Environ Monit Assess (2023) 195:383
https://doi.org/10.1007/s10661-023-10994-4

Assessment on the pollution level and risk of microplastics on bathing beaches: a case study of Liandao, China

Xiaowei Wu · Chongqing Zhong · Teng Wang · Xinqing Zou

Received: 20 June 2022 / Accepted: 28 January 2023 / Published online: 10 February 2023

Abstract Microplastic pollution on bathing beaches threatens the health of human beings and coastal organisms. There is a lack of assessment on the level of microplastic pollution and the health risk associated with plastics. As one of the earliest open bathing beaches in China, Liandao is well known as the two high-quality beaches. However, little is known about the extent of microplastic pollution on these bathing beaches. Based on the analysis of microplastic pollution abundance, distribution, shape, size, color, and composition at the Liandao bathing beaches, this study puts forward a novel approach to comprehensively evaluate the microplastic pollution level and risk level by using the Nemerow pollution index (NPI) and polymer hazard index (PHI). The results show that the average abundance of microplastics on the Liandao bathing beaches is 135.42 ± 49.58 items/kg; the main shapes are fibers, fragments, and granules. Most of the microplastics are transparent, brown, and black, accounting for 71.54%, and they have an average particle size of 0.63 ± 0.43 mm. The main components are PE, PP, PS, PET, and nylon, of which nylon appears in the highest proportion (54.77%). The microplastic NPI and PHI values are 0.38 and 74.81, respectively, indicating that the pollution level and health risk index of microplastics on the Liandao bathing beaches are both low. With the increase in population and per capita consumption, plastic waste generated on land will continue to increase. Finally, this study puts forward some suggestions regarding microplastic monitoring, plastic waste management, and environmental attitudes and behavior.

Keywords Bathing beach · Beach microplastic · Microplastic pollution · Microplastic risk · Beach management

X. Wu
School of History, Culture and Tourism, Huaiyin Normal University, Huaian 223300, China

C. Zhong
School of Urban and Environmental Sciences, Huaiyin Normal University, Huaian 223300, China

C. Zhong · X. Zou (✉)
School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing 210093, China
e-mail: zouxq@nju.edu.cn

T. Wang
College of Oceanography, Hohai University, Nanjing 210093, China

Introduction

In recent years, microplastics with particle sizes less than 5 mm have attracted great attention in the study of beach ecological risk. In 2004, Thompson first proposed the term "microplastic," which is now recognized as "PM2.5 in the ocean." As a new type of pollutant, microplastics have become one of the most important environmental problems in the world (Karthik et al., 2018; LaShanda et al., 2021; Qiu et al., 2015; Thompson et al., 2009; Wang et al., 2019). Bathing beaches refer to natural beaches and their adjacent seawater environment that have perfect infrastructure and operation management systems and can support swimming, sunbathing, and other activities (HY/T0276-2019). They have already become necessary places for people to go for coastal tourism, attracting an increasing number of tourists all over the world and causing more beach plastic consumption and garbage generation (Defeo et al., 2021). In previous studies, a large number of microplastics have been detected on many beaches around the world, and bathing beaches generally face the threat of microplastic pollution (Stolte et al., 2015; de Carvalho et al., 2016; Lozoya et al., 2016; Karthik et al., 2018; Bissen & Chawchai 2020; Wu et al., 2021). Some of the plastic garbage brought by recreational activities to the beach amounts to as much as 90% of the total amount of beach garbage (Sarafraz et al., 2016). Plastic products such as food packaging and entertainment products consumed by people during recreational activities are discarded and further decomposed into finer particles through physical and chemical weathering (Rocha-Santos & Duarte, 2014; Thompson et al., 2004). The strong ultraviolet radiation, wave physical wear, air oxidation, and turbulence on beaches exacerbate the splitting and degradation process, and beaches have become one of the main places for the production of microplastics (Barnes et al., 2009; Cole et al., 2011). These microplastic particles are very small and are very easily ingested by beach benthos or coastal organisms.

Horn et al. (2019) collected Pacific mole crabs at 38 California beaches and found that crabs at every beach had ingested microplastics. Once ingested, these microplastic particles will remain in organisms, sometimes directly blocking their digestive tracts and causing physical damage (Browne et al., 2010). In addition, due to their small size, these microplastic particles easily carry organic pollutants (Goldstein & Goodwin, 2013; Kaposi et al., 2014; Horn et al., 2019; Shi et al., 2020) and a large number of heavy metal contamination, trace elements (Brennecke et al., 2016; Isabel et al., 2019; Martins et al., 2020) that have potential toxic effects on some marine biological communities and humans. When people are relaxing on beaches, if the content of microplastics in beach sediment is high, the pollutants and trace elements carried by which may make people face greater risks to their health, including the more consumption of seafood (Vethaak & Leslie, 2016). Plastic particles have been found in human blood (Leslie et al., 2022) and feces (Gonzales, 2018). The study of microplastics on bathing beaches is of great significance to the health of tourists and beach ecological management.

At present, research on microplastics on bathing beaches is still in the basic stage, and most countries are in the period of baseline data accumulation. Research on microplastics on recreational beaches is extremely limited (Piehl et al., 2019; Yabanli et al., 2019; Bissen & Chawchai, 2020; Wu et al., 2021). Studies have focused mainly on the basic characteristics of beach microplastics, such as abundance, distribution, shape, size, and composition (Lots et al., 2017; Piehl et al., 2019; Pinheiro et al., 2019; Yabanli et al., 2019; Bissen & Chawchai, 2020; Pérez-Alvelo et al., 2021; Rey et al., 2021); influencing factors of microplastic pollution (Herrera et al., 2018; Isabel et al., 2019; Pinheiro et al., 2019; Tziourrou et al., 2019; Vidyasakar et al., 2018); and sources of microplastic pollution (Hengstmann et al., 2018; Herrera et al., 2018; Vidyasakar et al., 2018; Yabanli et al., 2019; Pérez-Alvelo et al., 2021). The density flotation method is often used for the extraction of microplastics (Hengstmann et al., 2018; Piñón-Colin et al., 2018), and ATR-FLIR spectrometry, Raman spectrometry, and the HIS-NIP method are usually used for the identification of microplastics (Esiukova et al., 2021; Lots et al., 2017; Piehl et al., 2019; Tsukada et al., 2021; Tziourrou et al., 2019). A few studies have also focused on the organic pollutants carried by microplastics (Shi et al., 2020), trace elements (Isabel et al., 2019), and microplastic hazards (Horn et al., 2019). A few studies have examined the level and risk assessment of microplastic pollution on bathing beaches. However, only Rangel-Bitrago et al. (2021) tried to build a microplastic pollution index model to study microplastic pollution on Colombian beaches. With the continuous deepening of microplastic pollution research, microplastic pollution levels and risk assessment will be an important concern.

Based on the analysis of the abundance, distribution, shape, size, color, and composition of microplastic pollution on bathing beaches, this study intends to comprehensively evaluate the pollution level and risk level of microplastics by using the advantages of the Nemerow pollution index (NPI) and polymer hazard index (PHI) for the first time. This is a novel approach to assess microplastic pollution at beaches. The results provide useful guidance for beach microplastic management. Liandao, located in China's economically developed Jiangsu Province, has two high-quality beaches, Sumawan and Dashawan, which rank among the first 28 bathing beaches opened in China (there is a total of 32 at present). It is a well-known scenic spot along the coast of central China. The main interference from human activities is beach recreation. In addition, its coastline is stable, so it is a good research area for studying the microplastic pollution of bathing beaches. The research results can reflect the general characteristics of bathing beaches in central China. We took the Liandao bathing beaches as the study area because they have good representativeness. They could provide some reference for the pollution level and risk assessment of microplastics on other bathing beaches and furthermore provide travel safety guidance and advocation of free-plastic-travel for beach recreation lovers.

Materials and methods

Study area

This study was carried out at the Liandao bathing beaches (119° 27′ E, 34° 46′ N), located in Lianyungang in northern Jiangsu Province, which is one of the most developed coastal provinces with the densest coastal population in China and one of six world-class urban agglomerations in the world. In 2018, this province had a population of 80.507 million, and the GDP reached RMB9259.54 billion (recreation and tourism contributed more than 10%, ranking first in the country). Lianyungang was one of the first 14 open coastal cities in China (opened to the world in 1981) and has an excellent tourism industry.

Liandao has two high-quality beaches, Dashawan (119° 27′ 56″ E, 34° 46′ 25.84″ N) and Sumawan (119° 29′ 6″ E, 34° 46′ 7.7″ N) (see Fig. 1). These two beaches were developed in the bedrock section. Dashawan beach, also known as Housha beach, covers an area of 21.75 hm^2, with a maximum width of approximately 300 m above the low tide level. The beach area of Sumawan is 7.69 hm^2, and the maximum width above the low tide level is approximately 200 m. The peak tourist season is from June to October. The Liandao bathing beaches are the most suitable sandy beach for recreation and tourism in this region. Furthermore, they have unique ecological value. They lie in the fringe where the sand

