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Spatial distribution and risk assessment of microplastics in surface sediments in semi-enclosed waters: a case study of Laizhou Bay

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Marine ecosystems are the most important sinks for microplastics (MPs) from inland sources, and the input of large quantities of MPs into the oceans poses a serious threat to marine organisms and ecosystems. However, the characteristics of MPs contamination and its risk in semi-enclosed seas remain poorly understood. In this research, we conducted a comprehensive analysis and evaluation of the distribution patterns and ecological risks related to MPs found in the surface sediments of Laizhou Bay. We gathered surface sediments from various locations within the bay, which were then processed and analyzed to assess the MP content. According to the results, MPs in Laizhou Bay were widely distributed, with abundances ranging from 36–2125.5 items/g d.w. at different points, with an average of 534.7 items/g d.w. The MP forms were mainly fragments (61.91%) and particles (37.45%), with polyamide (PA) (32.73%), polyethylene terephthalate (PET) (12.42%), and polyurethane (PU) (10.81%) being the most dominant polymer types. MPs mainly originated from marine aquaculture, fishing, and domestic plastic waste; the contribution from marine activities was higher than that from land-based inputs, and their migration and dispersion were mainly affected by the hydrodynamics of water body exchange and intra-bay circulation. According to the pollution load index, the risk index of MPs in Laizhou Bay ranged from 1 to 7.68, indicating a low pollution level. However, the polymer risk index indicated that microplastic pollution in Laizhou Bay was at high risk, and PU and polyvinyl chloride were identified as the primary high-risk sources. This study systematically analyzed the composition,

distribution, and multiple source characteristics of MPs in Laizhou Bay. The ecological risks associated with these MPs were assessed through the analysis of pollution load and polymer risk indices. This research offers a valuable dataset and a scientific foundation for understanding and managing MP pollution in semi-enclosed marine environments.

KEYWORDS

microplastics, Laizhou Bay, sediment, risk assessment, semi-enclosed sea area

1 Introduction

Microplastics, usually defined as plastic fragments or particles with a diameter smaller than 5 mm (Pervez et al., 2023; Jiang et al., 2020), can be categorized as primary and secondary microplastics (Zhang et al., 2020). Microbeads, among others, are primary microplastics (Kye et al., 2023), whereas secondary microplastics originate from the decomposition of large-sized plastics through complex and long-term chemical, biological, and physical processes, and can even decompose into nanoplastics ($< 1 \mu\text{m}$) (Tong et al., 2023; Han et al., 2020; Seeley et al., 2020). Microplastics do not easily degrade due to their small volume and high resistance to environmental processes (Zhang et al., 2020; Lv et al., 2022). Riverine and atmospheric transport (Sun et al., 2022; Pan et al., 2021), oceanic currents (Ikenoue et al., 2023), and human activities, such as aquaculture and ship navigation (Yao et al., 2021), contribute to the accumulation of seafloor sediments, which have become a significant microplastic sink (Nash et al., 2023). Owing to the ongoing continuous increase in plastic production and consumption worldwide (Harris et al., 2021), an estimated 4.8 to 12.7 million tons of plastic waste enter the oceans from coastal regions (Liu et al., 2021). Microplastics have been detected within the marine waters of most coastal countries (Eo et al., 2023; Rakib et al., 2022; Curren and Yew Leong, 2023; Higgins and Turner, 2023), and even in polar regions (Perfetti-Bolaño et al., 2022). Consequently, microplastic pollution in marine ecosystems has become a significant global issue (Sun et al., 2021).

As microplastics and organisms at lower trophic levels in marine ecosystems (Alam et al., 2019; Hou et al., 2024), such as plankton and microalgae (Walkinshaw et al., 2020), are similar in size, organisms with high nutrient levels through the food chain, including fish (Felline et al., 2022) and benthic organisms, such as sea cucumbers and oysters (Mohsen et al., 2019; Jahan et al., 2019), are at risk of accidental microplastics ingestion. These particles may then enter the food chain. Research has demonstrated that polyethylene (PE) microplastics induce intestinal damage in fish, potentially impeding growth and resulting in severe mortality (Xu et al., 2023). Moreover, microplastics have been detected in human tissue (Horvatits, 2022); research shows that microplastics with a diameter of $\leq 10 \mu\text{m}$ can enter the human body anywhere (Barceló et al., 2023). Polyvinyl chloride (PVC), polypropylene (PP), and

polyethylene terephthalate (PET) are the main polymers in microplastics (Zhu et al., 2024; Winiarska et al., 2024; Roslan et al., 2024; Guan et al., 2023). Research indicates that microplastics found in human tissues can lead to overall tissue damage (Bilbao-Kareaga et al., 2023), exacerbate the risk of arterial clogging (Marfella et al., 2024). Furthermore, studies have demonstrated that microplastics can accelerate premature aging in humans (Huang et al., 2024). Additionally, microplastics have been observed to form complexes with heavy metals, thereby functioning as metal transporters (Ashton et al., 2010), which further exacerbates pollution in the marine environment. Semi-enclosed seas are extensively utilized for mariculture (Xu et al., 2020), thereby increasing the likelihood of microplastics adversely impacting humans and the environment via the food chain. The hydrodynamic conditions in semi-enclosed seas, influenced by rivers, tides, and winds (Ulises et al., 2005; Mazoyer et al., 2020), affect water circulation and exchange. Rivers serve as a conduit for microplastics to enter the ocean from land (Hou et al., 2024), leading to substantial deposits in bays due to the hydrodynamic conditions present in semi-enclosed seas (Shi et al., 2022). This phenomenon plays a pivotal role in shaping the distribution patterns of microplastic abundance within bays (Liu et al., 2021). Consequently, there is a growing imperative to undertake comprehensive studies investigating the distribution and characterizing the nature of microplastics present within the sediments of semi-enclosed seas.

Numerous researchers have documented the distribution and contamination of microplastics in the surface sediment of semi-enclosed seas. Eo et al. (2023) investigated the distribution of microplastics in Dungyang Bay and Zhenhai Bay, Korea, and concluded that the distribution of microplastic contamination was influenced by anthropogenic activity. Ye et al. (2023) conducted a study on the presence of microplastics in the sediments of Liaodong Bay in the Bohai Sea by employing the pollution load index (PLI). Their findings indicated that the average abundance of microplastics varied between 32.33 to 49.91 items/kg d.w., with all sampling sites being categorized as hazardous. A more detailed analysis and study of microplastics in seawater, sediments, and fish from coastal rivers (Shi et al., 2022) to Laizhou Bay (Teng et al., 2020) was conducted, and the results confirmed that the riverine inputs were a primary source of microplastics within the Laizhou

Bay watershed–estuary–shore system. Moreover, the patterns of spatial distribution of microplastics in sediments differ from those found in surface seawater. Additionally, microplastics exhibit substantial variations in shape, size, and polymer type across surface seawater, sediments, and biota. While previous studies on semi-enclosed seas are abundant, they have not evaluated the risk of microplastic contamination of surface sediments in Laizhou Bay. Furthermore, these studies may produce inconsistent results regarding the types, sources, and abundance of microplastics due to the different locations of sampling sites.

Laizhou Bay is a paradigmatic example of a semi-enclosed bay, distinguished by its abundance of rivers along the coast and a protracted water exchange cycle. Laizhou Bay was selected as the sampling area for this study, and the distribution characteristics and pollution status of microplastics were investigated using the PLI and polymer index methods. This study had three main objectives: to (1) examine the distribution characteristics of microplastics found in the surface sediments of Laizhou Bay; (2) investigate the source of microplastics present in the sediments of Laizhou Bay; and (3) perform a risk assessment regarding microplastic pollution. The results of this research should provide a scientific basis for managing natural resources and governing the ecology of the Laizhou Bay waters.

