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Widespread occurrence of microplastics in marine bays with diverse drivers and environmental risk

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ABSTRACT

Microplastic contamination in the sediment of marine bays has attracted widespread attention, whereas the distribution, sedimentation, morphology and risk of microplastics at regional scale remain poorly understood. By introducing a data mining framework into microplastic research, we compiled a microplastic dataset of 649 samples from 24 bays to enhance the understanding of geographical difference and drivers, transfer, composition profile and environmental risk of sedimental microplastics. Microplastic abundance varied from 0.72 to 1963.96 items/kg dry weight, with higher concentrations mainly occurring in East Asian bays. The spatial pattern in abundance was driven by the river plastic emissions, aquaculture production and hydrodynamic condition. A significantly positive correlation between microplastic abundance in water and sediment was found, and microplastic sedimentation was related to polymer density, hydrodynamic conditions and sediment properties. The dominant shape and polymer of sedimental microplastics were fiber and polypropylene, respectively, and the similarity of microplastic composition decreased with increasing geographical distance. The environmental risks of microplastics were partitioned into three classes (Rank II-Rank IV) with a two-dimensional assessment system considering the bioavailability and toxicity of microplastics, and Asian bays were identified as potential high-risk areas. To reduce the environmental risk of sedimental microplastics in bays, priority should be given to the removal of microfibers, and control measures depend on the risk classes and dominant polymers. Microplastic abundance and composition were significantly affected by methodological choices regarding sampling, pretreatment and identification, suggesting a unified methodology is essential to further enhance our knowledge on the distribution and risk of microplastics in marine bays.

1. Introduction

Microplastics are ubiquitous in the coastal and marine sediments around the world, which can be largely attributed to the high consumption of plastic production, inadequate management of plastic waste, and persistence of microplastics. The global plastic production has increased from 1.5 million metric tons (Mt) in the 1950s to 368 million Mt in 2019 (Okoffo et al., 2021). The waste management infrastructure is lacking in most coastal countries, especially in developing countries, resulting in >1 million Mt of plastic waste entering ocean every year (Lebreton et al., 2017; Jambeck et al., 2015). Microplastics are the dominant items of plastic debris in the ocean, and the longevity and buoyancy of microplastics contribute to their widespread occurrence in the marine environment (Auta et al., 2017). Sediments are generally considered to be major sinks of microplastics, and sedimentation is related to the hydrodynamic conditions and the properties of

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sediment microplastics (Chen et al., 2021; Sun et al., 2021). Marine bays are considered to be accumulation zones of sedimental microplastics due to intense human activity and poor hydrodynamic conditions (Liu et al., 2021a), whereas the knowledge on the occurrence of sedimental microplastics detected in marine bays at regional or global scale is still lacking.

The spatial distribution and composition profile of sedimental microplastics are associated with anthropogenic activities, hydrodynamic regime and sediment properties. Abundance of sedimental microplastics is high in areas with intensive anthropogenic activities, including industry, tourism, aquaculture and domestic processes (Dai et al., 2018; Frere et al., 2017). The composition and diversity of microplastics are in good agreement with consumption patterns of plastic products (Sun et al., 2021). Hydrodynamic factors, such as current velocity, turbidity, turbulence and residual circulation, could affect the transportation and sedimentation of microplastics, thereby altering the microplastic distribution in coastal and marine sediments (Zhang et al., 2020). Silt fraction contributes to the elevated abundance of microplastics in sediments, as silt has larger specific surface area than sand and exhibits a high adsorption capacity for microplastics (Liu et al., 2021b; Qian et al., 2021). The transport of microplastics are also associated with their own properties (e.g., particle size and surface modification) and other environmental conditions (e.g., pH, light and dissolved organic matter) (Skaf et al., 2020). Although the impacts of above factors on the abundance of sedimental microplastics in marine bays are well known, the quantification of these effects is still limited.

The increasing global concerns about microplastics could be attributed to not only their ubiquity but also their risks for human and environmental health. The small size of microplastics (less than five millimeters in diameter) renders them accessible to a wide variety of organisms (e.g., zooplankton, benthic macroinvertebrates and fishes), potentially causing physical and toxicological effects (Cole et al., 2015; Redondo-Hasselerharm et al., 2020; Ye et al., 2021). Microplastics may enter the human body through both inhalation and ingestion, subsequently translocating from the gastrointestinal tract into the tissues likely by cellular internalization (Ramsperger et al., 2020; Vethaak and Legler, 2021). Microplastics can readily accumulate organic and inorganic pollutants (e.g., polycyclic aromatic hydrocarbons, dioxin-like chemicals and heavy metals) and are viewed as carriers of antibiotic resistance bacteria (Atugoda et al., 2021; Carbery et al., 2018). To assess the environmental risks of microplastics, studies have been conducted by considering several attributes, such as the safe concentration and toxicity level of polymer (Everaert et al., 2018; Guo et al., 2021; Peng et al., 2018). The implication of microplastics on environmental health is obvious, yet the differences in environmental risk of sedimental microplastics among marine bays are still largely unknown.