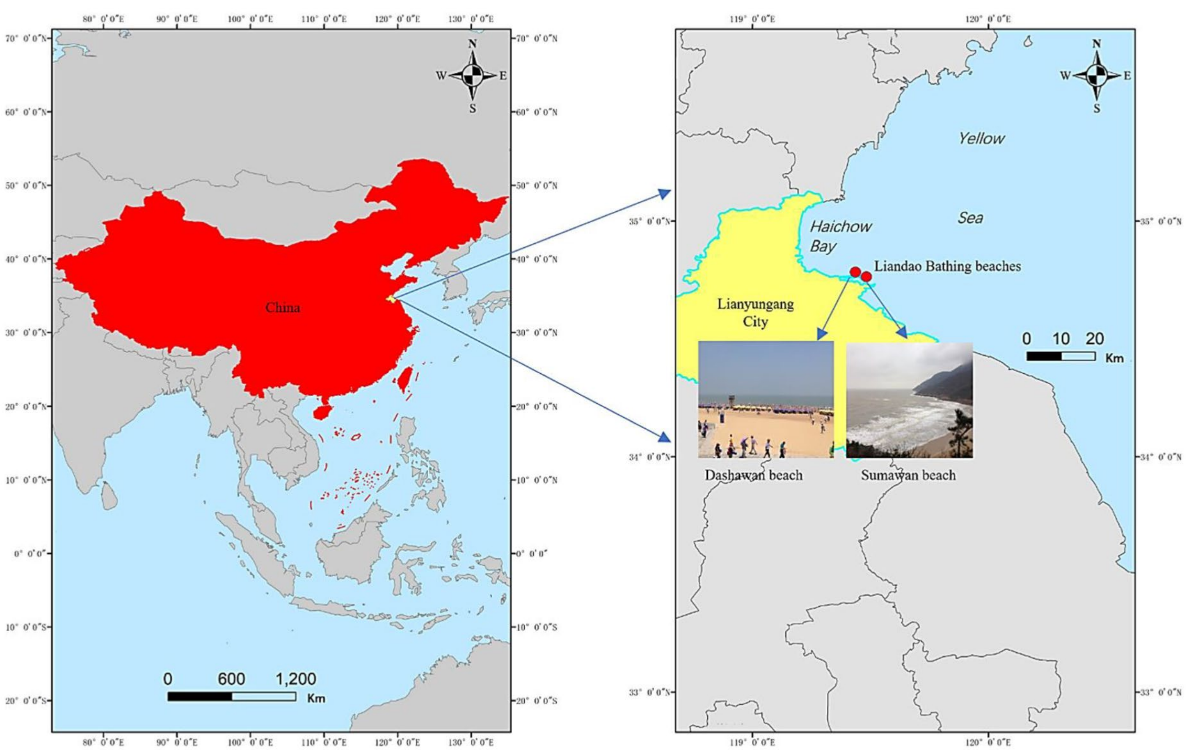


Fig. 1 Location of Liaodao bathing beaches

composition transitions from a sandy beach to muddy silt in the coastal area of the Yellow Sea. This coastal area has a warm temperate climate with a mean annual temperature of 14.8 °C, mean annual precipitation of 911.3 mm, annual average relative humidity of 69.8%, and prevailing winds from the southeast in summer and the northeast in winter. The Liandao bathing beaches are high-quality beaches that receive an abundance of tourists every year, especially during July and August. The daily tourist volume in August exceeded 20,000 before COVID-19 in 2020. Recreational activities include walking, camping, sunbathing, sand bathing, and collecting beach fauna (Fig. 2).

Methods

Microplastic sampling

Microplastic sampling was carried out from November 9 to 10, 2018. The microplastic sampling method of Claessens et al. (2011) was followed. Two sample transects with a width of 5 m perpendicular to the coastline (5 m along the coastline) were selected for each beach (Sumawan and Dashawan). The interval between the two transects was 100 m. One 50×50 cm^2 quadrat was selected at the high tide line, medium tide line, and low tideline of each transect.

In each quadrat, a metal frame of 50×50 cm (a surface area of 2500 cm^2) was pushed into the sediment, and the upper 5 cm sediment layer was collected from the frame with a stainless-steel spoon; approximately 3 kg of sand was collected and stored in an aluminum foil bag. Meanwhile, small plastic debris near the sampling area was also collected into another aluminum foil bag, which could be used as a reference when analyzing the composition and source of microplastics. At the same time, to measure the grain size, sediment samples were collected in each quadrat with a 3.5-cm diameter steel pipe buried 30 cm deep, placed in a bag with a label, and then brought back to the laboratory.

Laboratory analysis

1. Microplastic extraction

To avoid environmental pollution, the following preventive measures were taken in the extraction process: all materials and containers used for the first time were thoroughly cleaned and covered with aluminum foil immediately after cleaning. The researchers always wore laboratory work clothes during the analysis. After each experimental operation, all materials and containers were covered with aluminum foil. Before opening the petri dish storing microplastics to analyze and identify the samples, the workplace was thoroughly cleaned for stereomicroscope analysis (Nuelle et al., 2014).

The microplastic extraction methods of Nuelle et al. (2014) and Wang et al. (2016) were followed with some modifications. First, 200 g of dry sample from each sample was added to saturated sodium chloride solution (1.21 g/ml) fully stirred with a glass rod and allowed to stand for at least 24 hours. 1.2g/ml NaCl solution was mostly recommended (Andrady, 2011; Pinheiro et al., 2019; Bissen & Chawchai, 2020; Perez-Alvelo et al., 2021; Rangel-Buitrago et al., 2021), which was higher than the density of common plastic polymers such as polypropylene (PP: 0.9–0.91 g/ ml), polyethylene (PE:

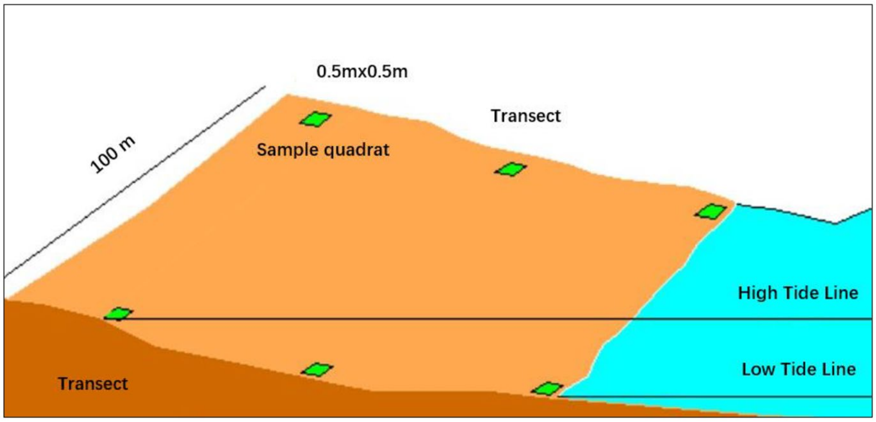


Fig. 2 Schematic representation of the sampling design with the transects and quadrats

0.917–0.965 g/ ml) and polystyrene (PS: 1.04–1.1 g/ ml). Then, the suspension overlying the sediment was removed by the siphon method. To fully extract the microplastics in the sample, the above flotation steps were repeated three times. Finally, the sample was vacuum filtered through filter paper (50 mm, pore diameter 1.0 μm. Shanghai Xinya Company, China), and filter paper was placed in the petri dishes. After natural drying, the microplastics were preliminarily identified and counted under a microscope with a magnification of up to 80 times. In order to test the extraction effect, 10 PE and 10 PP particles with a size of about 1mm were doped into 200g clean sediment. After the same extraction procedure, it was repeated three times with an average recovery of 93.33%, which proved that the above test was feasible. Preparation of the saline solution and the extraction of microplastics have been done at the Ministry of Education Key Laboratory for Coast and Island Development, Nanjing University, following Geochemistry Laboratory standards.

2. Microplastic identification

To identify microplastics, representative plastic-like particles were selected, and all were verified by μ-FTIR infrared spectrometry (μ-FTIR Thermo Nicolet IS 50) in the Laboratory of Jiangsu Police Institute. The obtained spectra were compared with the EZ OMNIC polymer spectra library to identify the polymer types of the microplastics. Only those spectra which matched over 90% with the standard database were acceptable, indicating that the verification of microplastics was reliable.

Microplastic pollution level evaluation: NPI

The NPI is widely used in pollution level assessment and to compare regional pollution differences. In this study, the NPI was used to determine the beach microplastic pollution level in the study area. Based on the abundance and composition of microplastics investigated, the calculation is shown in formula (1):

$$NPI = \sqrt{\frac{\frac{Q_i}{S_{i\ max}}^2 + \frac{Q_i}{S_{i\ ave}}^2}{2}} \tag{1}$$

where Q_i is the microplastic abundance of samples collected from each beach i; S_i is the reference standard value of microplastic abundance, which is taken from the average value of relevant data on microplastics on bathing beaches in the literature; *max* is the maximum value; and *ave* is the average value. According to the NPI evaluation method, if NPI $\leq$ 2, it indicates that the beach microplastic pollution is slight, and if NPI > 2, it indicates that the beach microplastic pollution is serious.

Microplastic health risk evaluation: PHI

The PHI is used to evaluate the health risks of microplastics (Lithner et al., 2011). The calculation is shown in formula (2):

$$PHI = \sum p_n S_n \tag{2}$$

where p_n is the average percentage of each microplastic polymer in all samples, and S_n is the risk score of each polymer. The risk scores of PP, PET, PE, PS, NY, PVC, and other polymers are 1, 10, 11, 30, 150, and 11,100, respectively. When $p_n \leq 100$, it indicates a low risk of microplastic pollution, and when $p_n > 100$, it indicates a high risk of microplastic pollution.

Data analysis

The statistics and calculation analysis were carried out using Excel (office 2013) and SPSS software (SPSS 2018). The nonparametric Kruskal–Wallis test was used to make multiple comparisons on the abundance of microplastics at high, medium, and low tide levels. If significant differences occurred in the test, the paired nonparametric Mann–Whitney U test was used to determine the differences. The significance level of all statistical analyses was 0.05.