2 Materials and methods

2.1 Study area

Laizhou Bay, situated in the northern region of the Shandong Peninsula, China ($37^{\circ} 10' - 37^{\circ} 50' \text{ N}$; $119^{\circ} 00' - 120^{\circ} 15' \text{ E}$), is a representative semi-enclosed bay bordered by land on three sides (Zhang et al., 2022). The bay's primary economic activities include the development of the petrochemical industry, ship transportation,

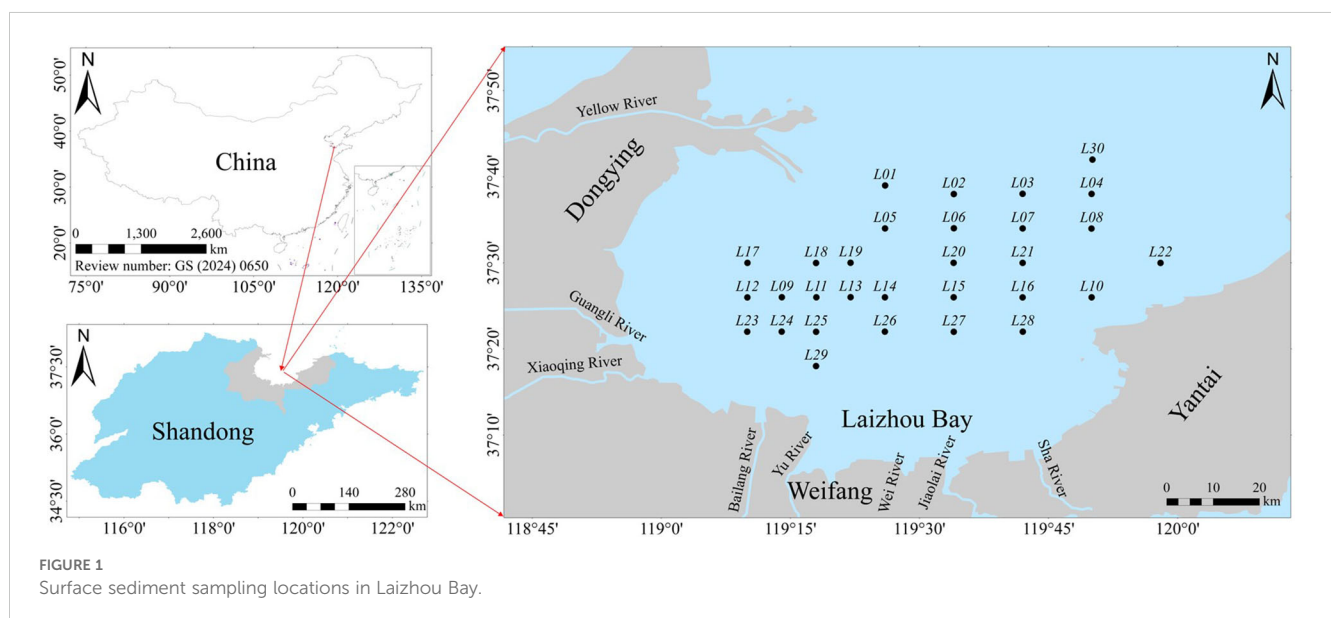
and aquaculture (Li X, et al., 2023). The region is abundant in fishery resources and possesses a distinctive natural environment. The region is characterized by numerous rivers that empty into the sea along the coast of Laizhou Bay, including the Jiao Lai, Ze, Yu, Yellow, Xiaoqing, and Bailang Rivers, which exhibit a high degree of interaction with seawater (Zhang et al., 2012).

2.2 Sediment sampling

To study the spatial distribution and source integrity of microplastics in the sea area, we systematically and uniformly set up sampling points. Thirty surface sediment samples were collected from the Laizhou Bay area in May 2023. The sampling points were equally spaced and are shown in Figure 1. During sample collection, a grab sampler was used. The depth of the collected sediment samples exceeded 20 cm, and the water depth ranged from 9 to 15.5 m. The collected sediment samples were separated on site, and only the 0–5-cm surface layer of the sediment samples was selected. The original weight of the sample for microplastic testing was at least 500 g (wet weight). To prevent the samples from being contaminated by other plastic products during the division process, the surface layer samples were separated using a wooden spatula and placed in tin foil. The samples were then stored at -15° C . All samples were sent for testing immediately after collection.

2.3 Separation and characterization of microplastics

A continuous flow separation flotation device for microplastics, developed by the Institute of Coastal Zone Research, Chinese Academy of Sciences (Jia et al., 2022), was utilized to separate the microplastics. After drying and crushing the surface sediment sample,



50 g was weighed and placed in a 5-L beaker for microplastic detection. Ten liters of saturated sodium chloride solution (NaCl, density up to 1.2 g/cm³) and sodium iodide solution (NaI, density up to 1.8 g/cm³) solutions were meticulously prepared and filtered through a nitrate fiber filter membrane (Whatman AE 98, Germany) with a pore size of 5 µm. The filtrate was then stored in a sealed 30-L container. The separation process involved two flotation passes. Initially, the filtered saturated NaCl solution was transferred to a 5-L sample cup at a flow rate of 1.0 L/min until the solution neared 2 L. The solution was thoroughly stirred and mixed for 10 min. Subsequently, the mixture was filtered using a stainless-steel sieve with a pore size of 15 µm (1000 mesh), effectively capturing the microplastics and concluding the first flotation stage. The aforementioned steps were then repeated, this time using 1.5 L of saturated sodium iodide solution on the sieve, to complete the second flotation. The filter membrane was subjected to biodegradation with 40 mL of hydrogen peroxide (30%), and the membrane was subsequently rinsed with distilled water to remove the degraded membrane. The remaining liquid was then filtered, and vacuum filtration was conducted using a polytetrafluoroethylene (PTFE) membrane with a pore size of 0.22 µm. The membrane was then rinsed with ultrapure water several times and subsequently placed in a 50-mL flask. Thereafter, 20 mL of anhydrous ethanol solution (99%) was added to the membrane, and the mouth of the flask was sealed with aluminum foil. The membrane was then filtered and rinsed with ultrapure water. The pretreatment was then finalized, and the waste liquid was poured into a specialized waste liquid bucket. To verify the feasibility and reliability of the continuous-flow separation flotation device for separating microplastics from the tidal beach samples, a microplastic recovery rate test was conducted. The mass of the two pre-prepared microplastics, polyethylene and polypropylene, was 0.4573 g. The final mass of the recovered microplastics was approximately 0.4445 g, and the recovery rate was approximately 97%. The pretreated flask was subsequently placed into an ultrasonic oscillator, operating at a temperature below 35°C and 40 Hz for a duration of 1 h. The surface of the filter membrane was then rinsed with ethanol, and ultrasonication was continued for an additional 0.5 h. After ultrasonication, the beaker was transferred to a thermostatic water bath (90°C) and concentrated to approximately 1.0 mL for online testing.

Microplastics were detected using an 8700 LDIR laser infrared imager for automated analytical testing of particles in the size range of 10–1000 µm (Jia et al., 2022). This device can rapidly achieve qualitative and quantitative analysis of microplastics, automatically obtain statistical data information, achieve single-wavelength rapid chemical imaging, automatically locate all microplastic particles, automatically conduct full-spectrum scanning and retrieval of microplastic particles, and automatically present statistical data on chemical composition, size, estimated mass, etc., of microplastics using a built-in spectral library of 41 of the most common polymers (over 420 reference spectra), with a match accuracy of over 65% of the results for qualitative analysis. Natural sources [cellulose, silicates, coal, chitin, and natural polyamides (PAs)] were eliminated from the results for qualitative and quantitative analysis.

2.4 Quality control

The laboratory personnel wore dust-free laboratory coats and nitrile gloves to prevent contamination by polyester microplastics. During the experiment, the doors and windows were closed and the containers containing the samples were sealed to prevent the indoor environment or fibers and other impurities in clothes from affecting the experimental results. The solutions utilized for the experiments (including NaCl and NaI solutions) were filtered using 5-µm filter membranes, and the experimental equipment was predominantly composed of glass and stainless steel. All vessels, measuring cylinders, beakers, forceps, and other instruments were thoroughly washed three times with ultrapure water prior to use. During the experiment, a blank control group and a comparison of sediment samples were established. The control test revealed an average of 31 interfering microplastics detected in the anhydrous ethanol, NaCl solution, and NaI solution utilized. The final abundance was calculated by subtracting the background value of 31. Sediment samples for comparison were obtained from the same site, and secondary measurements were conducted with a confidence level exceeding 90% for the final results.

2.5 Microplastics risk assessment methodology

The term “ecological risk” is defined as the probability of an impact of external factors on ecosystems, which could potentially compromise their integrity and security. In this study, the microplastics concentration was utilized as a surrogate for pollutants to assess the ecological risk of surface sediments in Laizhou Bay. The pollution load index (PLI) and polymer risk index (PRI) methods were employed to evaluate this risk.