Introducing data mining into microplastic research offers the potential to compare results from different studies, thus providing a regional and quantitative perspective on the microplastic pollution in marine bays. Microplastic contamination in the sediment has attracted widespread attention within individual marine bay, yet it remains to be poorly understood for a set of bays at regional scale. The accessibility of data in the published literature coupled with the development of data mining provide a feasible way to compile a dataset of microplastics (Guo et al., 2021; Halden 2015), which is essential for the regional analysis of occurrence, drivers, diversity and risks of sedimental microplastics detected in marine bays. The Sankey diagrams that frequently focus on energy flow have been widely used for visualization of data flow (Schmidt, 2008; Soundararajan et al., 2014; Liu et al., 2022), enabling a good presentation of the workflow for data mining from information acquisition to statistical analysis.

Herein, we provided a comprehensive understanding of microplastic contamination in the sediment of marine bays using a developed data mining framework, which consists of data extraction, data processing and statistical analysis. The main objectives of this article were to: (1) identify the geographical distribution and drivers of sedimental microplastics; (2) clarify the microplastic sedimentation and its influencing factors; (3) reveal the similarity of microplastic morphology; and (4) assess the environmental risk of microplastics and propose corresponding control measures. This study clarifies the occurrence, drivers, morphology and risk of sedimental microplastics, contributing to the mitigation of microplastic pollution in marine bays.

2. Methods

To identify the geographical distribution, influencing factors, morphology and environmental risk of sedimental microplastics in marine bays, we constructed a data mining framework that includes three workflows, namely data extraction, data processing and statistical analysis. The data extraction workflow aimed to crawl information related to sedimental microplastics of marine bays from online databases. The data processing workflow was constructed to obtain an available microplastic dataset by filtering the extracted information according to inclusion criteria. The data analysis workflow was developed to conduct spatial and causal analysis, similarity analysis and risk assessment of microplastics with the compiled dataset.

2.1. Data extraction

The literature search was conducted using Web of Science with a search term of bay microplastics (Fig. 1). A total of 36 papers providing information on sedimental microplastics were covered in this study. The information, including microplastic abundance and composition, methodologies and geographic coordinates, were extracted using the software Plot Digitizer (Kadic et al., 2016; Moeyaert et al., 2016; Xu and Boeing, 2014). To understand the sedimentation of microplastics in marine bays, the abundance data of microplastics in water were also collected from the 36 papers. A dataset of microplastics containing 700 samples from 27 bays across four continents was compiled. More details on the literature collection and data extraction are shown in Text S1.

To identify the drivers of microplastic abundance,the information on the properties of marine bays, including river plastic emissions, maritime activity and hydrodynamic condition were collected (Table S1 in Supplementary Material 1). The river plastic emissions of each bay was calculated based on the values estimated by Lebreton et al. (2017). The maritime activity was reflected by the aquaculture production, and the data was collected from the published literature and Food and Agriculture Organization of the United Nations (FAO). The hydrodynamic condition was indicated by the ratio of tidal range to average water depth, which was computed by data collected from published literature.

2.2. Data processing

To compare the results of various studies, the extracted data was processed as follows: (1) the unit of microplastic abundance (i.e., items/g dry weight) was unified as items/kg dry weight, and the data with the unit of items/m^2 or items/cm^2 were excluded; (2) shapes were classified as fiber, fragment, film, foam and pellet; and (3) polymer types were divided into eight categories, namely polypropylene (PP), polyester (PES), polyethylene terephthalate (PET), polyethylene (PE), polystyrene (PS), polyvinyl alcohol (PVC), nylon (NY) and others. Among the 700 samples, 649 samples meeting the criteria for comparative studies were used for statistical analysis (Supplementary Material 2).

2.3. Statistical analysis

The software of ArcGIS 10.5 was applied to reveal the spatial distribution of sedimenttal microplastics in marine bays. The linear regression analysis was adopted to quantify: (1) the relationship between microplastic abundance in water and sediment; and (2) the influence of river plastic emissions, maritime activity and hydrodynamic condition on microplastic abundance with Origin 9.0. The

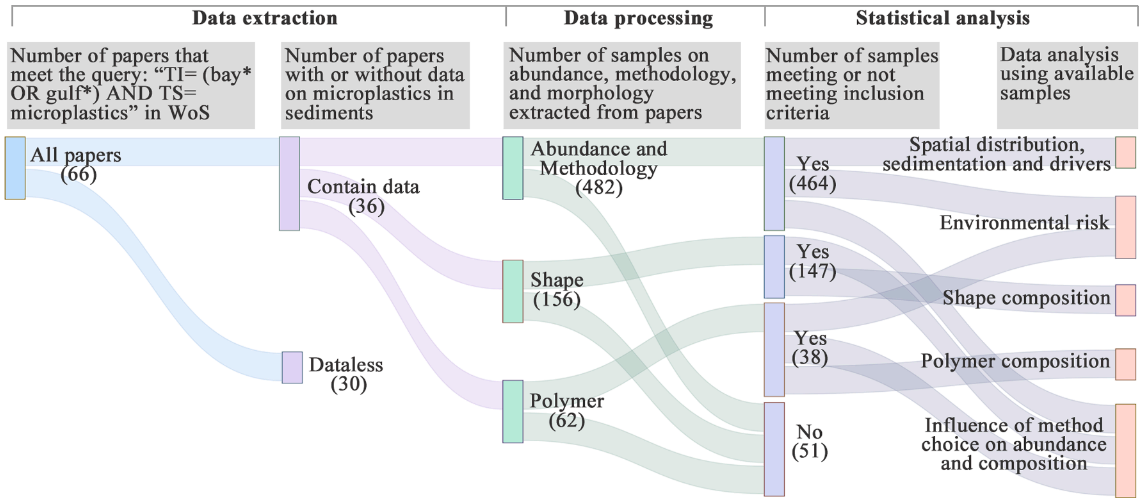

Fig. 1. Framework for data extraction, data processing and statistical analysis of microplastics in the sediment of marine bays. TI, TS and WoS refer to title, topic and Web of Science, respectively.

