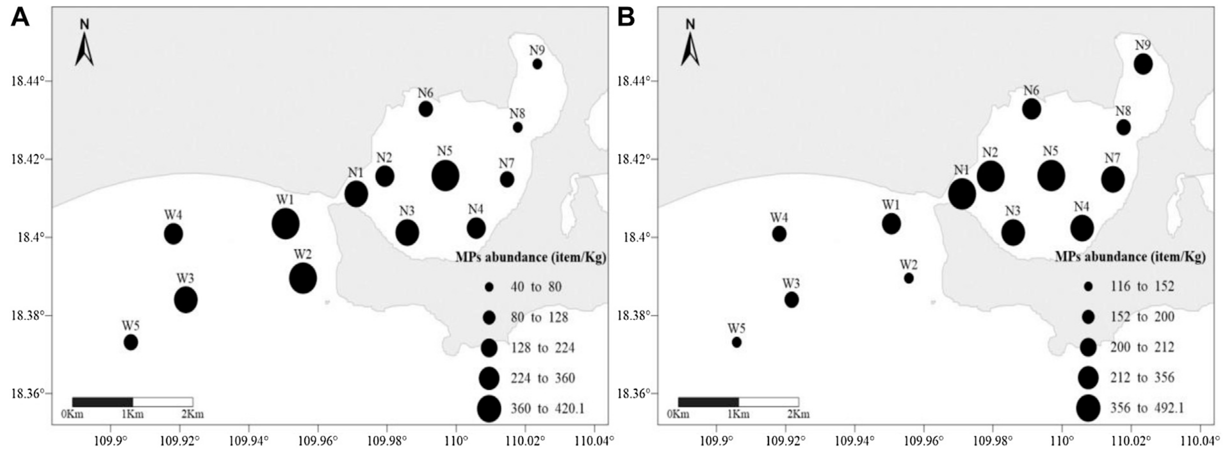

FIGURE 3 | Microplastic abundance in surface sediment during the rainy season **(A)** and dry season **(B)** (W1-W5 located outside Xincun Bay, N1-N9 located inside Xincun Bay).

TABLE 1 | Correlation analysis results.

Microplastic abundance		Microplastic abundance in SW (rainy season)	Microplastic abundance in SW (dry season)
Microplastic abundance in SS (rainy season)	Pearson correlation	.402	— —
	Sig. (Double tail)	.154	— —
Microplastic abundance in SS (dry season)	Pearson correlation	— —	−.007
	Sig. (Double tail)	— —	.982