(1). PLI is frequently employed to evaluate ecological risks in both aquatic and terrestrial environments (Tomlinson et al., 1980). The formula used for its assessment is outlined as follows (Xu et al., 2018):

$$CF_i = C_i / C_{oi}$$

$$PLI = \sqrt{CF_i}$$

$$PLI_{zone} = \sqrt[n]{PLI_1 PLI_2 \dots PLI_n}$$

In this context, C_i is the microplastic concentration at each sampling location, whereas C_{oi} is the background concentration of microplastics in the sediment prior to the expansion of the plastic industry. The contamination coefficient is indicated by CF_i . Due to the absence of a standardized method for evaluating the microplastic contamination risk and the lack of established background values for microplastic contamination in Laizhou Bay sediments, the lowest observed abundance of microplastics was adopted as the background value for this research (Rakib et al., 2022). The n-root of nPLI for all sites was obtained for the PLI_{zone} value of surface sediments in Laizhou Bay.

(2). The PRI reflects the risk of microplastics (Pan et al., 2021; Geng et al., 2023; Wang et al., 2024a) and is determined using the following equation:

$$PRI_i = \sum_{n=1}^n P_i * S_n$$

$$PRI_{zone} = \sqrt[n]{PRI_1 PRI_2 \dots PRI_n}$$

In this context, P_i is the proportion of each polymer within the sample, whereas S_n is the hazard score associated with a specific polymer. The scores for various polymers are as follows: polyethylene (PE) 11, polyurethane (PU) 7384, polypropylene (PP) 1, polyvinyl chloride (PVC) 10,551, polystyrene (PS) 30, polyethylene terephthalate (PET) 4, and polyamide (PA) 47 (Xu et al., 2018; Lithner et al., 2011; Peng et al., 2024). Additionally, PRI_i is the polymer risk index for microplastics in the samples, whereas PRI_{zone} is the polymer risk index for microplastics found in the sediments of the study area.

The classification of microplastic pollution risk management is supported by the pollution risk level criteria shown in Table 1 (Xu et al., 2018; Ye et al., 2023).

2.6 Data analysis and processing

The ArcGIS 10.8 software was used to generate maps depicting the locations of sampling stations as well as the distribution of microplastic abundance and associated risks. For statistical analysis and data visualization, Origin 2022 and Office 2016 were employed. A one-sample t-test was conducted using SPSS to assess the correlation between microplastic abundance in the sediment, with the significance level set at $p < 0.05$. The abundance of microplastics was quantified based on the number of items per gram of dry weight in the sediment, expressed in units of items/g d.w.

3 Result and discussion

3.1 Abundance and morphological characterization of microplastics

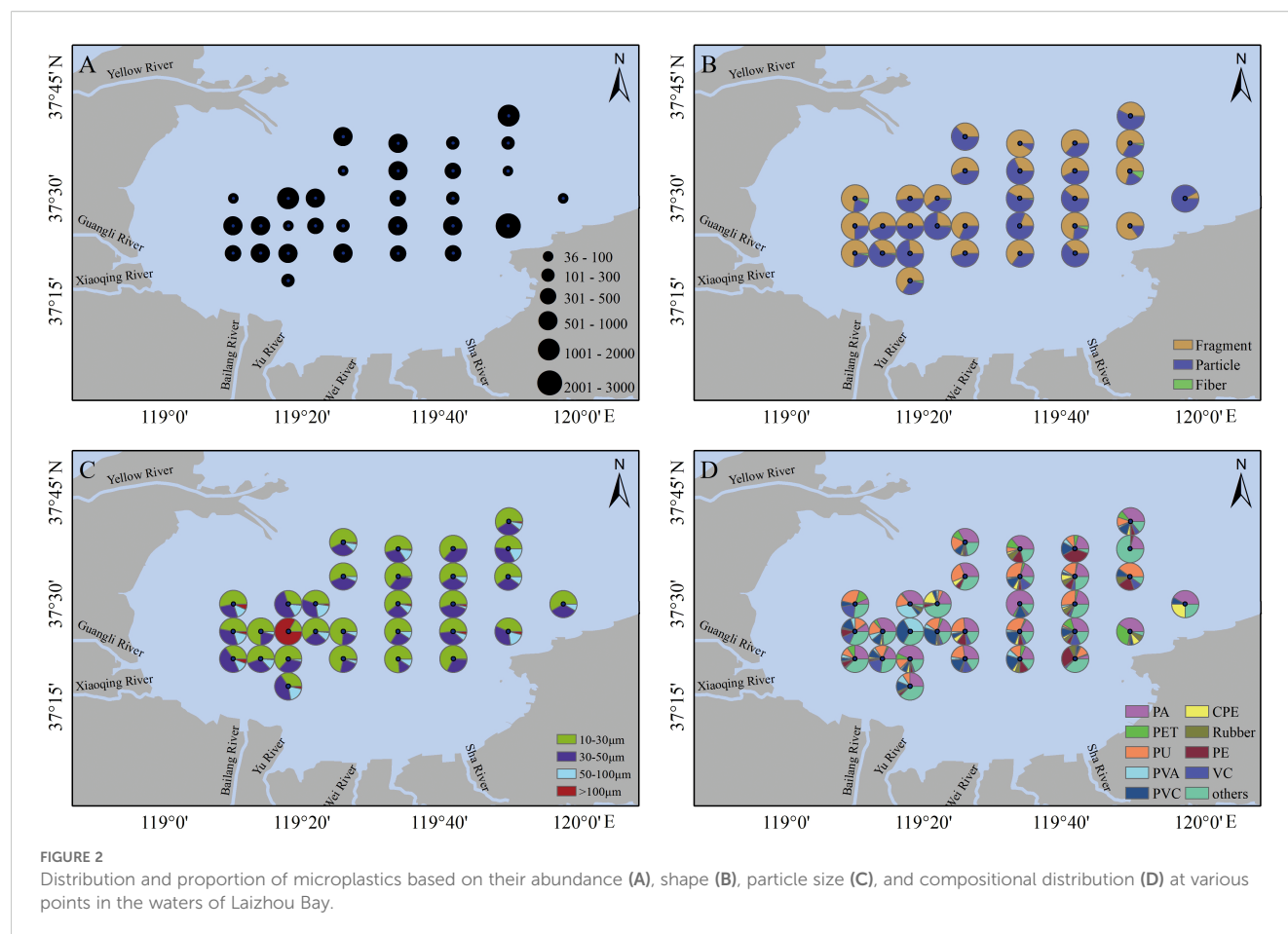
A total of 30 sampling sites of surface sediments were analyzed for microplastic contamination, with findings indicating the presence of microplastics at every location (Figure 2A). The concentration of microplastics in the sediment samples varied from 36 to 2125 items/g d.w., yielding an average of 534.7 items/g d.w. The most common abundance values fell within the range of

500–1000 items/g d.w., representing approximately 37% of the overall total. The one-sample t-test indicated that the abundance values of microplastics at different points in the surface sediments of Laizhou Bay were significantly different ($P < 0.05$). The different levels of abundance of microplastics were related to the marine circulation of Laizhou Bay. The hydrodynamic structure was relatively complex. The western area of the sea area in the summer exhibited clockwise circulation, whereas in the eastern area, it exhibited counterclockwise circulation, and in the middle area, it exhibited a northeast-oriented outflow (Sun et al., 2021). This is similar to the spatial distribution of microplastics in Laizhou Bay. Thus, circulation plays an important role in the distribution of microplastics in the sea area. Moreover, from the perspective of the distribution of microplastics, the abundance was relatively high in the direction of the extension of the Guangli, Xiaoqing, and Bailang Rivers toward the sea area, indicating concentration in this area. This is because aquaculture areas in the sea are mostly distributed in the extension areas of estuaries. Substances that are easily transported via rivers can further provide nutrients for aquaculture areas. However, this also leads to the further enrichment of microplastics in the extension areas of estuaries. The lowest abundance value was observed at point L11 (3.6 items/g d.w.), and the highest abundance value was recorded in the sea area of Yantai Laizhou Gripe Mouth (point L10; 2125.5 items/g d.w.). The findings demonstrate a substantial increase in magnitude relative to the microplastic abundance values (461.6 items/kg d.w.) observed in Laizhou Bay in 2017 (Teng et al., 2020). This discrepancy is primarily due to the absence of a standardized detection process for microplastics on a global scale (Ye et al., 2023); the discrepancy in detection methodologies may have led to substantial variations in the magnitude of the abundance. In this study, we employed laser infrared detection (Jia et al., 2022), which achieves substantially better microplastic detection than conventional methods, such as Raman (Chen et al., 2020) and Fourier transform infrared (Renner et al., 2017) spectroscopy. However, the disadvantage is that the color of the microplastic itself cannot be accurately identified. Furthermore, an increase in microplastic abundance was observed following years of sedimentation. The microplastics in the waters of Laizhou Bay exhibited higher concentrations compared with those found in Yueqing Bay (6.13 items/kg d.w.) and Zhenhai Bay (Korea, 2474 items/kg d.w.), which are also semi-enclosed seas. This phenomenon can be attributed to the presence of a greater number of rivers along the coast of Laizhou Bay, which is an active area for aquaculture and fishing. Consequently, the influx of microplastics into the bay was significantly higher compared with that in Yueqing Bay and Jinhae (South Korea) due to river inputs and marine activities.