sediment–water partitioning coefficients (K_d) were calculated to indicate the sedimentation of microplastics in marine bays (Wang et al., 2018). The GeoDetector tool was used to assess the influence of methodological choices on the microplastic abundance and composition. The Primer 6.0 was used to analyze the similarity of microplastic composition (i.e. shape and polymer) between samples. The geographical distance between sampling sites was calculated with ArcGIS, and the distance decay linear model was established by using Origin to analyze the effect of increasing geographic distance on the similarity of microplastic composition (Li et al., 2021).

A two-dimensional system considering the bioavailability and toxicity of microplastics was proposed to evaluate the environmental risk of microplastics. Microplastic bioavailability was reflected by the Nemerow pollution index (NPI), which could be calculated by Eq. (1):

$$NPI = \sqrt{\frac{\left(\frac{Ci}{Si}\right) max^2 + \left(\frac{Ci}{Si}\right) ave^2}{2}} \quad (1)$$

where C_i represents the measured microplastic abundance of each sample; S_i refers to the maximal microplastic abundance for regulatory standard; $(C_i/S_i)_{max}$ and $(C_i/S_i)_{ave}$ are maximal and average individual index of all samples (Han et al., 2018). S_i value was taken as 540 items/kg dry weight (Everaert et al., 2018). When the NPI value is ≤2 and >2, the corresponding bioavailability levels are low and high, respectively.

Microplastic toxicity was indicated by Polymer hazard index (PHI), which could be calculated by Eq. (2):

$$PHI = \sum Pn \times Sn \quad (2)$$

where P_n is the average percentages of each microplastic polymer in all samples and S_n is the hazard score of the polymer. The S_n was taken as values compiled by Lithner et al. (2011). When the PHI value for microplastics is ≤100 and >100, the corresponding toxicity degrees are low and high, respectively (Zhou et al., 2020). The assessment system yields four risk categories. Bays with high levels of bioavailability and toxicity are assigned to Rank I (highest risk); Those with high level of bioavailability and low level of toxicity, Rank II; Those with low level of bioavailability and high level of toxicity, Rank III; Those with low level of bioavailability and toxicity, Rank IV (lowest risk). More details on the statistical analysis are shown in Text S2 of Supplementary Material 1.

3. Results

3.1. Distribution, drivers and sedimentation of microplastics

The occurrences of microplastics were recorded in sediments of 24 bays, located in Asia (17 bays), Europe (5 bays), South America (1 bay) and North America (1 bay) (Fig. 2). The median abundance of microplastics spanned four orders of magnitude, with the minimum and maximum concentrations being 0.72 and 1963.96 items/kg dry weight, respectively. Lower median abundance (<50.00 items/kg dry weight) occurred in Brest Bay (0.72 items/kg), Jiaozhou Bay (18.00 items/kg), Gdansk Gulf (20.00 items/kg) and Haikou Bay (33.40 items/kg). Higher median abundance (>500.00 items/kg dry weight) occurred in Sanggou Bay (1963.96 items/kg), Beibu Gulf (926.47 items/kg), Xiangshan Bay (861.94 items/kg), Guanabara Bay (548.63 items/kg) and Lian Bay (523.65 items/kg).

Linear regression analysis showed that microplastic abundance was significantly influenced by the human population density, waste management efficiency, maritime activity and hydrodynamic condition of bays (Fig. 3). In particular, the river plastic emissions and aquaculture production were significantly positively correlated with microplastic abundance ($P < 0.01$; Fig. 3a-3b), whereas the ratio of tidal range to average water depth showed a significantly negative correlation with microplastic abundance ($P < 0.01$; Fig. 3c). The Geodetector q statistic indicated that microplastic abundance was also significantly affected by the methodological choices ($P < 0.05$), including the pore size of filter paper (PSFP), density separation (DS), drying temperature (DT), sampling depth (SD), identification method (IM) and digestion method (DM) (Fig. 4). Moreover, a significantly positive correlation was found between microplastic abundance in water and sediment of marine bays ($P < 0.01$; $R^2 = 0.20$; Fig. 5a). The sediment–water partitioning coefficients (K_d) of microplastics ranged from 0.55 to 2.57 × 10^6 L/kg, with higher values occurring in Hangzhou Bay, Blair Bay, Xiangshan Bay and Haikou Bay (Fig. 5b).