*(**Note:** SS, refers to surface sediment; SW, refers to surface water).*

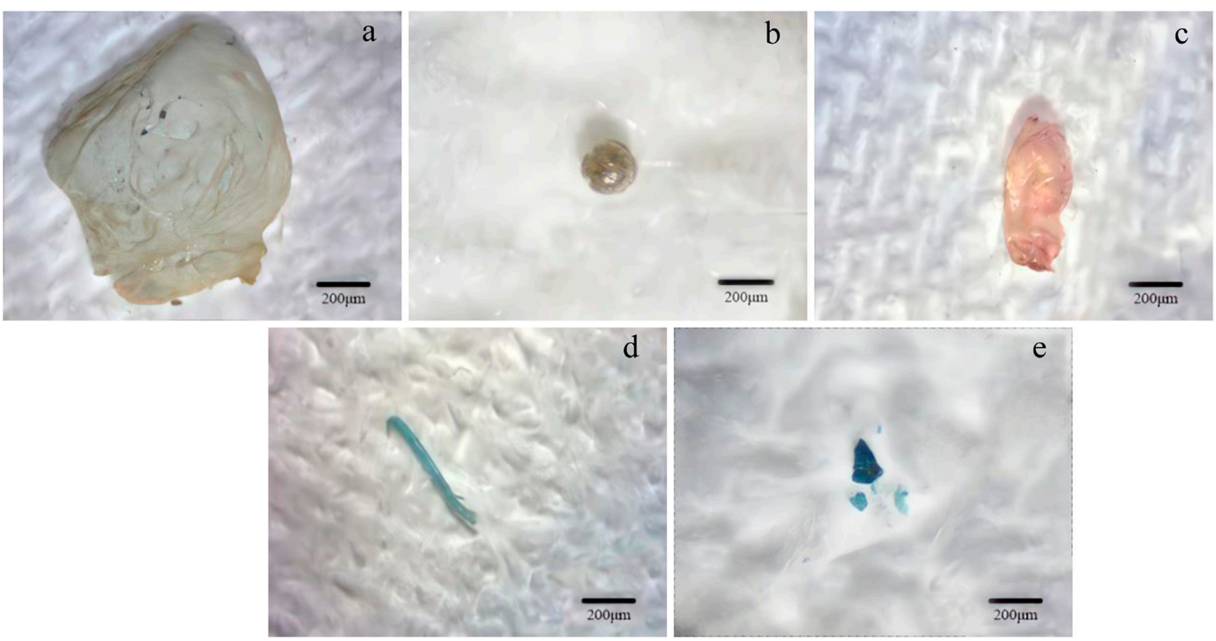

FIGURE 4 | Types of microplastics [**(A)**: white foam, **(B)**: transparent pellet, **(C)**: red film, **(D)**: blue fiber, **(E)**: blue fragment].