The analysis of microplastics in Laizhou Bay sediments revealed three predominant shapes: fragments, granules, and fibers. Among these, fragments were the most common, constituting 61.91% of the total microplastic count, whereas granules accounted for 37.45%. Fibrous microplastics were detected at 15 stations, constituting the least abundant category, with a percentage of 0.64%. Fragmented microplastics exhibited the widest distribution, as shown in

TABLE 1 Risk level criteria for microplastics based on the evaluation of PLI and PRI.

Values of PLI	<10	10-20	20-30	>30
Values of PRI	<10	10-100	100-1000	>1000
Risk level	Low	Middle	High	dangerous



Figures 2B and 3A, which is because fragmented microplastics are more buoyant than particulate microplastics and are more easily transported to a wider location by oceanic currents (Wang et al., 2018).

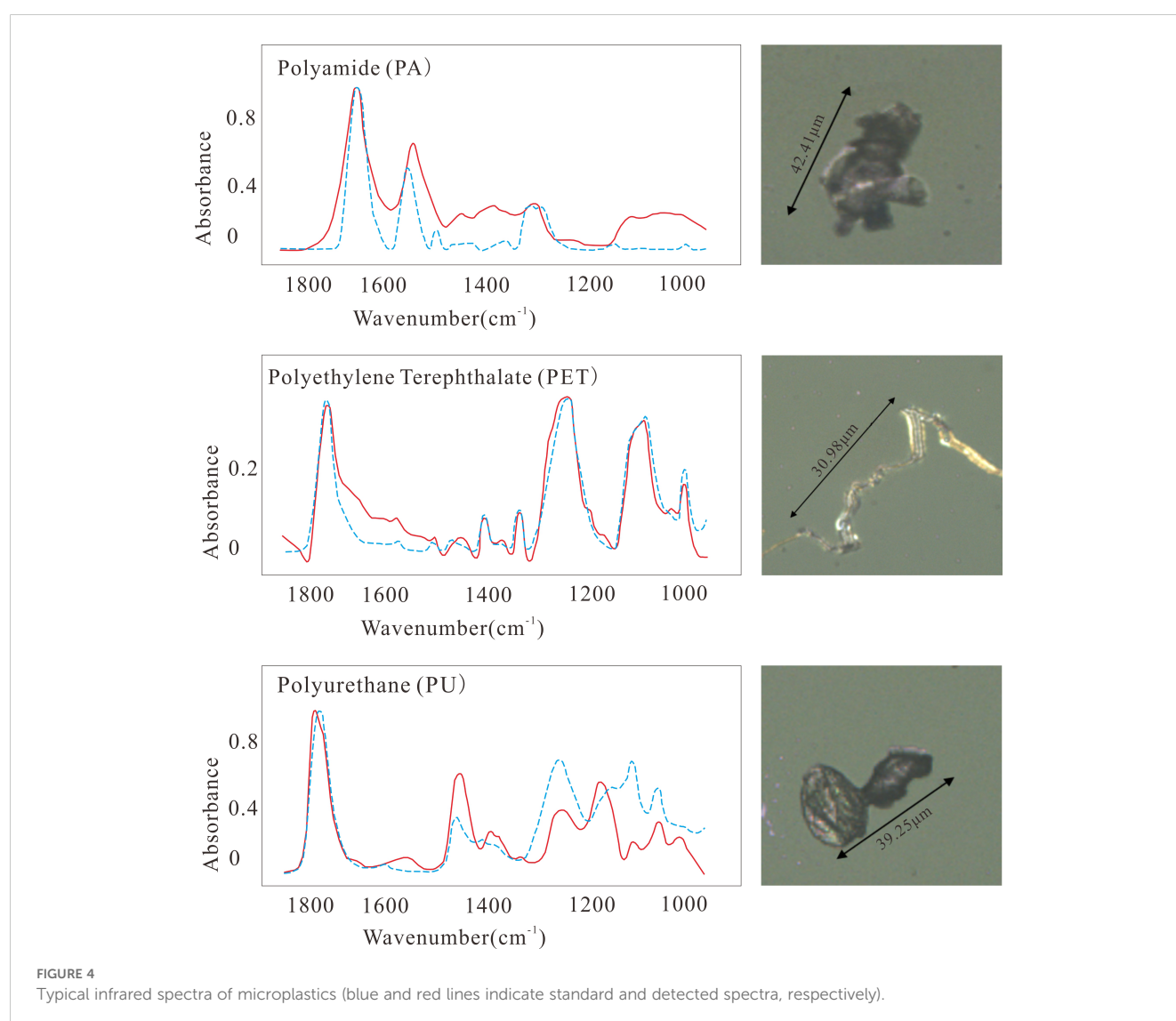
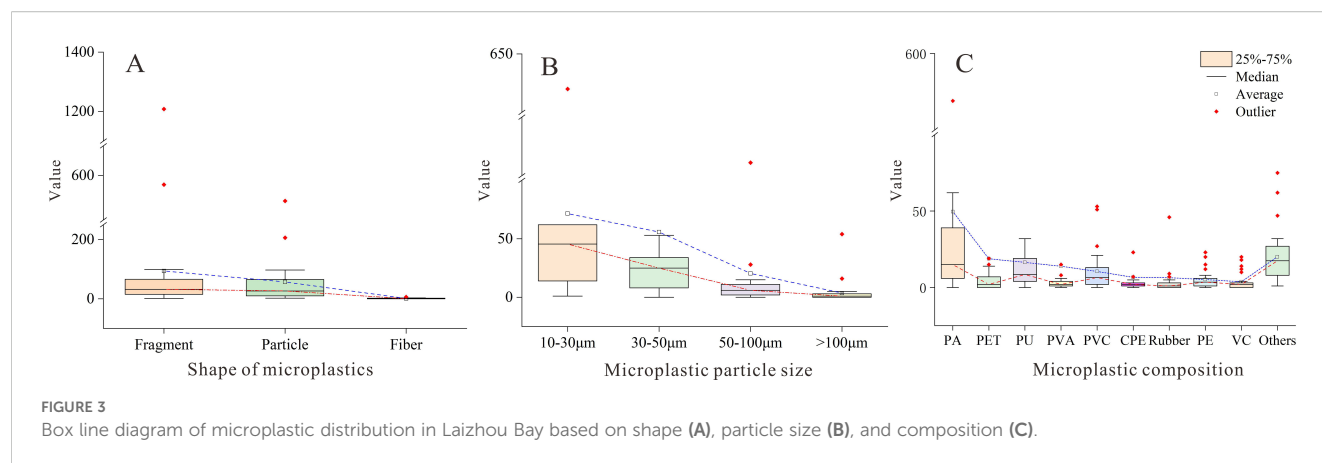
The particle size of microplastics in the surface sediment was divided into four categories: 10–30, 30–50, 50–100, and >100 μm . Granules smaller than 50 μm were found to be predominant, accounting for 84.00%, as shown in Figures 2C and 3B. Most of the stations exhibited a preponderance of microplastics in the 10–30- μm size category, accounting for 47% of the total. The remaining size categories accounted for a comparatively lower proportion. The proportion of particles within the 30–50 μm size range constituted 37% of the total, whereas those in the 50–100 μm size range represented 14%. Particles exceeding 100 μm accounted for only 2%. These findings indicate a consistent decline in the proportion of particles with increasing size.