Results

Microplastic characteristics and occurrences on the Liandao bathing beaches

Abundance and distribution of microplastics

In total, 325 microplastic particles ($d < 5$ mm) were detected from the Liandao bathing beach samples, with an average abundance of 135.42 ± 60.58 items/

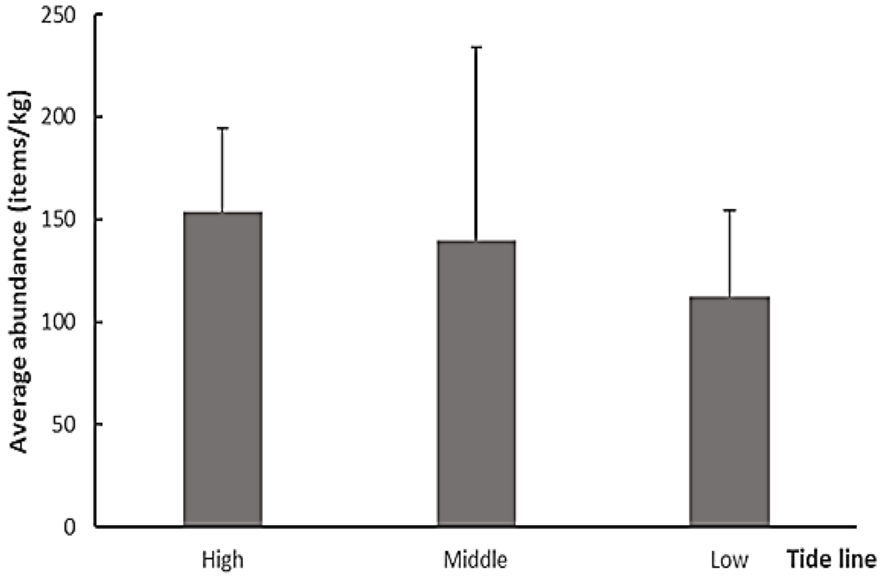


Fig. 3 Microplastic abundance of high, middle, and low tide lines in Liandao bathing beaches

kg (dry weight), of which the maximum abundance appeared at the high tide line (153.75 ± 23.75 items/kg), the minimum abundance appeared at the low tide line (112.50 ± 41.73 items/kg), and the intermediate abundance appeared at the middle tide line (140.00 ± 94.16 items/kg) (Fig. 3).

Microplastic characteristics

In view of previous studies, this study analyzes four aspects of the pollution characteristics of microplastics in the study area: shape, color, size, and composition. Figure 4 shows some microplastics recorded on the Liandao beaches.

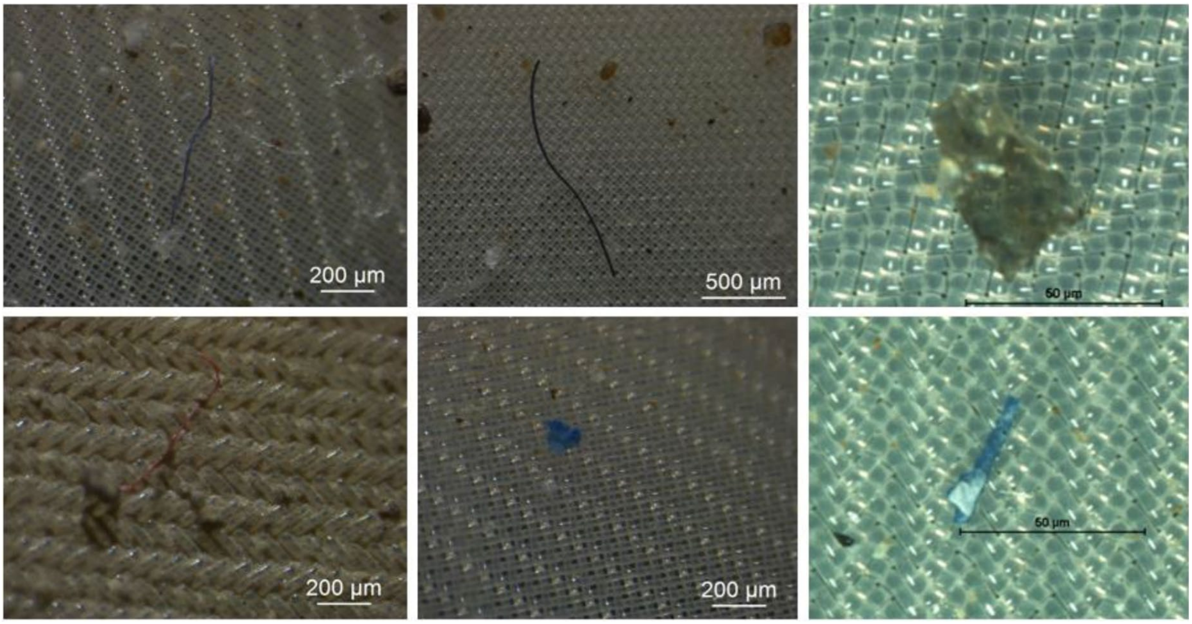


Fig. 4 Some microdebris recorded on the Liandao bathing beaches

1. Microplastic shape

As shown in Fig. 5a, five microplastic shapes were found on the Liandao bathing beaches: fiber, fragment, granule, foam, and film. Most of them are fibers, accounting for 54.46%, with an average abundance of 73.75 ± 11.25 items/kg, followed by fragments (25.23%, mean abundance of 34.17 ± 4.17 items/kg), granules (18.77%, mean abundance of 25.42 ± 13.75 items/kg), foam (1.22%, mean abundance of 1.67 ± 0.00 items/kg), and film (0.31%, mean abundance of 0.41 ± 0.41 items/kg).

2. Microplastic colors

As shown in Fig. 5b, eight microplastic colors were found in the sediment of the Liandao bathing beaches: transparent, brown, white, black, red, green, blue, and purple, among which transparent, brown, black, red, and white accounted for 38.77%, 24.31%, 18.46%, 10.15%, and 5.53%, respectively. Small amounts of blue (2.15%), green (0.31%), and purple (0.31%) were also observed in these samples. Colorful microplastics are distributed on the beach, among which brown and red microplastics are most

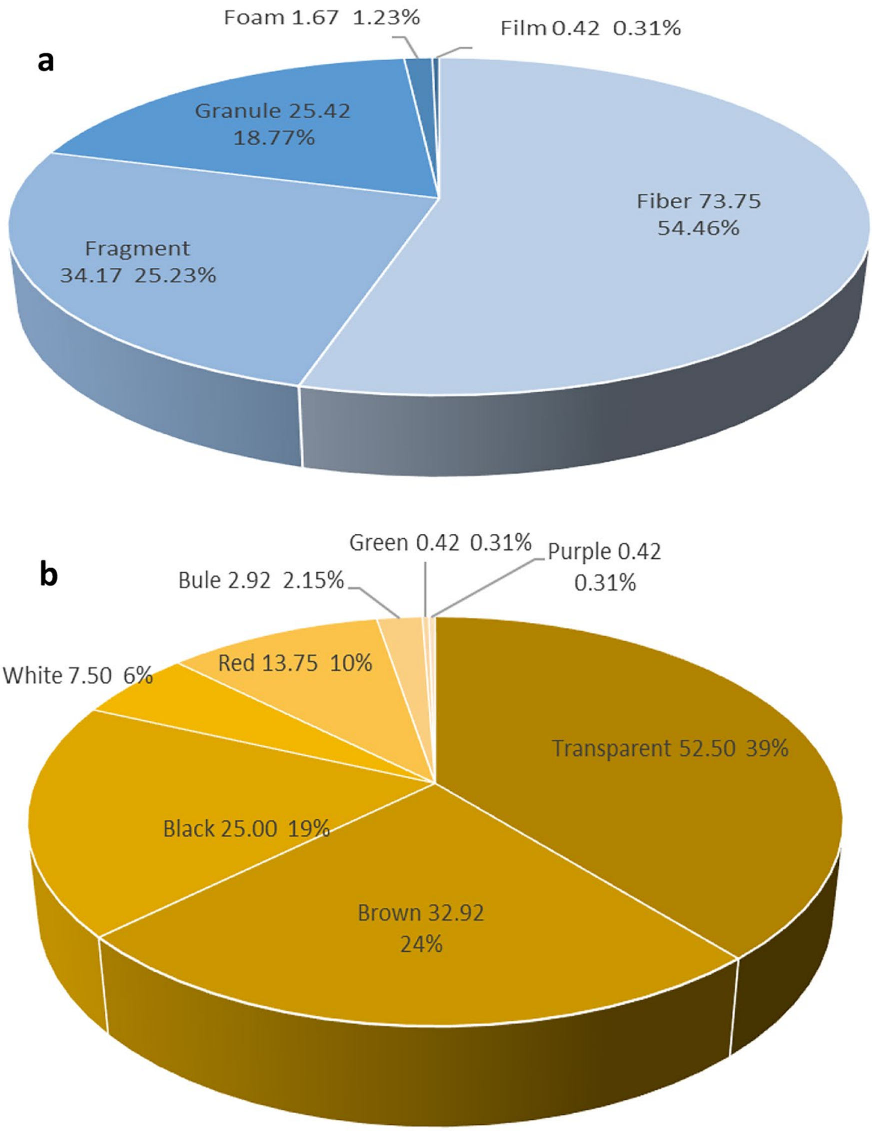


Fig. 5 Pie charts: **a** microplastic shapes of Liandao bathing beaches and **b** microplastic colors of Liandao bathing beaches

widely distributed. The average abundance of brown microplastics is as high as 32.92 ± 13.75 items/kg, followed by red microplastics, with an average abundance of 13.75 ± 2.08 items/kg. A small amount of green and purple microplastics were also found in the survey. These colorful microplastics may come from food and beverage packaging.

3. Microplastic size

As shown in Fig. 6a, the size of microplastics in the study area is distributed between 0.01 and 5 mm, with an average size of 0.63 ± 0.43 mm, with 52% in the range of 0.1–0.5 mm, 24% in the range of 0.5–1.0 mm, 13% in the range of 1.0–5.0 mm, and 11% less than 0.1 mm. In general, the fiber size was the largest (0.86 ± 0.73 mm), followed by foam (0.55 ± 0.44 mm), fragments (0.55 ± 0.22 mm), film (0.4 mm), and granules (0.28 ± 0.14 mm) (see Fig. 6b). The size of microplastic at high tide line is the largest 0.69 ± 0.70 mm, followed by 0.62 ± 0.63 mm at low tide line and 0.57 ± 0.50 mm at middle tide line (see Fig. 6c).