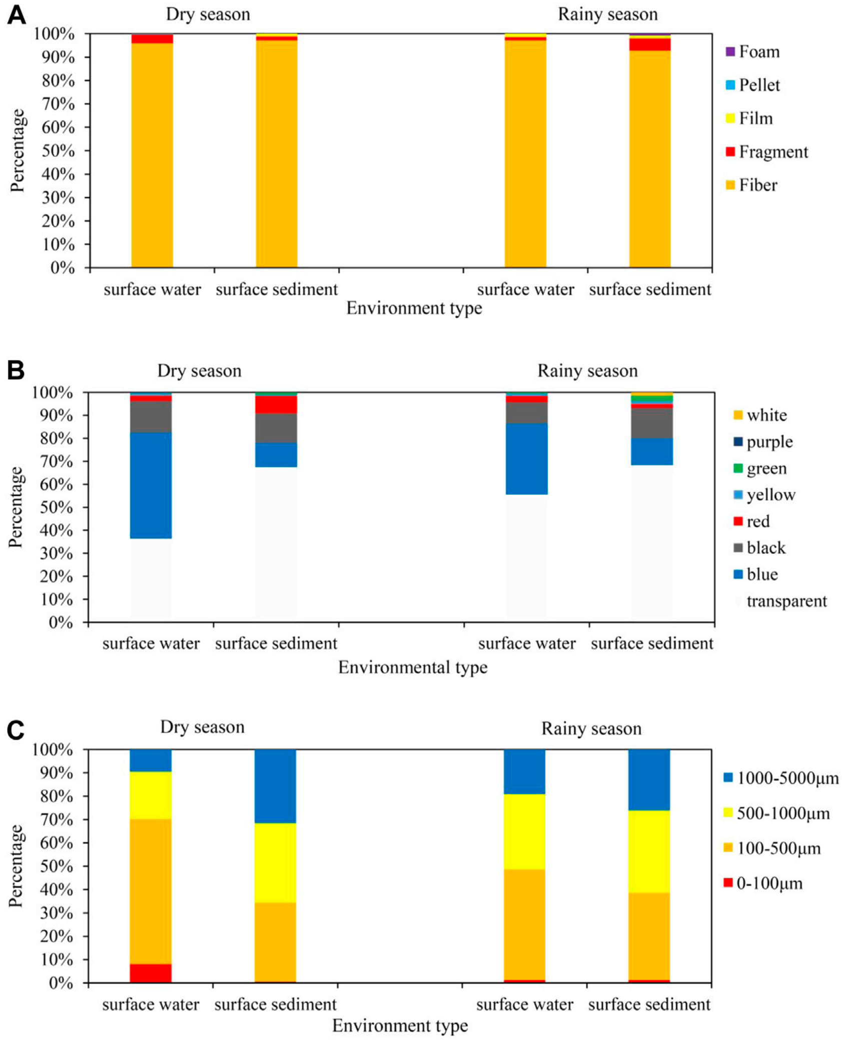

FIGURE 5 | Relative proportion of different shapes **(A)**, colors **(B)**, and sizes **(C)** of microplastics collected from the surface water and surface sediment in the rainy and dry seasons.

between the microplastic abundance in surface water and sediment at the same site (Pearson test, $p > .05$; **Table 1**).

3.2 Characterization of Microplastics in the Surface Water and Sediment

In this study, five microplastic shapes were identified: foam, pellet, film, fiber, and fragment (**Figure 4**). The dominant shape in all of the collected samples was fibers (95.7%), followed by fragments (3.0%), films (1.0%), foams (.2%), and pellets (.1%; **Figure 5**). Moreover, the proportion of microplastic shapes only varied in different environmental media. That is, in surface water and surface sediment, fibers (96.5%, 95.0%, respectively) and fragments (2.7%, 3.5%, respectively) were the dominant shapes.

As shown in **Figure 5**, transparent microplastics accounted for the largest proportion of all microplastics (57.0%), followed by blue (24.7%), black (12.2%), red (3.7%), green (1.0%), yellow (.8%), white (.4%), and purple (.2%). Specifically, within the rainy season, transparent microplastics accounted for 55.6% of the total, while in the dry season, there was a higher proportion of blue microplastics (46.1%), followed by transparent microplastics (36.4%). During the rainy and dry seasons, within sediment samples, transparent microplastics predominated (68.4% and 67.5%, respectively), followed by black (13.2% and 12.8%, respectively) and blue (11.6% and 10.6%, respectively).

The dominant microplastic size range in all samples was 100–500 μm (45.2%), followed by 500–1,000 μm (30.4%), 1,000–5,000 μm (21.6%), and 0–100 μm (2.8%) ranges (**Figure 5**). However, in surface sediment samples, the proportion of 500–1,000 μm (34.0%) microplastics was higher than that of 100–500 μm (33.8%) during the dry season.

A total of 3,401 particles were collected and considered microplastics. However, considering that performing FT-IR analysis for all samples is time-consuming and expensive (Aliabad et al., 2019), 100 particles were randomly separated and analyzed by micro-FTIR and Raman spectroscopy. The results indicated that 95 of the 100 analyzed particles were microplastics, while the remaining particles could not be identified. The most prominent types of identified microplastics were cellophane (54.4%), polypropylene (28.7%), polyethylene (12.3%), and polystyrene (.1%).

4 DISCUSSION

In this study, Xincun Bay was selected as a typical representative of lagoon bays to analyze the impact of human activities on the microplastic pollution in a bay. Although Xincun Bay is a small bay, it has diverse functional areas, including residential area, aquaculture area, and tourist area.

4.1 Relationship Between Human Activities and Microplastic Abundance

The results of the present study highlight that microplastic abundance in the surface sediments at N1 and N2 stations were significantly higher than those at other sites (384.0 item/kg and 272.0 item/kg, respectively). In contrast, among all stations in the bay, the surface water at stations N1 and N2 had the lowest microplastic abundance (31.0 item/L and 29.0 item/L, respectively).

Stations N1 and N2 are situated at the intersection of the Tanka fishing raft area, the aquaculture area, and Xincun Port, where human activities are intensive. The Tanka fishing raft area has existed in the Xincun Bay for approximately 2,000 years, and Xincun Bay is home to the largest Tanka community, a group known as "sea nomads" for their floating lifestyle (Zhang, 2014). Tanka fishermen not only carry out fishing and aquaculture production on fishing rafts, but also use these rafts as their personal residence (Hou et al., 2015). Therefore, washing effluents in daily life produce significant amounts of microplastics (He et al., 2020). Over time, the plastic gradually decomposes into microplastics and become deposited in surface sediments (Chen Y. et al., 2021). Thus, microplastic abundance in the surface sediment of the Tanka fishing raft area is significantly high.