3.2 Composition, distribution, and sources of microplastics

The 8700 LDIR laser infrared imager analysis of the samples showed that the surface sediment samples from Laizhou bay were rich in microplastic polymer types, with a total of 4550 microplastics detected, containing 27 microplastic types, indicating extensive

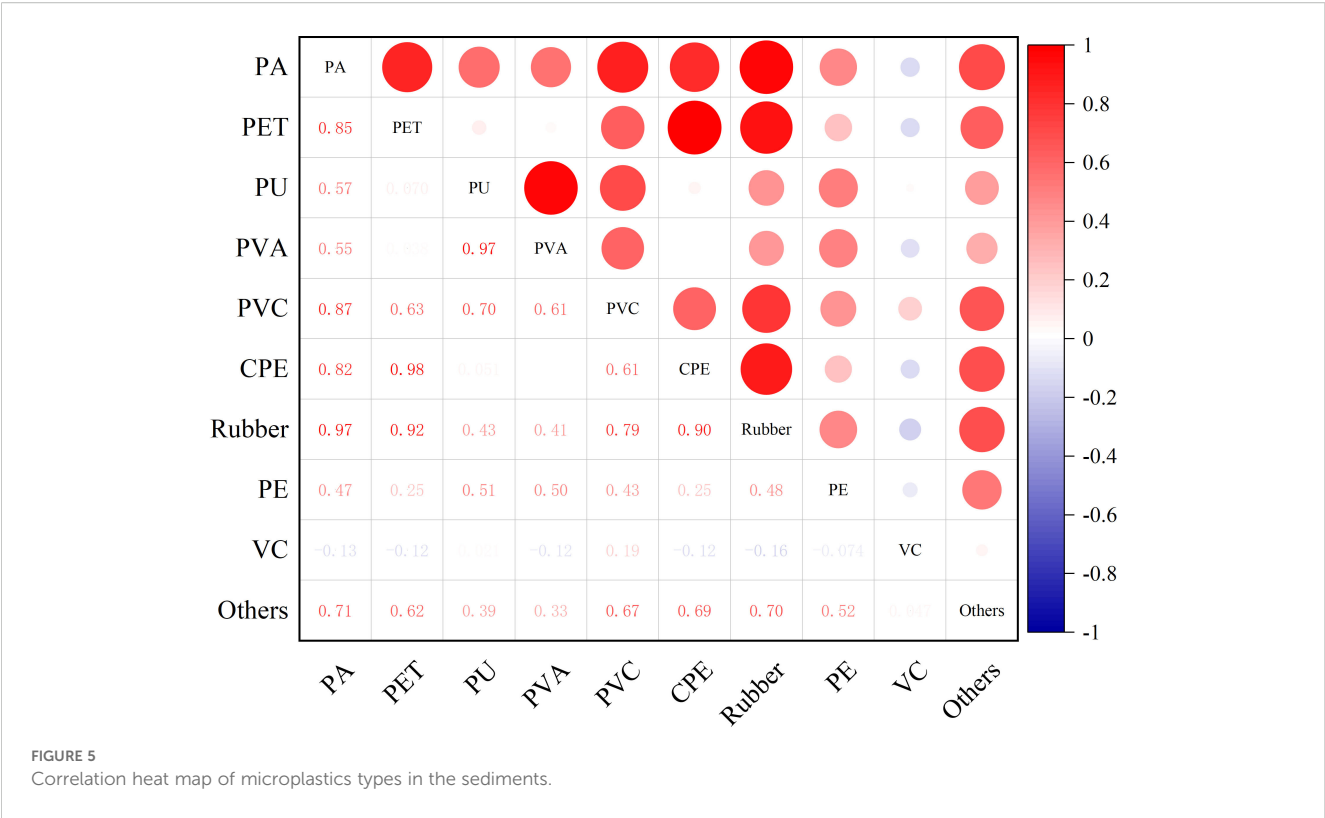
microplastic contamination in Laizhou Bay. Among the microplastics detected, PA (32.73%), PET (12.42%), and PU (10.81%) were the three main types of polymers, accounting for more than 55.96% of the total, as shown in Figure 3C. The infrared spectra of these three types of microplastics are shown in Figure 4. The proportions of PVA and PVC were 9.16% and 6.92%, respectively, not exceeding 10%. The contents of the other 22 types of microplastics ranged from 0.04–4.53%, which were less than 5%, and they accounted for 27.96% in total, including polyethylene chlorinated, rubber, polyethylene, vinyl chloride, methyle cellulose, polypropylene, polyether, polyacrylamide, polylactic acid, high density polyethylene, polymethylmethacrylate, polycarbonate, polyimide, polytetrafluoroethylene, polybutadiene, acrylonitrile butadiene, cellulose acetate, polycaprolactone, polysulfones, polystyrene, ethylene vinyl acetate, and polyacetal.

The spatial distribution of different types of microplastics in Laizhou Bay varied significantly, as illustrated in Figure 2D. Despite having the highest concentration, PA was present in smaller quantities in the extended sea area where it met the river, primarily concentrated in the central region. Polyethylene terephthalate was predominantly concentrated at point L10, with a proportion of 79% and accounting for 61% of the total. PU exhibited a more homogeneous distribution, excluding station L18. The number of microplastics detected at each station varied. At L10, 23 types of microplastics were identified, with PA accounting for



569 of the total, accounting for 40.16%. Notably, two types of microplastics, polybutadiene and poly(ethylene terephthalate), were exclusively present at this station. In contrast, only four types of microplastics were detected at L11, excluding PA, PET, and PU.

The analysis revealed that three primary types of microplastics (PA, PET, and PU) were present at different concentrations across the remaining sites. Laizhou Bay, characterized as a semi-enclosed body of water with limited exchange capacity, facilitates the dispersion of



microplastics influenced by circulation dynamics (Pan et al., 2021). The spatial distribution of microplastics is also related to their density (Wan et al., 2024). For example, the densities of PA and PET are 1.24 and 1.38 g/cm³, respectively. These are high-density polymers, and they are more likely to deposit in the marine environment (Chubarenko et al., 2016; Wu et al., 2019). This explains why microplastics are so widely distributed in surface sediments. Other microplastics exhibit lower density, which facilitates their transportation to the seafloor and subsequent deposition under the influence of circulation. Additionally, the transportation of microplastics by marine organisms should not be overlooked. Cultured oysters have been observed to possess a notable accumulation capacity for microplastics with small particle sizes. However, large-scale culture could modify microplastic sedimentation and transport processes (Li et al., 2024).

Owing to their small size, microplastics pose a significant challenge in terms of visual identification, thereby hindering the ability to trace their provenance. Consequently, the composition of microplastics has emerged as a pivotal factor in determining their source (Xu et al., 2019). Laizhou Bay, a semi-enclosed sea area, is characterized by its extensive marine culture area, spanning 41,157 hm², and hosts regular marine activities, including ship navigation and fishing. As shown in Figure 5, with the exception of vinyl chloride, different types of microplastics show strong spatial correlations, indicating that microplastics have a greater consistency in their sources of spatial inputs such as land or sea. The most prevalent microplastic detected in the surface sediments of Laizhou Bay was PA, which is predominantly derived from fishing

nets and other anthropogenic sources (Bošković et al., 2022). PA is extensively utilized in various production activities, such as mariculture, which generates a substantial quantity of fragments or particles through abrasion (Li Y, et al., 2023). This finding is consistent with the results of this study, which elucidates the pervasive distribution of PA in the Laizhou Bay region. PET was the second most abundant microplastic, primarily originating from textile fibers, beverage bottles, and fishing nets (Tajwar et al., 2022; Osorio et al., 2021). Its prevalence is well-documented, and studies have demonstrated that as much as 6 million fragments or fibers can be released from 5 kg of material (Sait et al., 2021). PU is the third most abundant microplastic, primarily utilized as a surface coating on ships. It is dislodged by the impact of water currents during navigation or fishing, subsequently accumulating in the sediment (Teng et al., 2020). However, another study reported the absence of PU (Sait et al., 2021), possibly attributable to variations in sampling density and detection methods. In previous studies on microplastics in inflowing water, the most abundant types of microplastics were cellophane, PET, polyvinylidene fluoride, EVA, and PE (Yang et al., 2021; Shi et al., 2022); however, in this study, except for PET, the contents of the other polymers were low. In particular, the content of EVA was only 0.04%, which was different from the results of the studies conducted by Sun et al. (2021) and Teng (2022). It is hypothesized that the amount of land-based microplastics entering Laizhou Bay through coastal rivers has decreased in recent years due to the further tightening of plastic management policies, which also indicates that the amount of microplastics generated from offshore activities has been higher than the land-based inputs in recent years.