4. Microplastic composition

When the FTIR spectra of each microplastic sample were compared with the standard database, based on the acceptable matching degree higher than 90% (Wu et al., 2021), there were 5 polymers on the Liandao bathing beaches: polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and nylon (PA) (Fig. 7), with nylon accounting for the highest proportion at 54.77%, followed by PP, 19.38%, and PE, 12.5%. Finally, PS accounted for 8.62%, and PET accounted for 4.62%. Most fibers are nylon and PET. Most fragments are made of PP, granules are PP and PE, foams are PS, and films are mainly PE. We also found that flax fiber, cellulose fiber, and calcium carbonate particles are the main interference factors.

Microplastic pollution levels at the Liandao bathing beaches

In this paper, we used the NPI to assess microplastic contamination levels. For the reference value S_i in formula (1), this study is based on collected data about beach microplastics on bathing beaches in the literature and finally takes their average value as 540 items/kg. For the acquisition of data related to beach microplastics on bathing beaches in the literature, this study uses the "ISI Web of Knowledge Platform" of the Nanjing University Library to search for "microplastics" and "beach" as parallel subject words. As of March 10, 2022, a total of 651 articles were displayed, of which 63 were refined again with "bathing beach." After individual analysis, 77 groups of beaches' microplastic abundance data with similar research methods and comparable calculation units were extracted (see Fig. 5 and Appendix, Table 2). After the above process, the S_i was finally determined to be 540, and the NPI of microplastics on the Liandao bathing beaches was then calculated. The results show that the comprehensive NPI of microplastics on the Liandao bathing beaches was 0.38, which indicates light pollution. The NPI values of the two beaches were 0.40 and 0.28, respectively (see Table 1), indicating light pollution levels).

Health risk of microplastics on the Liandao bathing beaches

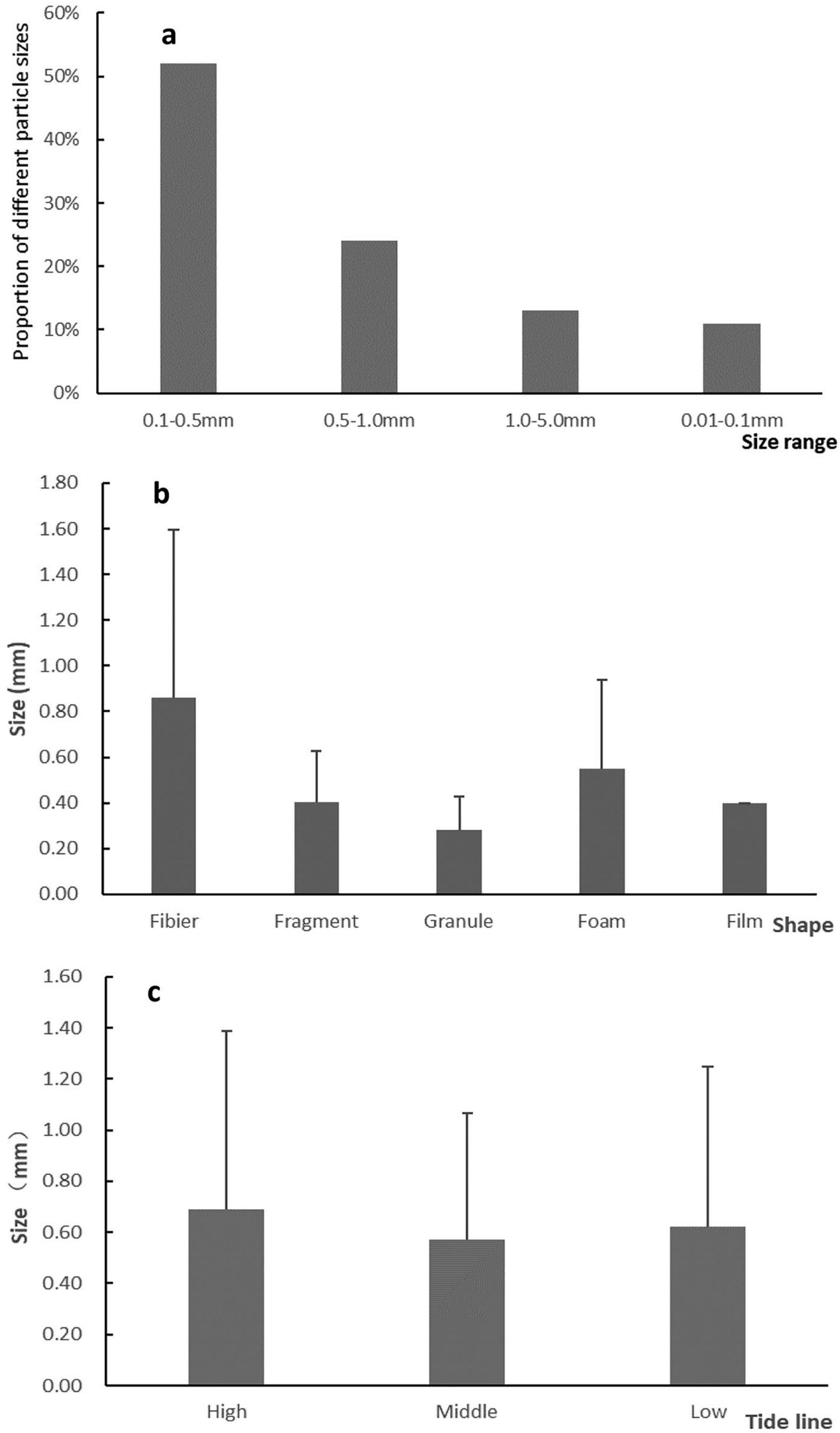
In this study, the PHI was used to evaluate the health risk of microplastics. According to formula (2), the PHI of the Liandao bathing beaches was 74.89, which was lower than the judgment value of 100, indicating a low risk. The PHI values of Dasha Bay and Suma Bay, the two Liandao bathing beaches, were 90.69 and 80.77, respectively (see Table 1), indicating a state of low microplastic risk.

Discussion

Differences in the microplastic characteristics of bathing beaches

The average abundance of microplastics on the Liandao bathing beaches is 135.42 ± 49.58 items/kg, which is significantly higher than that on the rural beach at Haichow Bay (84.17 items/kg) (Wu et al., 2021). Haichow Bay faces the Yellow Sea and is located on the central China coast. It is a typical open coast. The sea dynamic conditions of the bay are stable, as the coastline has changed little in the past 30 years. Therefore, the main external force affecting the beach is human activities. Rural beaches in the same bay are mainly affected by aquaculture and the recreation of a small number of surrounding residents. Before the 2020 COVID-19 outbreak, it was normal for the Liandao bathing beaches to be crowded during

Fig. 6 Microplastic size of Liandao bathing beaches. **a** Proportion of different sizes. **b** Size of different shapes. **c** Size of different tide lines



the peak season, with the instantaneous density of tourists near the low tide line as high as 2~3 people per square meter (Wu et al., 2020). Recreational activities were the direct source of microplastic pollution from land (Vidyasakar et al., 2018; Bissen & Chawchai, 2020; Jeyasanta et al., 2020). At the same

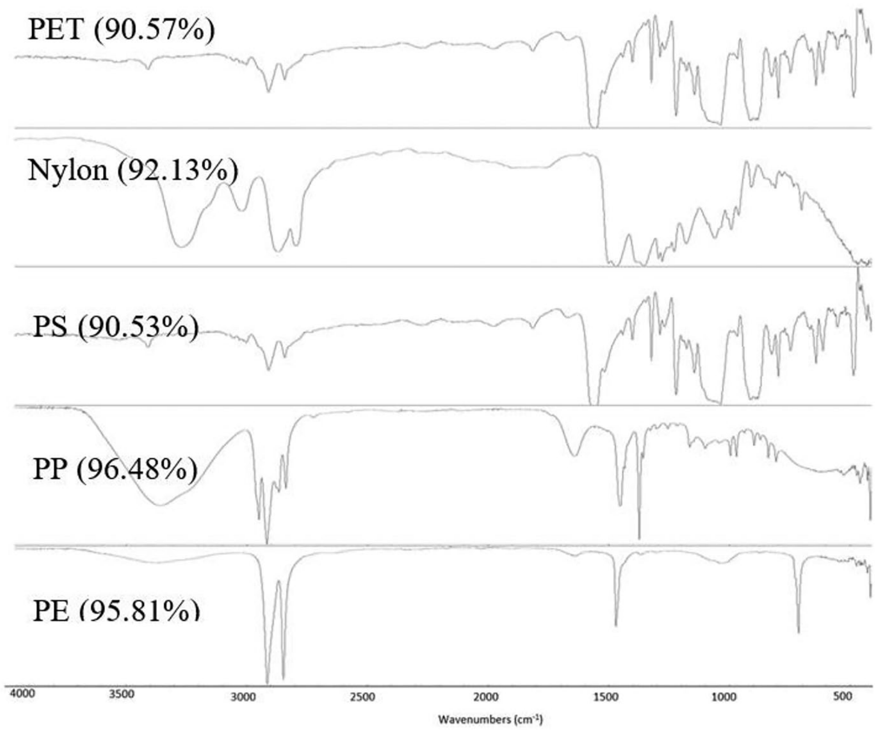


Fig. 7 The FTIR spectrum of microplastics found in Liandao bathing beaches and the match degrees with the standard spectrum

time, the survey found that the domestic sewage of some residents of Liandao is directly discharged into the sea, which may also cause microplastic pollution to a certain extent.