However, the Tanka fishing raft area is close to the mouth of Xincun Bay, which is only connected to the open waters by this bay mouth (Yang et al., 2016). Due to water exchange at the mouth of the bay, microplastics in the surface water would flow out of the bay along with the currents (Zhao et al., 2021). Although human activities in this region were intensive, microplastic abundance in the surface water of this zone was significantly lower than that in other areas of the bay. In addition, in recent years, life on boats has been unable to meet the modern needs of people's lives (Huang, 2019), therefore, an increasing number of fishermen are opting to live onshore. There were considerably fewer fishermen living on fishing rafts, which has resulted in a decrease in directly discharged microplastics into sea water (Chen, 2011). Furthermore, some local boat owners offered boat tours, which allowed tourists to enjoy the beautiful scenery from the water's surface. The Tanka boats always went back and forth between the fishing raft area and other areas inside Xincun Bay. Bao et al. (2020) reported that microplastics in surface water were scattered along with the direction of ships. This tourist style of Xincun Bay might also be a considerable factor affecting microplastic abundance. Owing to the above three reasons, the microplastic abundance in the surface water of this area was relatively low.

During the rainy and dry seasons, microplastic abundance in the surface sediment at station N7 (120 item/kg and 212 item/kg, respectively) was significantly lower than that of other stations. However, during both the rainy and dry seasons, station N7 had the highest microplastic abundance in surface water (48 item/L and 185 item/L, respectively). Station N7 is close to the national mangrove wetland protection area in the bay, where human activity is limited by the government. Consequently, this area lacked a direct source of microplastics. As shown in **Figure 2**, station N7 is in the southeast of Xincun Bay, where water exchange ability is markedly lower than that in other stations at the mouth of the bay (Liu et al., 2020). The south of Xincun Bay is surrounded by the Nanwan Peninsula, which effectively reduces the amount of wind reaching the southeast region of Xincun Bay, resulting in relatively calm surface water (Liu et al., 2020). The microplastics produced in other areas could easily stay in the surface water after entering this area. Accordingly, even though there were relatively few human activities at station N7, the microplastics in the surface water were extremely high.

Additionally, no correlation was observed between microplastic abundance in surface water and surface sediments at the same site in both dry and rainy seasons. The sedimentation of microplastics is a long-term process affected by water flow, weather, and the microplastic shape (Long et al., 2015). Thus, only long-term and intensive human activities might cause microplastics to accumulate in sediments (Alam et al., 2019). Furthermore, the characteristics of microplastics in sediments were more stable than flowing water, with slower transportation speeds, resulting in a higher abundance of microplastics in sediments (Irfan et al., 2020). Therefore, human activities had a greater impact on the microplastic abundance in sediments than on the microplastic abundance in surface water.

4.2 Relationship Between Seasonal Characteristics and Microplastic Abundance

The abundance of microplastics in surface water and sediment samples was higher during the dry season (72.6 ± 23.7 item/L and 240.6 ± 94.5 item/kg, respectively) than the rainy season (60.9 ± 21.5 item/L; 197.1 ± 79.0 item/kg). The seasonal variation patterns of the abundance of microplastics in this bay were considerably different from other bays. In most bays, such as Jiaozhou Bay in China (Zheng et al., 2019), Tokyo Bay in Japan (Wang Y. et al., 2021), Tampa Bay (Mexico) (McEachern et al., 2019), and Guanabara Bay, Brazil (Castro et al., 2020), microplastic abundance during the rainy season was higher than that in the dry season. This could be due to accumulation of microplastics in surface water and surface sediments during the dry season, followed by resuspension in