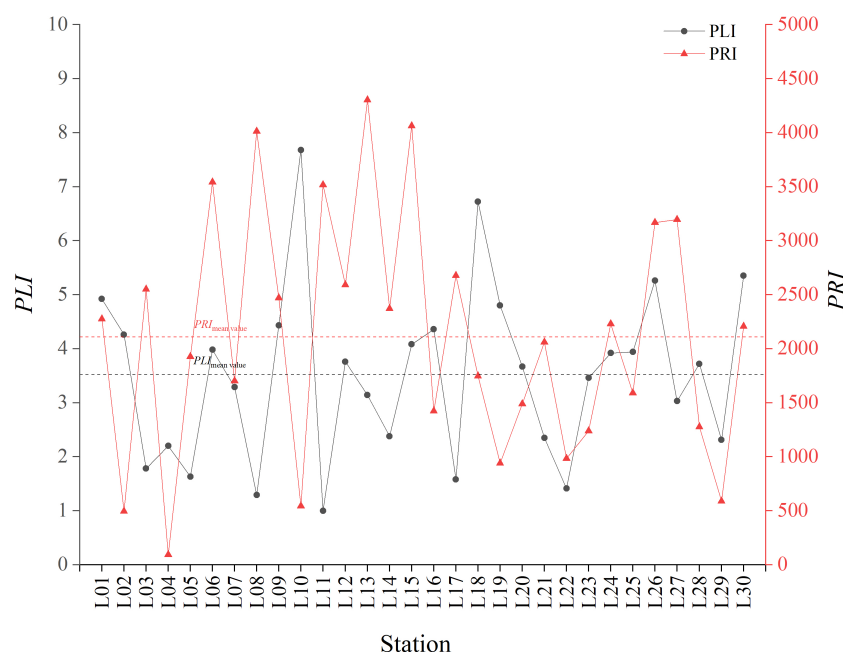


FIGURE 6
Risk distribution map of microplastics in the sediments.

3.3 Risk assessment of microplastics

The ecological risk posed by microplastics in the surface sediments of Laizhou Bay was evaluated using the PLI. PLI values at the sampling sites varied from 1.00 to 7.68, with an average of 3.52, whereas the overall PLIzone value for the area was 3.16, with all values remaining below the threshold of 10 (Figure 6). These values exceeded those observed in Liaodong Bay (PLIzone of 2.33) (Ye et al., 2023) and Yueqing Bay (PLIzone of 2.65) (Wang et al., 2024a). Based on the classification of microplastic contamination levels, all sampling sites fell into the low-hazard category, suggesting that microplastic contamination in the sediments of the study area is relatively stable and remains at a low level.

The PLI was calculated using the lowest microplastic abundance value, thereby ensuring that the effect of different microplastic components on the PLI could be ignored. Nevertheless, the toxic effect of microplastic components constitutes a pivotal component of microplastic pollution analysis. To address this critical aspect, the PRI was investigated in conjunction with hazard scores for the typical and abundant microplastics present in the samples. This approach served to compensate for the absence of a comprehensive pollution evaluation. The PRI values of each sampling site ranged from 93.62 to 4303.36, with the highest values observed at sites L04 and L13, yielding a mean value of 2108.62 and PRIzone value of 1701.98 (Figure 6). This value was higher than the PRI value of Haizhou Bay (Lu et al., 2023). This result indicates that the overall PRI of microplastics in sediments was at a very high risk level, which was due to the presence of PU and PVC, which accounted for relatively small proportions of 10.81% and 6.92%, respectively, but high scores of 7384 and 10551, making a significant contribution to the PRI value of Laizhou Bay. Thus, the risk level of microplastics in the sediment was very high.

The results of this study reveal a minimal correlation between microplastic abundance and the PRI, i.e., $P = -0.223$. Figure 6 supports these findings, highlighting the limitations of relying solely on abundance values to evaluate the risk of microplastic contamination in sediments. Consequently, neglecting the specific types of microplastics and their associated risks could lead to a significant distortion in the assessment of ecological risks to the environment.

4 Conclusion

This study investigated the characteristics and sources of microplastics in the surface sediments of Laizhou Bay as well as their associated ecological risks. The average abundance of microplastics was found to be 534.7 items per gram of dry weight. The predominant forms identified were fragments and particles, whereas fibers constituted a smaller proportion of the total microplastic composition. The detection and analysis of microplastic components were conducted using a laser infrared method, which revealed the predominant types to be PA, PET, PU, and PVC. The results also indicated that the input of microplastics from marine activities exceeded that from land-based sources. The PRI indicated that microplastics in the study area exhibited a high risk level, with PU and PVC identified as significant sources of high-risk pollution. It is imperative that plastic products utilized in marine activities be further regulated or enhanced. This study was constrained by the limitations of the laser infrared detection method in accurately determining the color of different microplastics, which introduced a degree of bias in the analysis of microplastic sources. This study provides basic data for understanding the distribution and influencing factors of microplastics in Laizhou Bay, while providing also a global

context for microplastic pollution when compared to other studies on marine microplastics in semi-enclosed sea areas around the world. In summary, a unified microplastic detection standard and evaluation method should be established in subsequent research and management to control harmful pollution caused by microplastics in coastal zones, shallow seas or deep seas in a timely manner.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

XZ: Data curation, Investigation, Software, Writing – original draft. HC: Conceptualization, Writing – original draft, Writing – review & editing. MY: Writing – original draft. YL: Writing – original draft. PC: Writing – original draft. QZ: Writing – original draft. XD: Writing – original draft. LK: Conceptualization, Writing – review & editing.

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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.

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References

- Alam, F. C., Sembiring, E., Muntalif, B. S., and Suendo, V. (2019). Microplastic distribution in surface water and sediment river around slum and industrial area (case study: Ciwalengke River, Majalaya district, Indonesia). *Chemosphere* 224, 637–645. doi: 10.1016/j.chemosphere.2019.02.188
- Ashton, K., Holmes, L., and Turner, A. (2010). Association of metals with plastic production pellets in the marine environment. *Mar. pollut. Bull.* 60, 2050–2055. doi: 10.1016/j.marpolbul.2010.07.014
- Barceló, D., Picó, Y., and Alfahhan, A. H. (2023). Microplastics: Detection in human samples, cell line studies, and health impacts. *Environ. Toxicol. Pharmacol.* 101, 104204. doi: 10.1016/j.etap.2023.104204
- Bilbao-Kareaga, A., Menendez, D., Peón, P., Ardura, A., and Garcia-Vazquez, E. (2023). Microplastics in jellyfying algae in the Bay of Biscay. *Implications consumers' Health Algal Res.* 72, 103080. doi: 10.1016/j.algal.2023.103080
- Bošković, N., Joksimović, D., Perošević-Bajčeta, A., Peković, M., and Bajt, O. (2022). Distribution and characterization of microplastics in marine sediments from the Montenegrin coast. *J. Soils Sediments* 22, 2958–2967. doi: 10.1007/s11368-022-03166-3
- Chen, Y., Leng, Y., Liu, X., and Wang, J. (2020). Microplastic pollution in vegetable farmlands of suburb Wuhan, central China. *Environ. pollut.* 257, 113449. doi: 10.1016/j.envpol.2019.113449
- Chubarenko, I., Bagaev, A., Zobkov, M., and Esiukova, E. (2016). On some physical and dynamical properties of microplastic particles in marine environment. *Mar. pollut. Bull.* 108, 105–112. doi: 10.1016/j.marpolbul.2016.04.048
- Curren, E., and Yew Leong, S. C. (2023). Spatiotemporal characterisation of microplastics in the coastal regions of Singapore. *Heliyon* 9, e12961. doi: 10.1016/j.heliyon.2023.e12961
- EO, S., Hong, S. H., Cho, Y., Song, Y. K., Han, G. M., and Shim, W. J. (2023). Spatial distribution and historical trend of microplastic pollution in sediments from enclosed bays of South Korea. *Mar. pollut. Bull.* 193, 115121. doi: 10.1016/j.marpolbul.2023.115121
- Felline, S., Piccardo, M., De Benedetto, G. E., Malitesta, C., and Terlizzi, A. (2022). Microplastics' Occurrence in Edible Fish Species (*Mullus barbatus* and *M. surmuletus*) from an Italian Marine Protected Area. *Microplastics* 1, 291–302. doi: 10.3390/microplastics1020021
- Geng, N., Zhao, G., Zhang, D., Yuan, H., and Li, X. (2023). Distribution, sources and risk assessment of microplastics in surface sediments of the Yellow River Delta wetlands. *Environ. Sci.* 44, 5046–5054. doi: 10.13227/j.hjxx.202210339
- Guan, Q., Jiang, J., Huang, Y., Wang, Q., Liu, Z., Ma, X., et al. (2023). The landscape of micron-scale particles including microplastics in human enclosed body fluids. *J. Hazardous Materials* 442, 130138. doi: 10.1016/j.jhazmat.2022.130138
- Han, M., Niu, X., Tang, M., Zhang, B. T., Wang, G., Yue, W., et al. (2020). Distribution of microplastics in surface water of the lower Yellow River near estuary. *Sci. Total Environ.* 707, 135601. doi: 10.1016/j.scitotenv.2019.135601
- Harris, L. S. T., Fennell, J., Fales, R. J., and Carrington, E. (2021). Spatial-temporal growth, distribution, and diffusion of marine microplastic research and national plastic policies. *Water Air Soil Pollut.* 232, 1–18. doi: 10.1007/s11270-021-05352-4
- Higgins, C., and Turner, A. (2023). Microplastics in surface coastal waters around Plymouth, UK, and the contribution of boating and shipping activities. *Sci. Total Environ.* 893, 164695. doi: 10.1016/j.scitotenv.2023.164695
- Horvath, (2022). Microplastics detected in cirrhotic liver tissue. *eBioMedicine* 82, 104147. doi: 10.1016/j.ebiom.2022.104147
- Hou, X., Li, J., Li, H., Du, S., Liu, S., Jiao, S., et al. (2024). Microplastics distribution, ecological risk and outflows of rivers in the Bohai Rim region of China - A flux model considering small and medium-sized rivers. *Sci. Total Environ.* 953, 176035. doi: 10.1016/j.scitotenv.2024.176035
- Huang, H., Hou, J., Xing, B., and Xi, B. (2024). Accelerated aging: The hidden harm of microplastic exposure. *Sci. Bull.* 69, 2357–2361. doi: 10.1016/j.scib.2024.05.020
- Ikenoue, T., Nakajima, R., Fujiwara, A., Onodera, J., Itoh, M., Toyoshima, J., et al. (2023). Horizontal distribution of surface microplastic concentrations and water-