Compared with the medium and low tide lines, the microplastic pollution level on the Liandao bathing beaches at the high tide line is much higher, which may be related to the high energy of the low tide line and the low energy of the high tide line (Karthik et al., 2018; Wu et al., 2021). In addition, the activities of people at the high tide line of the beach are relatively frequent, and the wear and tear of various entertainment service facilities (beach umbrellas, reclining chairs, etc.) and garbage disposal are more likely to cause microplastic pollution. In the microplastic literature, many scholars have sampled at high tide levels, and the results of this study indirectly and effectively prove the effectiveness of this approach (Lozoya et al., 2016; Naji et al., 2017; Piehl et al., 2019; Bissen & Chawchai, 2020; Rey et al., 2021; Pérez-Alvelo et al., 2021).

Table 1 Microplastic NPI and PHI of the Liandao bathing beaches

Beach	NPI	Pollution level	PHI	Risk level
Dashawan	0.40	Light	90.69	Low
Sumawan	0.28	Light	80.77	Low
Liandao	0.38	Light	74.89	Low

In addition, the entrance is closest to the climax line, where many recreational facilities are placed. It is also a place where tourists often eat and drink. Although there are dustbins, special cleaning facilities, and cleaners, there are still management loopholes. For example, it is common for tourists to throw items away at random, and cleaners often do not pick them up in time. Beach cleaning vehicles can collect only large pieces of plastic, while the cleaning effect is not obvious for plastic items smaller than 20 mm or even difficult to identify with the naked eye. A large number of small pieces of plastic were also found in the field investigation. Many research results have shown that the number of small plastics less than 20 mm is significantly correlated with the number of microplastics (Lee et al., 2013; Wu et al., 2021). Therefore, the high-density beach use in the peak season, the domestic sewage of nearby residents, and the generation of and difficulty in cleaning small plastic garbage items can explain why the abundance of microplastics is still higher on bathing beaches than on other types of beaches in the surrounding area, even though they have regular garbage cleaning management.

Microplastic pollution level and risk on the Liandao bathing beaches

To date, there is no widely accepted microplastic measurement standard, so it is difficult to directly compare the microplastic content of the Liandao bathing beaches with the results of other studies. However, the research results can be compared with the results of similar research methods and calculation units. Compared with previous studies in China, the microplastic content on the Liandao bathing beaches is equivalent to that on the beach of northern Bohai Bay. Compared with some foreign beaches, the microplastic content of the Liandao bathing beaches is similar to that of Mexico, Rugen Island (Baltic Sea), and some beaches in Europe, and the pollution level is relatively low (Fig. 8).

The pollution level and health risk index of the microplastics on the Liandao bathing beaches are both low. However, due to economic growth, with the increase in population and per capita consumption,

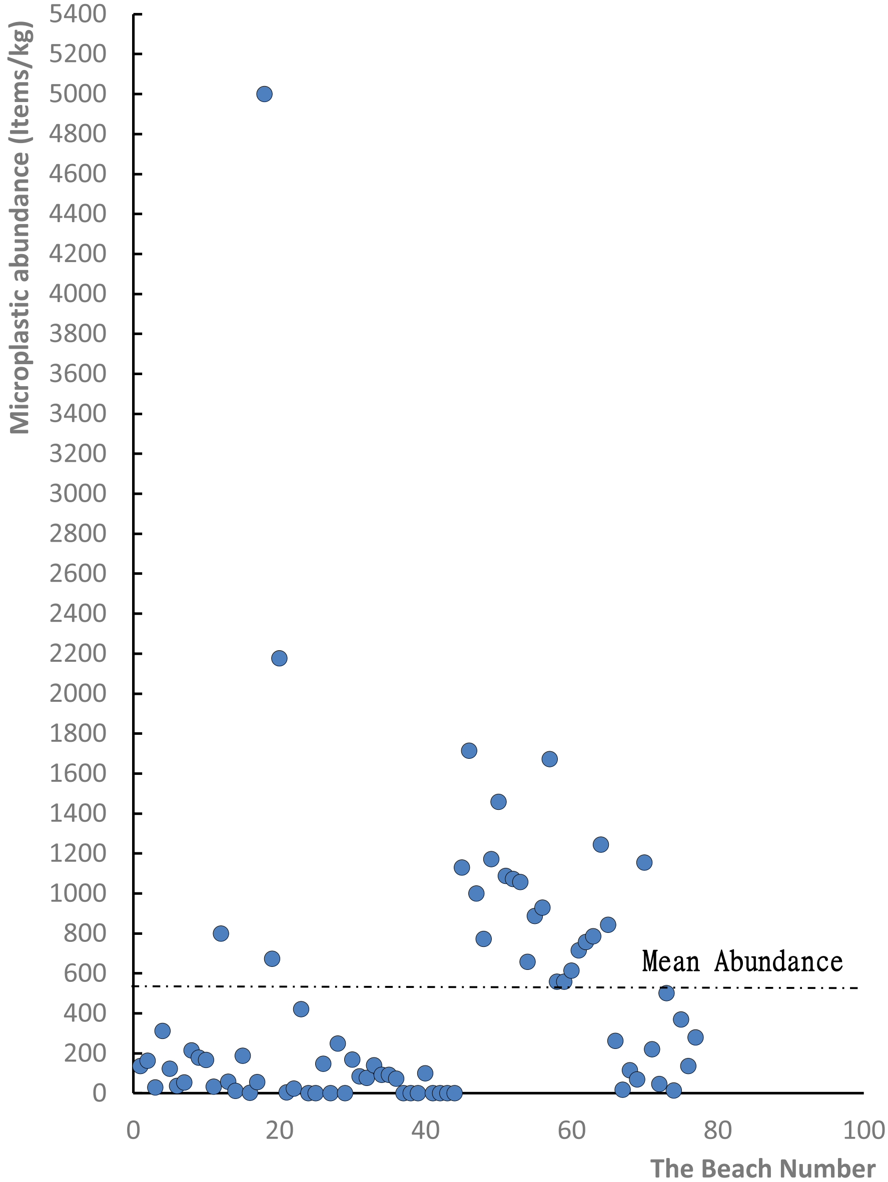


Fig. 8 Microplastic abundance of 77 bathing beaches in existing research

the plastic waste generated on land will continue to increase. Therefore, if plastic waste management is not improved, even beaches with low pollution and low risk may become potential areas of high microplastic pollution risk in the future.

It is worth noting that the NPI and PHI of Dashawan beach, which is usually jammed with visitors in the peak season, are both higher than those of Sumawan, another resort beach. Suma Bay is remote from the entrance to the Liandao bathing beaches and requires another bus to reach the beach, so the number of tourists is significantly lower than that of Dashawan. Therefore, under comparable conditions, beaches with higher recreational use intensity also have higher microplastic pollution levels and health risks.

In the NPI evaluation of microplastic pollution levels, there is no recognized clear value for the reference value S_i. Thus far, there is no clear research result showing how many microplastics cause definite harm to organisms or human bodies. Microplastic research is still in the primary data accumulation stage worldwide and has focused mostly on basic research and baseline accumulation of microplastic distribution, abundance, size, color, composition, and source analysis. With the enrichment of global basic research and the accumulation of baseline data, the value of S_i may be further modified and become more accurate. Regarding the health risk level of microplastics in the study area, it should be noted that there are still differences between polymers classified as dangerous and dangerous polymers. Ranking means that polymers are made of hazardous substances. These polymers may degrade and release or produce hazardous substances at the production, use, and end-of-life stages. Being listed in the grade indicates that a polymer has certain potential hazards.

It should be noted that there are two main reasons for selecting the microplastic data of other bathing beaches included in the comparison. Firstly, Microplastics were calculated by "items/kg." Secondly, the use of NaCl saturated solution density flotation to extract microplastics has been recommended since. There were more or less differences in the sampling and extraction methods. Although each study confirmed the validity of the data, it does bring some interference to the data comparison theoretically. This is also an unavoidable defect of this study. For example, in some studies, the intertidal zones parallel to the coastline were selected for sampling (Dekiff et al., 2014; Perez-Alvelo et al., 2021), especially close to the high tide lines (Bissen & Chawchai, 2020; Rey et al., 2021), and in others, as in this study, the intertidal zones were selected for sampling at high, low, and high tide lines respectively (Claessens et al., 2011; Mathalon & Hill, 2014). In the microplastic extraction process, 1.2 g/ml NaCl solution was mostly used (Andrady, 2011; Pinheiro et al., 2019; Bissen & Chawchai, 2020; Perez-Alvelo et al., 2021; Rangel-Buitrago et al., 2021), which was higher than the density of common plastic polymers such as polypropylene (PP: 0.9–0.91 g/ml), polyethylene (PE: 0.917–0.965 g/ml), and polystyrene (PS: 1.04–1.1 g/ml). The easily available, cheap, and eco-friendly NaCl is one of the most common salts for density separation recommended by researchers. Some researchers also tried to improve the extraction rate by using 1.36 g/ml at 40 ℃ (Liu et al., 2018) or 1.8 g/ml NaCl solution at 60 ℃ (Naji et al., 2017). Besides, the resulting particle recoveries (ranging from 68.8 to 97.5%) for the different sediment were used as correction factors for calculating the microplastic concentrations reported in their studies. The above differences also reflect that the current research on microplastics is still in the exploratory stage, and there is no unified sampling and extraction method.