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3.2. Similarity of microplastic composition

Based on the similarity of shape composition between pairs of samples, the 147 samples from 20 bays were divided into three groups at similarity levels ranging from 41 % to 49 % (Fig. 6a). Group I contained 107 samples from 15 bays (e.g. Sishili Bay, Thailand Gulf and Bohai Bay), and the dominant shape of microplastics in these samples was fiber (Fig. 6b). Group II contained 31 samples from 9 bays (e.g. Oman Gulf

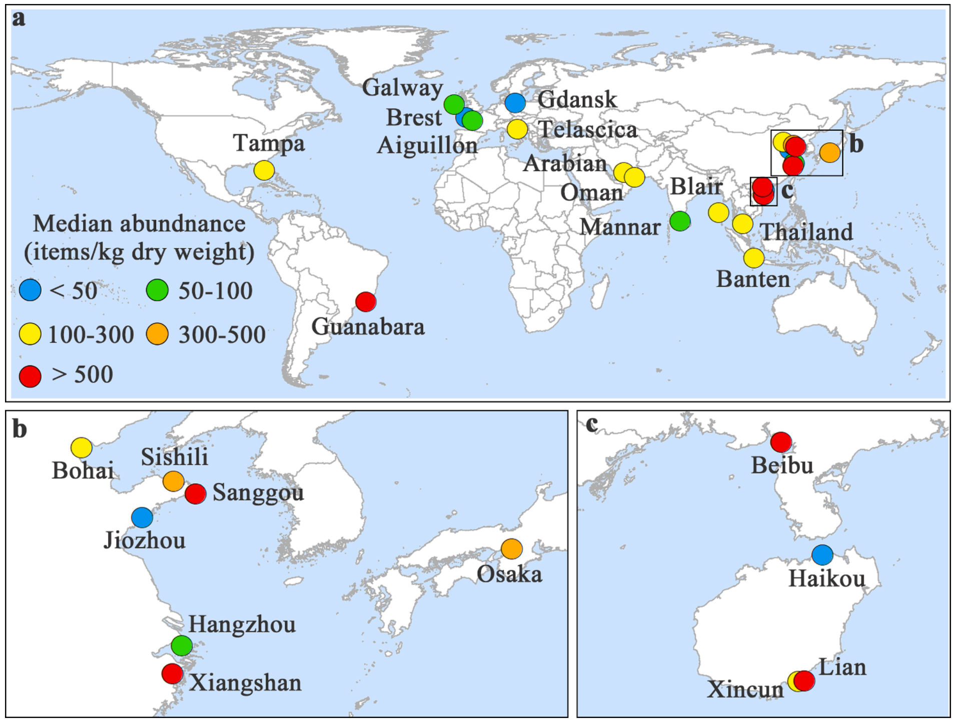

Fig. 2. Geographical distribution of microplastic abundance (a). More detailed views in selected regions (b-c).

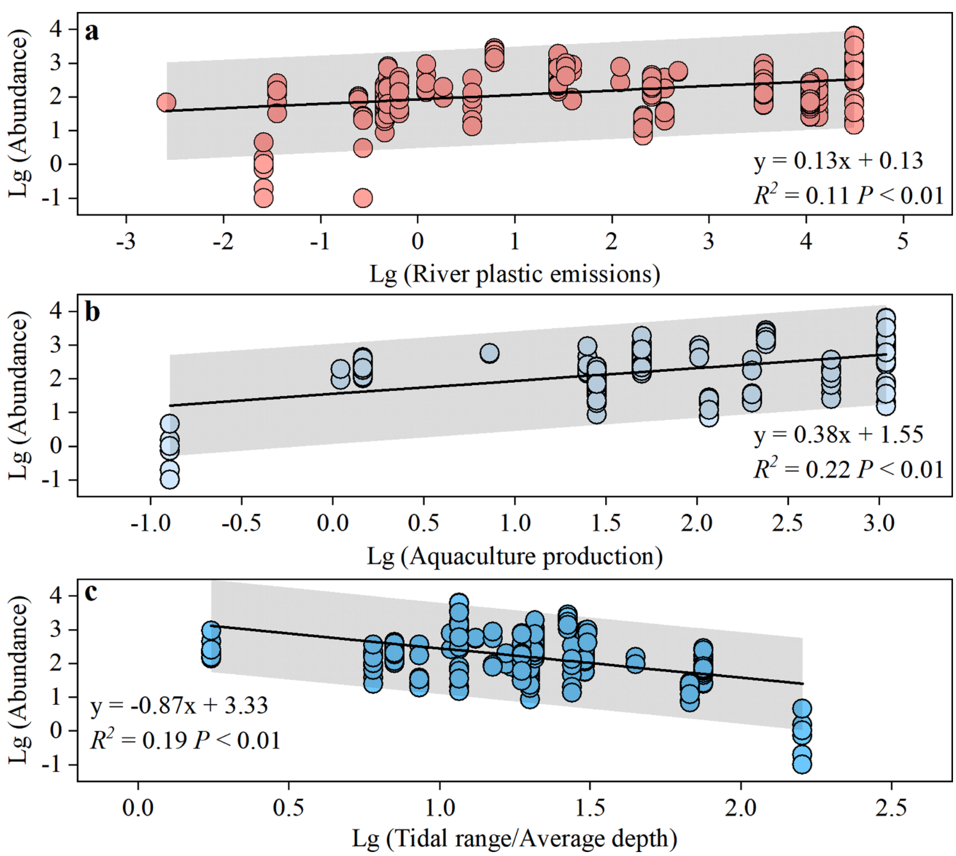

Fig. 3. The effects of river plastic emissions (a), aquaculture production (b) and ratio of tidal range to average water depth (c) on microplastic abundance. The shaded area denotes 95% prediction intervals.