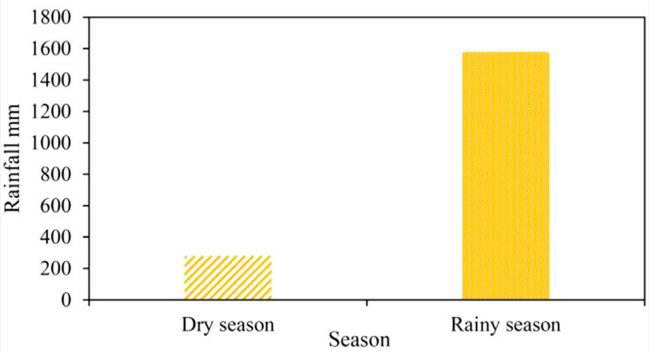

FIGURE 6 | Rainfall during the dry and rainy seasons in Xincun Bay. Rainy season was from May to October in 2020, and dry season was from November in 2020 to April of the following year (data from http://www.hainanqx.cn/UI/Index/Index.aspx).

the rainy season with increased rainfall, and migration to the deep sea with the water current.

Furthermore, during the rainy season, the average microplastic abundance in the inner surface water and surface sediments of Xincun Bay were both significantly lower than that in the outer surface water and surface sediments of the bay. Many typhoons and concentrated rainfall invaded Xincun Bay during the rainy season (**Figure 6**). According to Reisser et al. (2015), strong winds and waves cause the resuspension of microplastics in surface sediments. Moreover, the prevailing winds in Xincun Bay during the rainy season were predominantly in a northeast direction. Xincun Bay has only one bay mouth connected to open waters, which is south-oriented. The southward swells account for 53.8% of the annual swell (Gong et al., 2008). In addition, concentrated rainfall and strong winds during the rainy season cause heavy erosion of the aquaculture facilities in the Tanka fishing raft area. According to a current study, net ropes would break down, and plastic fibers would decompose under erosion into microplastics of smaller sizes (Zhang et al., 2021). Therefore, microplastics in the surface water in the Tanka fishing raft area could flow outside the bay with the southward swells. These combined conditions result in a lower average microplastic abundance inside the bay than outside.

Nevertheless, in the dry season, typhoon activity and precipitation were relatively reduced, resulting in a relatively quiet bay (**Figure 6**). Moreover, since the mouth of the bay faces southwest and the prevailing wind blows southwest, microplastics in surface water could flow more easily into the inner bay (Liu et al., 2020). In this condition, microplastics in Xincun Bay tended to be enriched in the surface water of the inner bay. Therefore, during the dry season, the average microplastic abundance in the surface water inside the bay was higher than that outside the bay. In addition, the calm environment in the bay also made for the settlement of surface water microplastics in the lagoon bay. Moreover, previous study showed that surface sediments represented the final destination of the microplastics in surface water (Chen et al., 2022). Therefore, in the dry season, the abundance of microplastics in the surface sediments of the inner bay was also significantly higher than that outside the bay.

Additionally, compared with other stations outside the Xincun Bay, station W1 was most close to the mouth of Xincun Bay. The above reasons also made station W1 had the highest abundance of microplastics in surface water (128 item/L; 87 item/L) and surface sediments (420 item/kg; 208 item/kg) of all stations outside the bay, whether in the rainy season or in the dry season. Moreover, W1 station was on a necessary route for fishing boats to enter and leave Xincun Port. Nuelle et al. (2014) found that fishing boats discharged waste water containing plastic particles during transport. Therefore, it was reasonable that the number of microplastics at stations on this route was higher than at other outside stations. However, comparing the position of station W1, station W5 was the furthest one from the bay's inlet among all stations located outside the bay. Human activities in Xincun Bay had rarely direct effects on the abundance of microplastics at station W5, as there were no direct sources of microplastics near the sampling site. Furthermore, Onink et al. (2019) found that the microplastic abundance and distribution in open sea areas were mainly affected by ocean currents and monsoons. Under complex ocean currents, microplastics flowing through the W5 station would migrate to all parts of the open sea. Therefore, whether in rainy or dry season, this station had the least microplastic abundance in surface water and sediments among all the sampling stations outside the bay.