Possible sources of microplastics on the Liandao bathing beaches

To date, no research efforts can fully and accurately determine the sources of microplastics. However, based on the comprehensive consideration of the research results, we can speculate about possible sources (Wang et al., 2019). Fibers and fragments are the two main shapes on the Liandao bathing beaches, accounting for 54.46% and 25.23%, respectively. The main components of fiber microplastics are PET and nylon. PET has the characteristics of antipilling and low water absorption and is widely used in garment materials and industrial fabrics. The fragmented microplastics are identified mainly as PP, which may come from the packaging of some products, including plastic bags and plastic boxes. The peak time on the Liandao bathing beaches is from June to October. In 2017, the annual maximum daily tourist volume exceeded 50,000. Due to the advantages of portability, price affinity, water resistance, and corrosion resistance of plastic products, plastic equipment and products are used mostly in entertainment facilities, such as beach tables and chairs, isolation floats, surfing buoys, isolation ropes, swimming rings, plastic slippers, sand carving tools (plastic shovels, plastic buckets, etc.), and toys (plastic water guns, etc.). In addition, plastic packaging of food and beverages is an important source of microplastics. Especially with the rapid development of the takeout and express delivery industry in China, plastic packaging from the express delivery industry has become an important pollution source. The fiber microplastics found on the beach may come from people's clothes, including the direct shedding of clothing fibers in recreational activities and the indirect pollution of household laundry water. Nylon is widely used in various fiber materials, such as clothing, carpets, ropes, and airbags. The fiber microplastics on the Liandao bathing beaches may also come from the wear and tear of entertainment facilities, fiber falling off clothes, and the discharge of washing water for tourists and residents on the island.

Microplastic management on bathing beaches

Recreational beach microplastics pose a direct risk to marine organisms and human health. For this study, we conducted a preliminary exploration of the microplastic pollution of the Liandao bathing beaches in Central China. The research results show the universality and diversity of microplastics, to which the government and local and civil organizations should pay great attention. According to the NPI and PHI analyses, the current microplastic pollution levels and health risks in Haichow Bay are both low. If we do not pay attention to strengthening management, with the increase in population and per capita consumption against the background of economic growth, the consumption of plastic waste will continue to increase. Even beaches with low pollution and low risk may become potential areas of high microplastic environmental risk in the future.

According to the preliminary research results on microplastics on bathing beaches, the following management suggestions are put forward.

(1) At the national level, as an important branch of coastal zone management, beach managers need to formulate special documents and consider microplastic pollution monitoring and management important management content. Beach plastic waste management systems should be clarified, including improving management links such as collection, transportation, treatment, and recycling, and incorporated into local political performance evaluations. Currently, the national and local governments have issued some relevant documents, such as "Opinions on the Comprehensive Establishment and Implementation of Marine Ecological Red Line System," "Opinions on Strengthening Pollution Prevention and Control in Coastal Waters," "Marine Ecological Red Line Protection Plan of Jiangsu Province (2016 ~ 2020)," and "Implementation Plan of Marine Ecological Red Line Protection of Lianyungang (2016–2020)" in 2016. However, the management of beaches is still rough. Except for the relevant management regulations for mature bathing beaches, there are no special beach management systems or documents. The current implementation of regulations on the management of bathing beaches also needs to be improved and supplemented. In the study, we found that a large number of small plastics less than 20 mm still exist, the existing beach cleaning machines still have difficulty achieving comprehensive removal, and the existing garbage cleaning and recycling work still needs to be strengthened and improved. In addition, it is necessary to improve the garbage cleaning system of all beaches. We suggest that management of small and microbeach units be fully implemented.

(2) We suggest investing more funds to support beach monitoring and beach microplastic research and encouraging nongovernmental organizations, research institutions, and government management departments to establish special public welfare organizations for beach waste management and recycling. The National Oceanic and Atmospheric Administration (NOAA) established the Marine Debris Program (MDP) as early as 2006 and formulated millennium development goals to achieve five goals: removal, prevention, research, regional coordination, and emergency response. The mission of the MDP is to investigate and prevent the adverse effects of marine debris. NOAA established the Marine Debris Foundation in December 2020 as a charitable and nonprofit organization to support its marine debris activities. The aims of the Marine Debris Foundation include encouraging, receiving, and managing private property gifts in an effort to address marine and coastal debris litter and other issues related to marine debris (https://marinedebris.noaa.gov/). China's marine environmental protection public welfare industry is still in the early stage of development. Due to the lack of industry information, it is difficult to effectively

plan the development direction. Government departments should pay attention to guidance. On the one hand, they should encourage more public welfare organizations to participate in marine and coastal zone management. On the other hand, they can help better meet the needs of these areas and strengthen supervision and management. Recreational beaches provide not only recreational and leisure areas for people but also an environment for microplastics to enter the sea. Within the existing coastal zone monitoring scope, it is necessary to carry out long-term and continuous monitoring of microplastic pollution on recreational beaches. In this way, we can accumulate data from both horizontal spatial scales and vertical time dimensions to fully grasp the microplastic pollution of coastal beaches in China.

(3) We advocate strengthening people's understanding and educating them about plastics and microplastics to effectively improve low-plastic-use and non-plastic-use behaviors among tourists. When people travel, hedonism often prevails, and their attitude and behavior toward environmental protection are easily lower than their usual practices at home. As a result, they will consume more goods and produce more waste, especially disposable plastic waste. Owing to the rapid development of fast-food express delivery services in China in recent years, the consumption of plastic packaging bags and boxes has increased significantly, aggravating the situation of plastic waste pollution. Environmental education helps people realize the transformation from being close to the beach to understanding the beach and then protecting the beach, from low-level perceptual experience to high-level special protection. Environmental education suggestions can be carried out in three spatial dimensions: family environmental education, school environmental education, and community environmental education.

(4) We suggest formulating a clear "plastic limit" or "no plastic" convention on beaches, guiding people's behavior, and issuing suggestions to the whole society. For example, consumers can refuse disposable plastic items, encourage the use of environmental protection bags, and advocate "plastic-free travel." The specific convention involves all aspects of people's lives. We put forward six suggestions for reference:

1. Start with shopping: reuse, including reusable shopping bags of various materials such as plastic; bring your own bags to avoid or reduce the use of new shopping bags provided by merchants; repeat the use of express packaging (such as foam liners in express mail and packaging with foam pads).
2. Start with clothes: practice waste utilization, including donating and recycling old clothes, when buying clothes; try to choose cotton, linen, or textiles rather than recycled plastics.
3. Start with food: refuse disposable tableware and packaging, including takeout containers; recycle plastic bottles; choose foods that are not packaged independently; take your own water cup when you go out, and do not buy plastic bottled drinks, use disposable water cups or drink plastic bottled drinks; bring your own tableware when eating out and refuse disposable tableware such as disposable straws.
4. Start with hygiene: practice plastic-free actions, including bringing daily necessities when traveling, using large cans of daily chemical products, and purchasing nonabrasive plastic products.
5. Start with the office: reduce plastic use, try not to seal documents in plastic, use electronic office strategies as much as possible to reduce printing, try to print on both sides or use wastepaper with one blank side, and use inked pens to reduce the use of water pens and ballpoint pens.
6. Start with waste disposal: reduce plastic use and waste generation, starting with personal waste reduction; accurately recycle recyclable waste materials; set out special recyclable trash cans for recyclable office consumables (such as plastic bottles and selenium cartridges); do a good job of garbage classification; respond to calls for national and local garbage classification; and ensure that garbage is handled correctly.

(5) We promote sustainable reuse, refilling, recycling, upgrading, reuse, and degradation methods. Recycling usually refers to reusing previously processed or discarded materials. Upgrading refers to increasing the value of existing chemicals or materials. Upgrading recycling means upgrading and reusing existing chemicals or materials, and recycling means retaining chemicals and materials in the value chain. It is essential for new methods to address the challenges associated with the heterogeneity of plastic waste and the performance degradation caused by mechanical recycling. The chemical recovery and upgrading

recovery of polymers can be realized through the separation strategy, promoting the closed-loop recovery of chemicals inherent in the macromolecular design and the transformation process of changing the lifecycle landscape. Another way to upgrade the recycling or upgrading of waste polymers focuses on the innovative transformation of determining precise functions and customized material characteristics to increase the value beyond chemical recycling (LaShanda et al., 2021). At the same time, the solution must strike a balance between the understanding of how the progress of plastic technology can improve the human condition and the necessary circular consideration and life-cycle management strategy.

Conclusion

Beach microplastic pollution poses a great potential threat to organisms and people's health. This paper focuses on microplastics on bathing beaches that are in close contact with people. We took the Liandao bathing beaches, the earliest open bathing beaches in China, as the study area based on the analysis of their basic characteristics, such as beach microplastic pollution abundance, distribution, shape, size, color, and composition. We used a novel approach to assess microplastic pollution at beaches that the NPI and PHI were utilized to evaluate the microplastic pollution levels and risk levels for the first time. The results showed that the average abundance of microplastics on the Liandao bathing beaches was 135.50 ± 34.41 items/kg, the maximum was at the high tide line, and the abundance was 153.75 ± 23.75 items/kg. In this study, 5 kinds of microplastics (fibers, fragments, granules, foams, and films) were found, of which fiber was the majority, accounting for 54.46%. The colors were mostly transparent, brown, and red. The average particle size was 0.63 ± 0.43 mm, of which 52% were in the range of 0.1–0.5 mm. Microplastic components included PE, PP, PS, PET, and nylon, of which nylon accounts for the highest proportion of 54.77%, and fibers are nylon and PET. Most fragments were made of PP, granules were PP and PE, foams were PS, and the main films were PE. We also found that flax fiber, cellulose fiber, and calcium carbonate particles were the main interference factors. The NPI and PHI analysis results showed that the Liandao bathing beaches had light microplastic pollution and low risk. Under similar conditions, the higher the degree of recreational use is, the higher the beach microplastic pollution level and health risk. With the increase in population and per capita consumption, plastic waste generated on land will continue to increase. If plastic waste management is not improved, even beaches with low pollution and low risk may become potential areas with a high risk of microplastic pollution in the future. At present, China's bathing beaches still use the single index health assessment method based on water quality monitoring, which makes it difficult to meet the needs of new environmental changes and beach ecosystem management. We suggest that it is necessary to carry out long-term and continuous monitoring of the microplastic pollution of recreational beaches within the existing coastal zone monitoring range and include microplastic pollution in the beach quality assessment system. Managers should strengthen people's understanding, educate them regarding microplastic pollution, and effectively improve people's awareness and environmental protection behavior in the process of tourism. We can also formulate a clear convention on a "plastic limit or no plastic" policy on beaches to guide people's behavior and send out initiatives to the whole society. A clear plastic waste management system should be formulated and incorporated into the local political performance evaluation. This study is an early study on the microplastic pollution level and risk on bathing beaches in China and provides a reference for the study of microplastics on other bathing beaches.