Fig. 4. The effects of methodological choices on microplastic abundance and the proportion of common shapes and polymer types. SD, DT, DM, DS, PSFP and IM refer to sampling depth, drying temperature, digestion method, density separation, pore size of filter paper and identification method. The q value is proportional to the degree of influence, and asterisk (*) indicates the influence is significant at a *p*-value of 0.05.

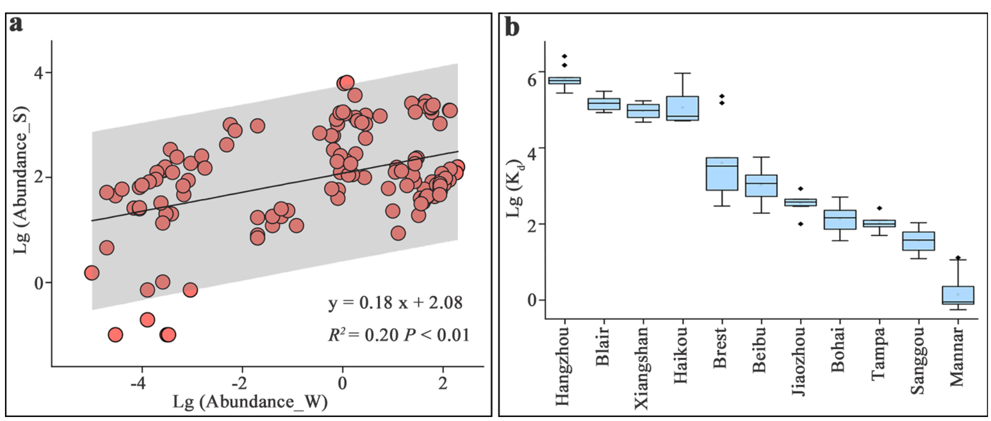

Fig. 5. Relationship between microplastic abundance in water and sediment (a); Sediment-water partitioning coefficients (K_d) of microplastics in marine bays (b). Abundance_W and abundance_S refer to microplastic abundance in water and sediment, respectively.

and Mannar Gulf), and fragment was the most abundant shape. Group III included 9 samples from Sanggou Bay and Jiaozhou Bay, with pellet being the predominant shape. The similarity coefficients for samples within bays were significantly higher than those between bays, with a mean value of 0.77 and 0.59, respectively ($P < 0.01$; Fig. 6c). The similarity in shape composition between samples was significantly negatively correlated with geographical distance, but the relationship was very weak ($P < 0.01$; $R^2 = 0.02$; Fig. S1a).

According to the similarity of polymer composition between pairs of samples, the 38 samples from 14 bays were classified into five clusters at similarity levels ranging from 44 % to 58 % (Fig. 6d). Cluster I included 16 samples from 6 bays (e.g. Bohai Bay, Brest Bay, Lian Bay, Mannar Gulf and Sanggou Bay), and the dominant polymer type in these samples was PE (Fig. 6e). Cluster II contained 11 samples from Beibu Gulf and Aiguillon Bay, with PP being the predominant polymer type. Cluster III consisted of 9 samples from Blair Bay, Haikou Bay, Hangzhou Bay, Sishili Bay and Xiangshan Bay, and the most abundant polymer type was cellulose, such as rayon (RA). The dominant polymer types in Guanabara Bay (cluster IV) and Jiaozhou Bay (cluster V) were PS and PET, respectively. The similarity coefficients between samples within bays were significantly greater than those between samples between bays, with a mean value of 0.73 and 0.39, respectively ($P < 0.01$; Fig. 6f). A significant negative correlation was found between geographical distance and the similarity in polymer composition among paired samples ($P < 0.01$; $R^2 = 0.20$; Fig. S1b). Moreover, shape and polymer composition were significantly influenced by the methodological choices (Fig. 4).

3.3. Environmental risk of microplastics

The NPI indicated that the bioavailability levels of microplastics varied widely among bays (Fig. 7). Beibu Gulf and Sanggou Bay presented high bioavailability levels (NPI > 2), with NPI values being 8.48 and 4.42, respectively. Low bioavailability levels (NPI ≤ 2) were identified in Bohai Bay, Guanabara Bay, Lian Bay, Sishili Bay, Xiangshan Bay, Brest Bay, Jiaozhou Bay, Aiguillon Bay, Blair Bay, Mannar Gulf, Hangzhou Bay and Haikou Bay, with NPI values ranging from 0.01 to 1.61.Values of the PHI ranged from 3.40 to 995.73, and two categories, characterized by a high and low toxicity potential, were distinguished in bays. High toxicity levels (PHI > 100) were observed in Guanabara Bay, Blair Bay, Mannar Gulf, Aiguillon Bay, Haikou Bay, Jiaozhou Bay and Bohai Bay, with PHI values varying from 145.05 to 995.73. Sanggou