column microplastic inventories in the Chukchi Sea, western Arctic Ocean. *Sci. Total Environ.* 855, 159564. doi: 10.1016/j.scitotenv.2022.159564

Jahan, S., Strezov, V., Weldekidan, H., Kumar, R., Kan, T., Sarkodie, S. A., et al. (2019). Interrelationship of microplastic pollution in sediments and oysters in a seaport environment of the eastern coast of Australia. *Sci. Total Environ.* 695, 133924. doi: 10.1016/j.scitotenv.2019.133924

Jia, W., Karapetrova, A., Zhang, M., Xu, L., Li, K., Huang, M., et al. (2022). Automated identification and quantification of invisible microplastics in agricultural soils. *Sci. Total Environ.* 844, 156853. doi: 10.1016/j.scitotenv.2022.156853

Jiang, B., Kauffman, A. E., Li, L., Mcfee, W., Cai, B., Weinstein, J., et al. (2020). Health impacts of environmental contamination of micro- and nanoplastics: a review. *Environ. Health Prev. Med.* 25, 1–15. doi: 10.1186/s12199-020-00870-9

Kye, H., Kim, J., Ju, S., Lee, J., Lim, C., and Yoon, Y. (2023). Microplastics in water systems: A review of their impacts on the environment and their potential hazards. *Heliyon* 9, e14359. doi: 10.1016/j.heliyon.2023.e14359

Li, X., Han, B., Wang, G., Gao, W., Zheng, L., Chi, W., et al. (2023). Analysis of PAHs content, source and risk assessment in surface sediments from Laizhou Bay and Bohai Bay. *Mar. Pollut. Bull.* 197, 115698. doi: 10.1016/j.marpolbul.2023.115698

Li, J., Liu, J., Wang, X., Zhang, T., Wang, D., Shan, E., et al. (2024). Vertical transfer of microplastics in nearshore water by cultured filter-feeding oysters. *J. Hazardous Materials* 475, 134769. doi: 10.1016/j.jhazmat.2024.134769

Li, Y., Xiao, P., Donnici, S., Cheng, J., and Tang, C. (2023). Spatial and seasonal distribution of microplastics in various environmental compartments around Sishili Bay of North Yellow Sea, China. *Mar. Pollut. Bull.* 186, 114372. doi: 10.1016/j.marpolbul.2022.114372

Lithner, D., Larsson, Å., and Dave, G. (2011). Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. *Sci. Total Environ.* 409, 3309–3324. doi: 10.1016/j.scitotenv.2011.04.038

Liu, K., Zhang, Z., Wu, H., Wang, J., Wang, R., Zhang, T., et al. (2021). Accumulation of microplastics in a downstream area of a semi-enclosed bay: Implications of input from coastal currents. *Sci. Total Environ.* 791, 148280. doi: 10.1016/j.scitotenv.2021.148280

Lu, L., Gao, S., Lu, J., and Fu, G. (2023). Microplastic distribution and ecological risk in water and sediments of marine ranching area in Haizhou Bay. *Regional Stud. Mar. Sci.* 68, 103274. doi: 10.1016/j.rsma.2023.103274

Lv, M., Jiang, B., Xing, Y., Ya, H., Zhang, T., and Wang, X. (2022). Recent advances in the breakdown of microplastics: strategies and future perspectives. *Environ. Sci. Pollut. Res.* 29, 65887–65903. doi: 10.1007/s11356-022-22004-0

Marfella, R., Prattichizzo, F., Sardù, C., Fulgenzi, G., Graciotti, L., Spadoni, T., et al. (2024). Microplastics and nanoplastics in atherosclerosis and cardiovascular events. *New Engl. J. Med.* 390, 900–910. doi: 10.1056/NEJMoa2309822

Mazoyer, C., Vanneste, H., Dufresne, C., Ourmières, Y., Magaldi, M. G., and Molcard, A. (2020). Impact of wind-driven circulation on contaminant dispersion in a semi-enclosed bay. *Estuarine Coast. Shelf Sci.* 233, 106529. doi: 10.1016/j.jess.2019.106529

Mohsen, M., Wang, Q., Zhang, L., Sun, L., Lin, C., and Yang, H. (2019). Microplastic ingestion by the farmed sea cucumber *Apostichopus japonicus* in China. *Environ. Pollut.* 245, 1071–1078. doi: 10.1016/j.envpol.2018.11.083

Nash, R., Joyce, H., Pagter, E., Frias, J., Guinan, J., Healy, L., et al. (2023). Deep sea microplastic pollution extends out to sediments in the northeast Atlantic ocean margins. *Environ. Sci. Technol.* 57, 201–213. doi: 10.1021/acs.est.2c05926

Orosio, E. D., Tanchuling, M. A. N., and Diola, M. B. L. D. (2021). Microplastics occurrence in surface waters and sediments in five river mouths of Manila Bay. *Front. Environ. Sci.* 9. doi: 10.3389/fenvs.2021.719274

Pan, Z., Liu, Q., Jiang, R., Li, W., Sun, X., Lin, H., et al. (2021). Microplastic pollution and ecological risk assessment in an estuarine environment: The Dongshan Bay of China. *Chemosphere* 262, 127876. doi: 10.1016/j.chemosphere.2020.127876

Peng, X., Zhang, G., Yan, Y., Yao, C., Liu, Q., Tang, Q., et al. (2024). Characteristics of microplastic distribution and ecological risk assessment of surface sediments in coastal wetlands of Yancheng, Jiangsu. *Mar. Environ. Sci.* 43, 320–328. doi: 10.13634/j.cnki.mes.2024.02.017

Perfetti-Bolaño, A., Araneda, A., Muñoz, K., and Barra, R. O. (2022). Occurrence and distribution of microplastics in soils and intertidal sediments at fildes bay, maritime Antarctica. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.774055

Pervez, R., Lai, Y., Song, Y., Li, X., and Lai, Z. (2023). Impact of microplastic pollution on coastal ecosystems using comprehensive beach quality indices. *Mar. Pollut. Bull.* 194, 115304. doi: 10.1016/j.marpolbul.2023.115304

Rakib, M. R. J., Hossain, M. B., Kumar, R., Ullah, M. A., Al Nahian, S., Rima, N. N., et al. (2022). Spatial distribution and risk assessments due to the microplastics pollution in sediments of Karnaphuli River Estuary, Bangladesh. *Sci. Rep.* 12, 8581. doi: 10.1038/s41598-022-12296-0

Renner, G., Schmidt, T. C., and Schram, J. (2017). A new chemometric approach for automatic identification of microplastics from environmental compartments based on FT-IR spectroscopy. *Analytical Chem.* 89, 12045–12053. doi: 10.1021/acs.analchem.7b02472