Author contribution Xiaowei Wu, Chongqing Zhong, and Xinqing Zou contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Xiaowei Wu, Chongqing Zhong, and Teng Wang. The first draft of the manuscript was written by Xiaowei Wu. Chongqing Zhong and Professor Zou supervised the research. Professor Zou provided funding support. All authors read and approved the final manuscript. Xiaowei Wu contributed to the revision.

Funding This study was supported by the Natural Science Foundation of China [41471431], the Natural Science Foundation of Jiangsu Province [BK20130056], and Major Projects of Philosophy and Social Sciences in Colleges and Universities in Jiangsu Province [2021SJZDA034].

Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Appendix

Table 2 The abundance of microplastics on the bathing beaches reported from different parts of the world and along the coast of China (present study)

No	Bathing beach	Average abundance (items/kg)	Reference
1	Liaodao beach, China	135	Present study
2	Bohai Bay beach, China	163	Yu et al., 2016
3	Xiamen Bay beach A, China	28.1	Liu et al., 2018
4	Xiamen Bay beach B, China	312	
5	Persian Gulf Beach, Iran	122	Naji et al., 2017
6	Bathing beach, Singapore	37	Nor & Obbard, 2014
7	Belgium bathing beach A	52.8	Claessens et al., 2011
8	Belgium bathing beach B	213.4	
9	Slovenia bathing beach	177.8	Laglbauer et al., 2014
10	Bathing beach A in the northern Mediterranean coast	166	Constant et al., 2019
11	Bathing beach B in the northern Mediterranean coast	33	
12	Bathing beach C in the northern Mediterranean coast	798	
13	Bathing beach A in the southern Mediterranean coast	58	
14	Bathing beach B in the southern Mediterranean coast	12	
15	Bathing beach C in the southern Mediterranean coast	187	
16	Norderney bathing beach, Germany	1.77	Dekiff et al., 2014
17	Portugal bathing beach	55	Frias et al., 2016
18	Canada bathing beach	5000	Mathalon & Hill, 2014
19	Bathing beach A, Italy	672	Vianello et al., 2013
20	Bathing beach B, Italy	2175	
21	Bathing beach A, Puerto Rico	2.92	Perez-Alvelo et al., 2021
22	Bathing beach B, Puerto Rico	23.3	
23	Thailand beach	420	Bissen & Chawchai, 2020
24	Sicily beach, Italy	160	Lots et al., 2017
25	Denia beach, Spain	156	
26	Barcelona beach, Spain	148	
27	Cassis beach, France	124	
28	Dikili beach, Turkey	248	
29	Pilion beach, Greece	232	
30	Tel Aviv beach, Israel	168	
31	San Mauro beach, Italy	84	
32	Bosnia bathing beach	76	
33	Vik beach, Iceland	140	
34	Porto beach, Portugal	92	
35	Smola beach, Norway	92	
36	Madeira beach, Portugal	72	
37	Troms beach, Norway	156	
38	Normandy beach, France	143	
39	Normandy beach, France	124	
40	Rottumeroog beach, Netherlands	100	
41	Drøbak beach, Norway	700	
42	Klaipéda beach, Lithuania	164	

Table 2 (continued)

No	Bathing beach	Average abundance (items/kg)	Reference
43	Fyns Hoved beach, Denmark	128	
44	Bjergje Nord beach, Denmark	88	
45	Punta Roca beach	1129	Rangel-Buitrago et al., 2021
46	Salgar beach	1714	
47	Pradomar beach	1000	
48	Pradomar beach	771	
49	Puerto Colombia beach A	1171	
50	Puerto Colombia beach B	1457	
51	Puerto Velero beach A	1086	
52	Puerto Velero beach B	1071	
53	Puerto Pelero—Punta Velero beach	1057	
54	Puerto Velero—Mirador beach	657	
55	Caño Dulce beach	886	
56	Playa Mendoza beach	929	
57	Palmarito beach	1671	
58	Playa Linda beach	557	
59	Santa Veronica beach	557	
60	Santa Veronica beach	614	
61	Salinas del Rey beach	714	
62	Loma de Piedra beach	757	
63	Bocatocinos beach	786	
64	Punta Astilleros beach	1243	
65	Galerazamba beach	843	
66	Little Antilles beach (Caribbean)	261	Bosker et al., 2018
67	Hong Kong beach	16.8	Lo et al., 2018
68	Rugen Island beach	114.72	Hengstmann et al., 2018
69	Southern Baltic beach	68	Esiukova et al., 2021
70	Dhaka Peninsula beach	1154.4	Yabanli et al., 2019
71	Indian beach A	220	Tiwari et al., 2019
72	Indian beach B	45	
73	Canadian beach	500	Ballent et al., 2016
74	Russian beach A	13	Esiukova, 2016
75	Russian beach B	368	
76	Mexico beach	135	Teresita et al., 2018
77	Indian beach	279	Sathish et al., 2019

References

Andrady, A. (2011). Microplastics in the marine environment. *Marine Pollution Bulletin, 62*, 1596–1605.

Ballent, A., Corcoran, P., Madden, O., et al. (2016). Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary and beach sediments. *Marine Pollution Bulletin, 110*(1), 383–395.

Barnes, D. A., Galgani, F., Thompson, R. C., et al. (2009). Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society of London Series B-Biological Science, 364*, 1985–1998.

Bissen, R., & Chawchai, S. (2020). Microplastics on beaches along the eastern Gulf of Thailand– A preliminary study. *Marine Pollution Bulletin, 157*, 111345.

Bosker, T., Guaita, L., & Behrens, P. (2018). Microplastic pollution on Caribbean beaches in the Lesser Antilles. *Marine Pollution Bulletin, 133*, 442–447.

Brennecke, D., Duarte, B., Paiva, F., et al. (2016). Microplastics as vectors for heavy metal contamination from the marine environment. *Estuarine, Coastal and Shelf Science, 178*(5), 189–195. https://doi.org/10.1016/j.ecss.2015.12.003

Browne, M. A., Galloway, T. S., & Thompson, R. C. (2010). Spatial patterns of plastic debris along estuarine shorelines. *Environmental Science and Technology, 44*, 3404–3409.

Claessens, M., Meester, S. D., Landuyt, L. V., et al. (2011). Occurrence and distribution of microplastics in marine sediments along the Belgian coast. *Marine Pollution Bulletin, 62*(10), 2199–2204.

Cole, M., Lindeque, P., Halsband, C., et al. (2011). Microplastics as contaminants in the marine environment: A review. *Marine Pollution Bulletin, 62*, 2588–2597.

Constant, M., Kerhervé, P., Mino-Vercellio-Verollet, M., et al. (2019). Beached microplastics in the Northwestern Mediterranean Sea. *Marine Pollution Bulletin, 142*, 263–273.

de Carvalho, D. G., & Antonio, B. N. J. (2016). Microplastic pollution of the beaches of Guanabara Bay, southeast Brazil. *Ocean and Coastal Management, 128*, 10–17. https://doi.org/10.1016/j.ocecoaman.2016.04.009

Defeo, O., Mclachlan, A., Armitage, D., et al. (2021). Sandy beach social–ecological systems at risk: Regime shifts, collapses, and governance challenges. *Frontiers in Ecology and the Environment, 19*, 564–573.

Dekiff, J. H., Remy, D., Klasmeier, J., et al. (2014). Occurrence and spatial distribution of microplastics in sediments from Norderney. *Environment Pollution, 186*, 248–256.

Esiukova, E. (2016). Plastic pollution on the Baltic beaches of Kaliningrad region, Russia. *Marine Pollution Bulletin, 114*(2), 1072–1080.

Esiukova, E., Lobchuk, O., Haseler, M., et al. (2021). Microplastic contamination of sandy beaches of national parks, protected and recreational areas in southern parts of the Baltic Sea. *Marine Pollution Bulletin, 173*, 113002.

Frias, L., Gago, J., Otero, V., et al. (2016). Microplastics in coastal sediments from southern Portuguese shelf waters. *Marine Environment Resource, 114*, 24–30.

Goldstein, M. C., & Goodwin, D. S. (2013) Gooseneck barnacles (Lepas spp.) ingest microplastic debris in the North pacific subtropical gyre. *PeerJ, 1*, e184.

Gonzales. (2018). Your Poop is probably full of plastic. Wired online.

Hengstmann, E., Tamminga, M., Bruch, C., et al. (2018). Microplastic in beach sediments of Isle of Rugen (Baltic Sea) – Implementing a novel glass elutriation column. *Marine Pollution Bulletin, 126*, 263–274.

Herrera, A., Asensio, M., Martinez, I., et al. (2018). Microplastic and tar pollution on three Canary Islands beaches: An annual study. *Marine Pollution Bulletin, 129*(2), 494–502.

Horn, D., Miller, M., Anderson, S., et al. (2019). Microplastics are ubiquitous on California beaches and enter the coastal food web through consumption by Pacific mole crabs. *Marine Pollution Bulletin, 139*, 231–237.

Isabel, A., Dario, M., Erika, R., et al. (2019). Trace elements in microplastics in Cartagena: A hotspot for plastic pollution at the Caribbean. *Marine Pollution Bulletin, 139*, 402–411.