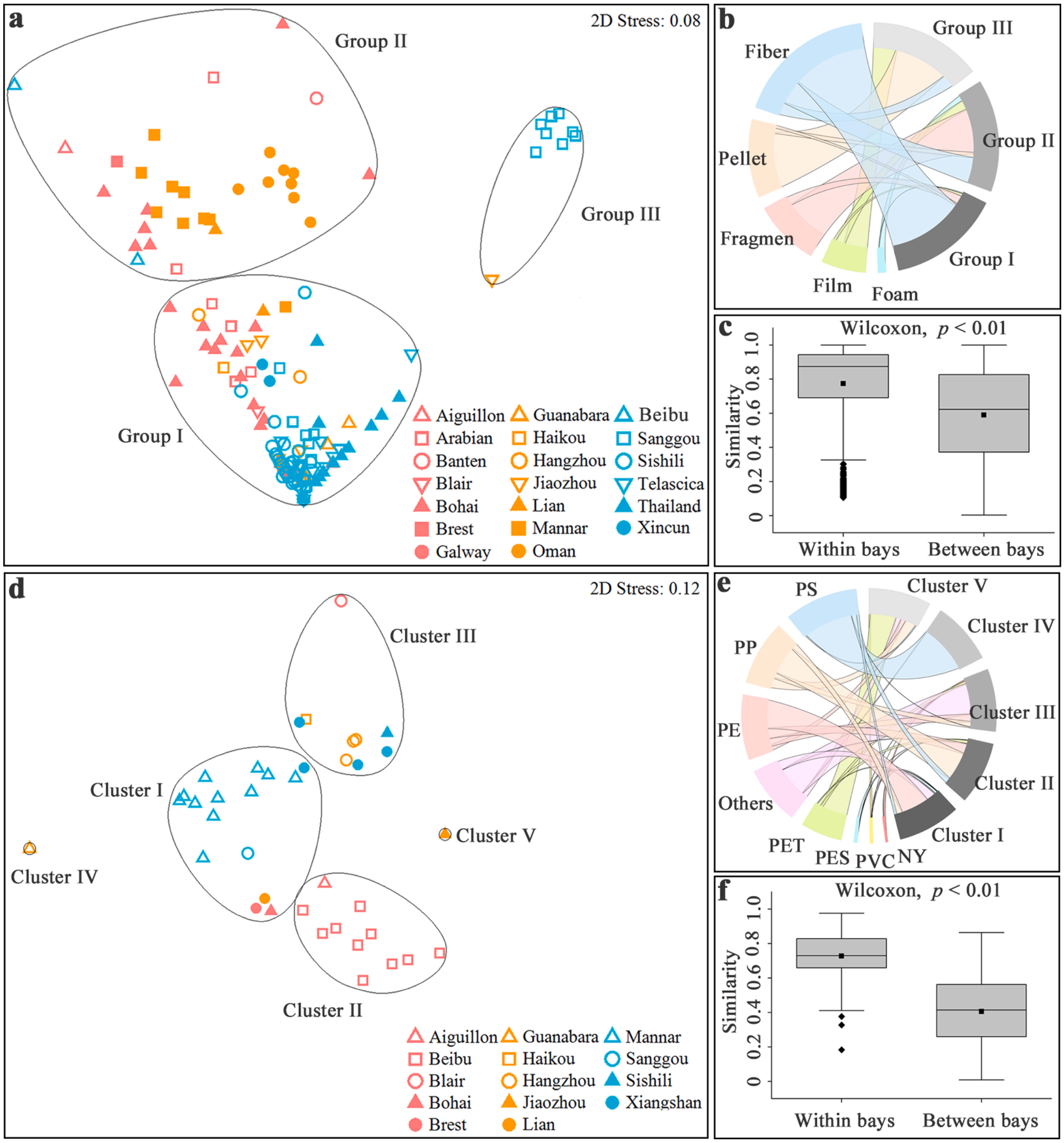

Fig. 6. Similarity in the shape (a-c) and polymer (d-f) composition of microplastics. Classification of samples via Nonmetric Multidimensional Scaling (a, d); Morphological composition of each group (b, e); Similarity coefficients between samples within and between bays (c, f); PS, PP, PE, PET, PES, PVC and NY refer to Polystyrene, Polypropylene, Polyethylene, Polyethylene terephthalate, Polyester, Polyvinylchloride and Nylon, respectively.

Bay, Sishili Bay, Lian Bay, Brest Bay, Beibu Gulf, Xiangshan Bay and Hangzhou Bay presented low toxicity levels (PHI $\leq$ 100), with PHI values ranging from 3.40 to 56.70.

Based on the proposed assessment system, the environmental risk of sedimental microplastics in bays can be divided into three classes: Rank II, Rank III and Rank IV (Fig. 7). Marine bays with high levels of bioavailability and low levels of toxicity (Rank II) included Beibu Gulf and Sanggou Bay. Marine bays with low levels of bioavailability and high levels of toxicity (Rank III) were Blair Bay, Mannar Gulf, Aiguillon Bay, Haikou Bay, Jiaozhou Bay, Guanabara Bay and Bohai Bay. Marine bays with low levels of bioavailability and toxicity (Rank IV) included Brest Bay, Hangzhou Bay, Xiangshan Bay, Sishili Bay and Lian Bay.