Roslan, N. S., Lee, Y. Y., Ibrahim, Y. S., Tuan Anuar, S., Yusof, K. M. K. K., Lai, L. A., et al. (2024). Detection of microplastics in human tissues and organs: A scoping review. *J. Global Health* 14, 4179. doi: 10.7189/jogh.14.04179

Sait, S. T. L., Sørensen, L., Kubowicz, S., Vike-Jonas, K., Gonzalez, S. V., Asimakopoulou, A. G., et al. (2021). Microplastic fibres from synthetic textiles: Environmental degradation and additive chemical content. *Environ. Pollut.* 268, 115745. doi: 10.1016/j.envpol.2020.115745

Seeley, M. E., Song, B., Passie, R., and Hale, R. C. (2020). Microplastics affect sedimentary microbial communities and nitrogen cycling. *Nat. Commun.* 11, 1–10. doi: 10.1038/s41467-020-16235-3

Shi, H., Yu, D., Yin, L., Sui, Y., Liu, Y., Qiao, S., et al. (2022). Source-sink process of microplastics in watershed-estuary-offshore system. *J. Cleaner Production* 338, 130612. doi: 10.1016/j.jclepro.2022.130612

Sun, J., Peng, Z., Zhu, Z. R., Fu, W., Dai, X., and Ni, B. J. (2022). The atmospheric microplastics deposition contributes to microplastic pollution in urban waters. *Water Res.* 225, 119116. doi: 10.1016/j.watres.2022.119116

Sun, X., Wang, T., Chen, B., Booth, A. M., Liu, S., Wang, R., et al. (2021). Factors influencing the occurrence and distribution of microplastics in coastal sediments: From source to sink. *J. Hazardous Materials* 410, 124982. doi: 10.1016/j.jhazmat.2020.124982

Tajwar, M., Shreya, S. S., Gazi Md, Y., Hasan, M., and Saha, S. K. (2022). Microplastic contamination in the sediments of the Saint Martin's Island, Bangladesh. *Regional Stud. Mar. Sci.* 53, 102401. doi: 10.1016/j.rsma.2022.102401

Teng, J. (2022). *Characterization of microplastic pollution in Laizhou Bay and its ecotoxic effect on typical bivalve shellfish* (University of Chinese Academy of Sciences, Yantai, Shandong Province, China) (Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences). doi: 10.27841/d.cnki.gytha.2021.000014

Teng, J., Zhao, J., Zhang, C., Cheng, B., Koelmans, A. A., Wu, D., et al. (2020). A systems analysis of microplastic pollution in Laizhou Bay, China. *Sci. Total Environ.* 745, 140815. doi: 10.1016/j.scitotenv.2020.140815

Tomlinson, D. L., Wilson, J. G., Harris, C. R., and Jeffrey, D. W. (1980). Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgoländer Meeresuntersuchungen* 33, 566–575. doi: 10.1007/BF02414780

Tong, Y., Lin, L., Tao, Y., Huang, Y., and Zhu, X. (2023). The occurrence, speciation, and ecological effect of plastic pollution in the bay ecosystems. *Sci. Total Environ.* 857, 159601. doi: 10.1016/j.scitotenv.2022.159601

Ulses, C., Grenz, C., Marsaleix, P., Schaaff, E., Estournel, C., Meulé, S., et al. (2005). Circulation in a semi-enclosed bay under influence of strong freshwater input. *J. Mar. Syst.* 56, 113–132. doi: 10.1016/j.jmarsys.2005.02.001

Walkinshaw, C., Lindeque, P. K., Thompson, R., Tolhurst, T., and Cole, M. (2020). Microplastics and seafood: lower trophic organisms at highest risk of contamination. *Ecotoxicology Environ. Saf.* 190, 110066. doi: 10.1016/j.ecoenv.2019.110066

Wan, S., Xu, G., Xiong, P., Qiao, H., Chen, X., Gu, L., et al. (2024). Microplastic pollution characteristics and ecological risk assessment in the Wuding River Basin, China. *Environ. Pollut.* 356, 124228. doi: 10.1016/j.envpol.2024.124228

Wang, Z., Su, B., Xu, X., Di, D., Huang, H., Mei, K., et al. (2018). Preferential accumulation of small (<300 μm) microplastics in the sediments of a coastal plain river network in eastern China. *Water Res.* 144, 393–401. doi: 10.1016/j.watres.2018.07.050

Wang, Y., Zhong, Z., Chen, X., Sokolova, I., Ma, L., Yang, Q., et al. (2024a). Microplastic pollution and ecological risk assessment of Yueqing Bay affected by intensive human activities. *J. Hazardous Materials* 461, 132603. doi: 10.1016/j.jhazmat.2023.132603

Winiarska, E., Jutel, M., and Zemelka-Wiacek, M. (2024). The potential impact of nano- and microplastics on human health: Understanding human health risks. *Environ. Res.* 251, 118535. doi: 10.1016/j.envres.2024.118535

Wu, N., Zhang, Y., Zhang, X., Zhao, Z., He, J., Li, W., et al. (2019). Occurrence and distribution of microplastics in the surface water and sediment of two typical estuaries in Bohai Bay, China. *Environ. Science: Processes Impacts* 21, 1143–1152. doi: 10.1039/C9EM00148D

Xu, T., Cui, J., Xu, R., Cao, J., and Guo, M. Y. (2023). Microplastics induced inflammation and apoptosis via ferroptosis and the NF-κB pathway in carp. *Aquat. Toxicol.* 262, 106659. doi: 10.1016/j.aquatox.2023.106659

Xu, P., Peng, G., Su, L., Gao, Y., Gao, L., and Li, D. (2018). Microplastic risk assessment in surface waters: A case study in the Changjiang Estuary, China. *Mar. Pollut. Bull.* 133, 647–654. doi: 10.1016/j.marpolbul.2018.06.020

Xu, P., Peng, G., Zhu, L., Bai, M., and Li, D. (2019). Spatial and temporal distribution of microplastics in the Yangtze River Estuary and risk evaluation. *China Environ. Sci.* 39, 2071–2077. doi: 10.19674/j.cnki.issn1000-6923.2019.0248

Xu, C., Yang, B., Dan, S. F., Zhang, D., Liao, R., Lu, D., et al. (2020). Spatiotemporal variations of biogenic elements and sources of sedimentary organic matter in the largest oyster mariculture bay (Maowei Sea), Southwest China. *Sci. Total Environ.* 730, 139056. doi: 10.1016/j.scitotenv.2020.139056

Yang, Z., Hu, H., Wang, X., Jiao, J., Wang, X., and Chen, G. (2021). Characterization of microplastic inputs to the inlet streams of Laizhou Bay. *Mar. Lakes Marshes Bull.* 5, 73–81. doi: 10.13984/j.cnki.cn37-1141.2021.05.010

Yao, C., Liu, X., Wang, H., Sun, X., Qian, Q., and Zhou, J. (2021). Occurrence of microplastics in fish and shrimp feeds. *Bull. Environ. Contamination Toxicol.* 107, 684–692. doi: 10.1007/s00128-021-03328-y

Ye, Y., Zhang, A., Teng, J., Yang, X., Yuan, X., Wang, Q., et al. (2023). Pollution characteristics and ecological risk of microplastic in sediments of Liaodong Bay from the northern Bohai Sea in China. *Mar. Pollut. Bull.* 187, 114505. doi: 10.1016/j.marpolbul.2022.114505

Zhang, B., Chen, L., Chao, J., Yang, X., and Wang, Q. (2020). Research progress of microplastics in freshwater sediments in China. *Environ. Sci. pollut. Res.* 27, 31046–31060. doi: 10.1007/s11356-020-09473-x

Zhang, M., Lu, Q., Wang, D., Ding, D., Cui, Z., and Shi, H. (2022). Spatiotemporal evolution of nutrients and the influencing factors in Laizhou Bay over the past 40 years. *Mar. pollut. Bull.* 184, 114186. doi: 10.1016/j.marpolbul.2022.114186

Zhang, R., Zhang, G., Zheng, Q., Tang, J., Chen, Y., Xu, W., et al. (2012). Occurrence and risks of antibiotics in the Laizhou Bay, China: Impacts of river discharge. *Ecotoxicology Environ. Saf.* 80, 208–215. doi: 10.1016/j.ecoenv.2012.03.002

Zhu, L., Kang, Y., Ma, M., Wu, Z., Zhang, L., Hu, R., et al. (2024). Tissue accumulation of microplastics and potential health risks in human. *Sci. Total Environ.* 915, 170004. doi: 10.1016/j.scitotenv.2024.170004