4.3 Comparison of Microplastic Abundance in Xincun Bay and Other Areas

Microplastic abundance in the surface water of Xincun Bay during the rainy and dry seasons was 34300 ± 12900 item/m^3 and 81600 ± 27400 item/m^3, respectively. The microplastic concentrations were markedly higher than those found in most ocean systems, such as Tokyo Bay (Japan) (Wang Y. et al., 2021), South China Sea (He, 2018), Jinzhou Bay (China) (Qu et al., 2021), Jiaozhou Bay (China) (Zheng et al., 2019), East China Sea (Liu et al., 2018), and Tianjin Coast (Bai et al., 2020) (**Table 2**). Microplastic abundance observed in this study was also markedly higher than the average abundance in the surface water in China (0.3–545.0 item/m^3) (Zhu et al., 2018).

Microplastic abundance in the surface sediments of Xincun Bay during the rainy and dry seasons was 167.6 ± 71.7 item/kg and 288.4 ± 96.8 item/kg, respectively. The average microplastic abundance in the surface sediments was lower than that of other bays, such as Kendari Bay (Indonesia) (Kozak et al., 2021), Sanya Bay (China), Haikou Bay (China), and Wanning Xiaohai Bay (China) (Huang, 2020b) (**Table 2**).

However, compared with microplastics in the sediments, microplastics in the surface water are readily influenced by external conditions, including strong winds, rainfall, and ocean waves (Wang et al., 2021d). Indeed, considering that surface waters are not the final destination for buoyant plastic debris in the ocean, the associated microplastic abundance does not accurately reflect the degree of microplastic pollution in the area (Morét-Ferguson et al., 2010; Cozar et al., 2014). Moreover, in our comparison of microplastic abundances in areas with intensive human activities and non-human activity areas, microplastic abundance was low in surface water within

TABLE 2 | Microplastic abundances observed in the bays around the world.

Project	Study area	Abundance	References
Surface water	Jinzhou Bay	.93 ± .59 item/m^3	Qu et al. (2021)
	Jiaozhou Bay	.2 ± .1 item/m^3	Zheng et al. (2019)
	Tianjin Coast	210–1,170 item/m^3	Bai et al. (2020)
	East China Sea	.011–2.198 item/m^3	Liu et al. (2018)
	South China Sea	2,569 ± 1770 item/m^3	He (2018)
	Zhoushan Coast	163.42 item/m^3	Wang et al. (2019)
	Monterey Bay	1.32 ± .70 item/m^3	Kashiwabara et al. (2021)
	Tokyo Bay	3.98 item/m^3	Wang et al. (2021c)
	Gulf of Mexico	1.05 item/m^3	Sulistiowati et al. (2021)
Surface sediments	Haikou Bay	7,934 item/kg	Qi (2020)
	Sanya Bay	6,872 item/kg	Huang et al. (2020c)
	Wanning Xiaohai	8,714 item/kg	Zhang et al. (2020a)
	Haizhou Bay	330 ± 260 item/kg	Li et al. (2020)
	Kendari Bay	426.82–424.92 item/kg	Kozak et al. (2021)

areas with high human activities, whereas that of surface sediments was significantly higher in these active areas compared to other regions. Therefore, compared to most bays, the microplastic pollution level in the surface sediments of Xincun Bay was relatively low.

Although the pollution degree of microplastics in Xincun Bay was relatively low, it was still necessary to actively carry out the treatment of microplastics, such as banning the use of non-degradable plastics and improving the relevant system of plastic pollution. In addition, it is necessary to raise citizens' awareness of environmental protection and maintain ecological balance.