4. Discussion

4.1. Geographical difference and drivers of microplastic abundance

Regional variations in microplastic abundance between bays were observed, with higher abundance in East Asia and lower abundance in Europe (Fig. 2). Microplastic abundance showed a significantly positive relationship with river plastic emissions (Fig. 3a), suggesting that regional variability in abundance is likely attributed to the widely uneven geographic distribution in the quantity of plastics entering bays from land. High population densities and a large proportion of plastic waste being mismanaged in East Asia (e.g. 76 % in China and 81 % in Indonesia) contribute to a high input of plastics from land, which ultimately leads to higher microplastic abundances in these regions (Lebreton et al., 2017; Neumann et al., 2015; Van Wijnen et al., 2019). The low mismanaged rate of plastics in Europe (e.g. 2 % in France and Ireland) is subsequently reflected in the relatively low levels of plastic

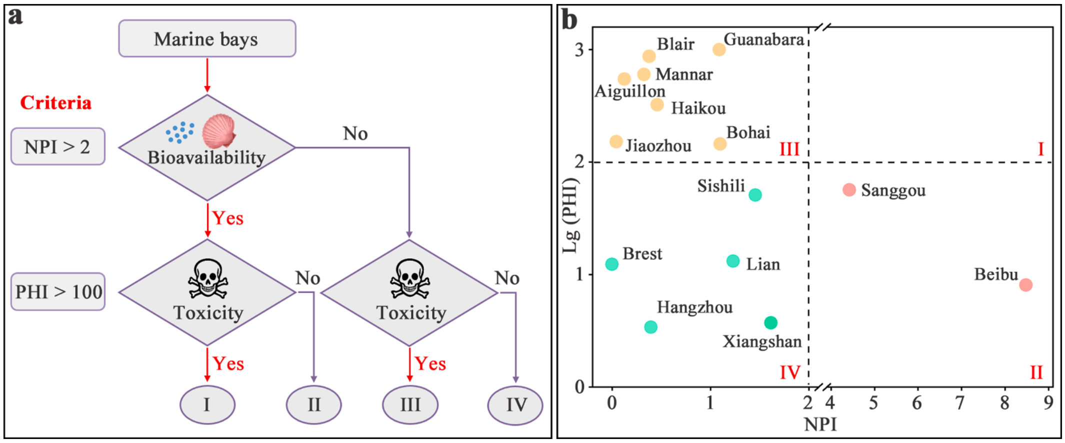

Fig. 7. Environmental risk of microplastics. Risk assessment system (a); Risk ranks of marine bays. NPI and PHI refer to Nemerow pollution index and Polymer hazard index of microplastics, respectively.

abundance in sampled bays (Jambeck et al., 2015). However, it is important to note that Europe exports a large proportion of its waste, including waste plastic, to Asia and the Pacific and so, whilst plastic waste may be more problematic in Asian areas, the source of that waste is global (Brooks et al., 2018). The geographical distribution pattern of sedimental microplastics in global reservoirs is similar to that in bays (Guo et al., 2021), and the hotspots of microplastic accumulation in sediments of bays were consistent with that of global riverine microplastics export (Van Wijnen et al., 2019), confirming the significant contribution of terrestrial input to the spatial distribution of microplastics.

The aquaculture production showed a significantly positive relationship with microplastic abundance, suggesting that aquaculture and fishing activities are also significant contributors to the regional variation in microplastic abundance in bays. This hypothesis could be confirmed by the fact that bays with the highest microplastic abundance (>1000 items/kg dry weight) are all important aquaculture areas of China, such as Sanggou Bay and Beibu Gulf. A significantly negative relationship was found between microplastic abundance and the ration of tidal range to average water depth (Fig. 3c), indicating that the distribution pattern of microplastics is associated with hydrodynamic conditions of bays. For example, Brest Bay and Hangzhou Bay are affected by strong tidal currents, resulting in lower microplastic abundances than in bays with weaker hydrodynamic conditions (e.g. Xiangshan Bay) (Frere et al., 2017; Wang et al., 2020b). Tidally driven water exchange contributes to the dilution of microplastics in waters and the resuspension of microplastics in sediments, thereby reducing the abundance of sedimental microplastics. Microplastic abundance was significantly affected by the methodological choices (Fig. 4), suggesting the results on the geographical distribution and drivers of microplastics might be related to the methodological differences between studies.

4.2. Microplastic sedimentation and its influencing factors

Microplastic abundance in sediment was significantly positively correlated with that in water, but the relationship was weak ($P < 0.01$; $R^2 = 0.20$; Fig. 5a). This can be attributed to the variation in microplastic sedimentation between bays, as indicated by the sediment–water partitioning coefficients (K_d) shown in Fig. 5b. Higher values of K_d occurred marine bay (e.g., Hangzhou Bay, Blair Bay, Xiangshan Bay and Haikou Bay) dominated by high-density microplastics such as cellulose (Fig. 6d-6e), suggesting the microplastic sedimentation in marine bays might be associated with the polymer density (Jiang et al., 2019; Lenaker et al., 2021). Exception was occurred in Jiaozhou Bay, where microplastics are dominated by high-density polymer (i.e., PET), but the value of K_d was relatively low. This underscores the fact that polymer density alone may not determine the microplastic sedimentation in marine bays (Chen et al., 2018; Sun et al., 2021; Zhang et al., 2020).