Jeyasanta, K. I., Sathish, N., Patterson, J., et al. (2020). Macro-, meso- and microplastic debris in the beaches of Tuticorin district, Southeast coast of India. *Marine Pollution Bulletin, 154*, 111055.

Kaposi, K. L., Mos, B., Kelaher, B. P., et al. (2014). Ingestion of microplastic has limited impact on a marine larva. *Environmental Science and Technology, 48*, 1638.

Karthik, R., Robin, R. S., Purvaja, R., et al. (2018). Microplastics along the beaches of southeast coast of India. *Science of the Total Environment, 645*, 1388–1399.

Laglbauer, B., Franco-Santos, R. M., Andreu-Cazenave, M., et al. (2014). Macrodebris and microplastics from beaches in Slovenia. *Marine Pollution Bulletin, 89*(1–2), 356–366.

LaShanda, K., Thomas, E., Brett, H., et al. (2021). Toward polymer upcycling-adding value and tackling circularity. *Science, 373*(6550), 66–69. https://doi.org/10.1126/science.abg4503

Lee, J., Hong, S., Song, Y., et al. (2013). Relationships among the abundances of plastic debris in different size classes on beaches in South Korea. *Marine Pollution Bulletin, 77*, 349–354.

Leslie, H. A., Van Velzen, M., & Brandsma, S., et al. (2022) Discovery and quantification of plastic particle pollution in human blood. *Environment International, 24,* 107199. https://doi.org/10.1016/j.envint.2022.107199

Lithner, D., Larsson, A., & Dave, G. (2011). Environment and health hazard ranking and assessment of plastic polymers based on chemical composition. *Science of the Total Environment, 409*, 3309–3324.

Liu, Q., Liang, H., Xi, G., et al. (2018) Microplastic pollution of the beaches in Xiamen Bay, China. *Environmental Science* (in Chinese). https://kns.cnki.net/kcms/detail/11.1895.X.20181015.1645.021.html

Lo, H., Xu, X., Wong, C., et al. (2018). Comparisons of microplastic pollution between mudflats and sandy beaches in Hong Kong. *Environmental Pollution, 236*, 208.

Lots, F., Behrens, P., Vijver, M., et al. (2017). A large-scale investigation of microplastic contamination: Abundance and characteristics of microplastics in European beach sediment. *Marine Pollution Bulletin, 123*, 219–226.

Lozoya, J. P., Teixeira de Mello, F., Carrizo, D., et al. (2016). Plastics and microplastics on recreational beaches in Punta del Este (Uruguay): Unseen critical residents? *Environment Pollution, 218*, 931–941.

Martins, I., Rodríguez, Y., & Pham, C. (2020). Trace elements in microplastics stranded on beaches of remote islands in the NE Atlantic. *Marine Pollution Bulletin, 156*, 111270.

Mathalon, A., & Hill, P. (2014). Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia. *Marine Pollution Bulletin, 81*(1), 69–79.

Naji, A., Esmaili, Z., & Khan, F. (2017). Plastic debris and microplastics along the beaches of the Strait of Hormuz, Persian Gulf. *Marine Pollution Bulletin, 114*, 1057–1062.

Nor, N. M., & Obbard, J. P. (2014). Microplastics in Singapore's coastal mangrove ecosystems. *Marine Pollution Bulletin, 79*(1–2), 278–283.

Nuelle, M. T., Dekiff, J. H., Remy, D., et al. (2014). A new analytical approach for monitoring microplastics in marine sediments. *Environment Pollution, 184*, 161–169.

Perez-Alvelo, K., Llegus, E., Forestier-Babilonia, J., et al. (2021). Microplastic pollution on sandy beaches of Puerto Rico. *Marine Pollution Bulletin, 164*, 112010.

Piehl, S., Mitterwallner, V., Atwood, C., et al. (2019). Abundance and distribution of large microplastics (1–5 mm) within beach sediments at the Po River Delta, northeast Italy. *Marine Pollution Bulletin, 149*, 110515.

Pinheiro, L., Monteiro, R., Ivar do Sul, J., et al. (2019). Do beachrocks affect microplastic deposition on the strandline of sandy beaches? *Marine Pollution Bulletin, 141*, 569–572.

Piñón-Colin, T., Rodriguez-Jimenez, R., Pastrana-Corral, M., et al. (2018). Microplastics on sandy beaches of the Baja California Peninsula. *Mexico. Marine Pollution Bulletin, 131*, 63–71. https://doi.org/10.1016/j.marpolbul.2018.03.055

Qiu, Q., Peng, J., Yu, X., et al. (2015). Occurrence of microplastics in the coastal marine environment: First observation on sediment of China. *Marine Pollution Bulletin, 98*, 274–280.

Rangel-Buitrago, N., Velez-Mendoza, A., Mantilla-Barbosa, E., et al. (2021). Plastic pollution on the Colombian central Caribbean beaches. *Marine Pollution Bulletin, 162*, 111837.

Rey, S. F., Franklin, J., & Rey, S. J. (2021). Microplastic pollution on island beaches, Oahu, Hawai`i. *PLoS ONE, 16*(2), e0247224.

Rocha-Santos, T., & Duarte, A. C. (2014). A critical overview of the analytical approaches to the occurrence, the fate and the behavior of microplastics in the environment. *Trends in Analytical Chemistry, 65*, 47–53. https://doi.org/10.1016/j.trac.2014.10.011

Sarafraz, J., Rajabizadeh, M., & Kamrani, E. (2016). The preliminary assessment of abundance and composition of marine beach debris in the northern Persian Gulf, Bandar Abbas City, Iran. *Journal of the Marine Biological Association of the United Kingdom, 96*(1), 131–135. https://doi.org/10.1017/S0025315415002076

Sathish, N., Jeyasanta, K., Patterson, J., et al. (2019). Abundance, characteristics and surface degradation features of microplastics in beach sediments of five coastal areas in Tamil Nadu, India. *Marine Pollution Bulletin, 142*, 112–118.

Shi, J., Sanganyado, E., Wang, L., et al. (2020). Organic pollutants in sedimentary microplastics from eastern Guangdong: Spatial distribution and source identification - ScienceDirect. *Ecotoxicology and Environmental Safety, 193*, 110356.

Stolte, A., Forster, S., Gerdts, G., et al. (2015). Microplastic concentrations in beach sediments along the German Baltic coast. *Marine Pollution Bulletin, 99*, 216–229.

Teresita, P., Ruben, R., Miguel, A., et al. (2018). Microplastics on sandy beaches of the Baja California Peninsula, Mexico. *Marine Pollution Bulletin, 131*, 63–71. https://doi.org/10.1016/j.marpolbul.2018.03.055

Thompson, R. C., Olsen, Y., Mitchell, R. P., et al. (2004). Lost at sea: Where is all the plastic? *Science, 304*(5672), 838.

Thompson, R. C., Swan, S. H., Moore, C. J., et al. (2009). Our plastic age. *Philosophical Transactions of the Royal Society of London Series B-Biological Science, 364*, 1973–1976.

Tiwari, M., Rathod, T. D., Ajmal, P. Y., et al. (2019). Distribution and characterization of microplastics in beach sand from three different Indian coastal environments. *Marine Pollution Bulletin, 140*, 263–273. https://doi.org/10.1016/j.marpolbul.2019.01.055

Tsukada, E., Fernandes, E., Vidal, C., et al. (2021). Beach morphodynamics and its relationship with the deposition of plastic particles: A preliminary study in southeastern Brazil. *Marine Pollution Bulletin, 172*, 112809.

Tziourrou, P., Megalovasilism, P., Tsounia, M., et al. (2019). Characteristics of microplastics on two beaches affected by different land uses in salamina island in saronikos gulf, east mediterranean. *Marine Pollution Bulletin, 149*, 110531.

Vethaak, A. D., & Leslie, H. A. (2016). Plastic debris is a human health issue. *Environmental Science and Technology, 50*, 6825–6826.

Vianello, A., Boldrin, A., Guerriero, P., et al. (2013). Microplastic particles in sediments of Lagoon of Venice, Italy: First observations on occurrence, spatial patterns and identification. *Estuarine, Coastal and Shelf Science, 130*, 54–61. https://doi.org/10.1016/j.ecss.2013.03.022

Vidyasakar, A., Neelavannan, K., Krishnakumar, S., et al. (2018). Macrodebris and microplastic distribution in the beaches of rameswaram coral island, gulf of mannar, southeast coast of india: A first report. *Marine Pollution Bulletin, 137*, 610–616.

Wang, T., Zou, X., Li, B., et al. (2019). Preliminary study of the source apportionment and diversity of microplastics: Taking floating microplastics in the South China Sea as an example. *Environment Pollution, 245*, 965–974.

Wang, Y., Li, X., & Zhang, D. (2016). Study of methods for extracting microplastics in sediments. *World Sci-Tech R & D, 1*, 105–109.

Wu, X., Zhong, C., Wang, T., et al. (2021). Occurrence and distribution of microplastics on recreational beaches of Haichow Bay, China. *Environmental Science and Pollution Research, 28*(5), 6132–6145. https://doi.org/10.1007/s11356-020-10987-7

Wu, X., Zou, X., Zhong, C., et al. (2020) Assessing the response of sandy beach macrobenthos to recreation and the ecological status of the beach ecosystem at Liandao, China. *Marine Ecology, 4*1(1):0–e12580.

Yabanli, M., Yozukmaz, A., Sener, I., et al. (2019). Microplastic pollution at the intersection of the Aegean and Mediterranean Seas: A study of the Datça Peninsula (Turkey). *Marine Pollution Bulletin, 145*, 47–55.

Yu, X., Peng, J., Wang, J., et al. (2016). Occurrence of microplastics in the beach sand of the Chinese inner sea: the Bohai Sea. *Environment Pollution, 214*, 722–730.