4.4 Source Analysis of Microplastics in the Environment of Xincun Bay

The color and type of microplastics indicate their origin (Wang et al., 2017). In this study, transparent microplastics constituted the largest fraction of all samples, followed by blue items and black items. Furthermore, in the sampling sites, transparent was the most common color observed in the plastic waste from tourism, such as plastic bottles and disposable transparent lunch boxes. Zhang N. et al. (2020) reported that weathering changes the surface properties and functional groups of plastics, leading to different colored plastics to fade. This might be a reason for the greater number of transparent microplastics. In addition, the blue and black microplastics were presumably derived from aquaculture ropes, fishing nets, and woven bags in the bay, as field observations confirmed that there were black and green aquaculture ropes and blue plastic woven bags in our sampling sites.

Of all the microplastics identified in this study, fiber microplastics were the most dominant type, which is in agreement with the previous reports of microplastics in other marine environments, such as Zhanjiang Bay (Yao et al., 2021), Sishili Bay (Zhang et al., 2019), and Macajalar Bay (Esquinas et al., 2020). According to field sampling, the fiber microplastics in this study might have been derived from laundry wastewater in the Tanka fishing raft area, plastic equipment in the aquaculture area, and plastic waste in tourist areas.

Microplastic components found in this study primarily included cellophane, polypropylene (PP), polyethylene (PE), and polystyrene (PS). Overall, the abundance of microplastic composition observed in all environmental media (surface water or surface sediment) in our study area was cellophane (54.4%) > PP (28.7%) > PE (12.3%) >PS (0.1%). Notably, no polystyrene was observed in samples from surface water. Cellophane is a transparent, non-toxic, and tasteless plastic that is often used to make food packaging bags. Xincun Bay is a tourist attraction, as a result of which it had a lot of discarded packaging bags, which might be the main source of cellophane. Some studies have reported cellophane as the most common polymer type both in surface water and sediments (Wu et al., 2020). In our study, a relatively high abundance of polypropylene (PP; 28.7%) and polyethylene (PE; 12.3%) was detected. Since nowadays PP and PE were the most abundant applied plastics in urban, industry food packaging, and agriculture (Bagheri et al., 2020). Therefore, this result is reasonable. In this study, polyethylene (PE) and polypropylene (PP) in Xincun Bay originate from bottle caps, woven bags, packing bags, drink bottles, and fishing nets (Feng et al., 2021).

The Tanka fishing raft area, aquaculture area, tourist area, and residential area are all potential sources of microplastic pollution in Xincun Bay. In these areas, domestic wastewater, plastic waste, discarded net ropes, and plastic mariculture facilities produce a notable amount of microplastics, which together cause microplastic pollution in Xincun Bay.

5 CONCLUSION

This was the first to investigate the distribution and sources of microplastics in surface water and sediments in the Xincun Lagoon Bay of China. Diverse functional areas, intensive human activities, and notable seasonal characteristics all made Xincun Bay a representative lagoon bay to analyze the relationship between microplastic pollution and human activities in a lagoon bay. The results of the current research showed that human activities would not directly reflect the degree of microplastic pollution in a lagoon bay. Geographical and seasonal characteristics also affect microplastic distribution and abundance. The major constituent of microplastics was cellophane, and it was mainly found in the form of transparent fibers, suggesting that the microplastics in the study area mainly originated from aquaculture, tourism, and daily life. Our results could provide basic information for studies on environmental microplastics and support the government in formulating the plastic management systems.

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.

AUTHOR CONTRIBUTIONS

YW contributed in field work, data analysis and writing. WM, CS, and XW also contributed in investigation work. QX provide funding support. FG contributed in writing–review and editing work. All authors contributed to the article and approved the submitted version.

FUNDING

This work was supported by the National Key Research and Development Program of China (Project code: 2019YFD0901304) and the National Natural Science Foundation of China (Project code: 42076097, 42166007).

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Conflict of Interest: The 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.