Hydrodynamic conditions of marine bays also contribute to the microplastic sedimentation. In particular, relatively lower values of K_d were found in Jiaozhou Bay and Brest Bay, where wave- or tide-generated currents significantly affect the vertical transfer of microplastic, resulting in a reduced time for sedimentation (Frere et al., 2017; Liu et al., 2005). Sediment properties including clay content and grain size are important factors influencing the microplastic sedimentation. For instance, sediments in Hangzhou Bay mainly consist of strongly cohesive clay, which is liable to adsorb microplastics and hence promote the microplastic sedimentation (Yu et al., 2019). Moreover, the large proportion of low-density microplastics (e.g., PE, PP and PS) in sediments indicates the microplastic sedimentation might be associated with ageing processes that alter the density of particles, biofilm formation that makes microplastics less hydrophobic, or incorporation into marine aggregates that facilitates the sinking of microplastics (Besseling et al., 2018; Leiser et al., 2021).

4.3. Environmental risk and control measures of microplastics

The three classes of environmental risk (Rank II-Rank IV) identified above will each require different control measures. In particular, control measures for bays belonging to Rank II need to be devoted to the reduction of microplastic abundance more broadly, which could be realized through identifying the predominant type of microplastics and then reducing their inputs to bays. Fibrous microplastics with adverse effects on aquatic species were the dominant category in 73 % of samples (Fig. 6a), demonstrating the priority of microfibers in reducing environmental risk. The predominance of microfibers occurs not only in marine bays but also in rivers and biota (Kukkola et al., 2021; Xu et al., 2021). Significant removal of microfibers from bays is unlikely to be feasible. Conversely, identifying and eliminating some of the major inputs of fibers/microfibers is a more promising route to mitigate the microplastic risks. Specifically, the reduction of microfiber emissions could be achieved by placing place a protective coating on the surface of synthetic fabrics, introducing domestic laundry retention devices, expanding the domestic water collection systems, and using tertiary treatment technologies in waste water treatment plants (Arias et al., 2022; Roy 2018).

The reduction in microplastic inputs also requires identifying potential sources of microplastics, which could be indicated by their polymer types. Microplastics in bays were recorded with a variety of polymer types, including PE, PP, PES, PS, NY, PVC and RA (Fig. 6e). The dominance of PE and PP is related to the scale of their global manufacture and use (Koelmans et al., 2019). In particular, PE and PP accounted for 50 % of China's plastic consumption in 2018 (Xu et al., 2020), and PE represented 49 % of European demand for plastics in 2016 (Sathish et al., 2020). Lower similarity of polymer composition between bays indicates the geographical differences in the sources of microplastics, and similar sources may occur in bays belonging to the same cluster. For example, extensive use of fishing nets and textiles made of rayon contribute to the microplastic pollution of bays in cluster III, such as Hangzhou Bay, Sishili Bay and Xiangshan Bay (Chen et al., 2018; Wang et al., 2020b; Zhang et al., 2019). The similarity of polymer composition weakened with the increase of geographic distance (Fig. S1b), suggesting that bays with closed geographical locations had similar sources of microplastics.

In contrast, control measures for bays belonging to Rank III should mainly focus on the management of the predominant types of high-hazard polymers (HHPs). Management concepts and measures such as the circular economy and five R's (i.e. reduce, reuse, recycle, recover and redesign) are highly recommended to reduce the amount of HHPs we generate (Thompson et al., 2009). Technological developments and behavioral changes encouraged through legislation would also help to improve the waste management of HHPs, hence reducing the toxicity levels of microplastics (Wang et al., 2020a; Xu et al., 2020). The HHPs vary among bays, which needs to be considered in the development of control measures. For example, PVC was the most common form of high-hazard polymer in Bohai Bay, Aiguillon Bay and Jiaozhou Bay (Ouyang et al., 2020; Phuong et al., 2018; Wu et al., 2020), but in Guanabara Bay and Mannar Gulf it was PES (Alves and Figueiredo, 2019; Sathish et al., 2020) and in Blair Bay and Haikou Bay it was PU (Goswami et al., 2020; Qi et al., 2020). It is worth noting that plastic waste generated on land or bay will continue to grow with increased population and increased per capita consumption due to economic growth (Jambeck et al., 2015). This means that without improvements in plastic waste management, bays belonging to the Rank IV (lowest risk) maybe become potential areas with high environmental risk of microplastics in the future.

5. Conclusions and perspective

Using a data mining framework for the scientific literature, this study provided fundamental insights into the distribution and drivers, composition and environmental risk of sedimental microplastics detected in bays and highlighted the knowledge gaps that need to be filled. Microplastic abundance varied among regions, with higher concentrations detected in East Asian bays. This spatial distribution pattern was likely associated with regional variability in river plastic input, aquaculture activity and hydrodynamic conditions. The microplastic abundance in sediment was significantly positive correlated with that in water, and microplastic sedimentation was associated with polymer density, hydrodynamic conditions and sediment properties. Three classes of environmental risk of sedimental microplastics were identified in marine bays with an assessment system considering bioavailability and toxicity, and Asian bays were identified as potential higher-risk areas. Diverse effects and the dominance of fibrous microplastics in marine bays indicate the priority of microfibers in reducing environmental risk of microplastics. The similarity of polymer composition between bays was low, suggesting the variability in the spatial distribution of microfiber sources.

Despite our efforts to make the data and results reliable and rigorous, challenges remain in understanding the geographical difference, drivers and environmental risk of sedimental microplastics in bays. On the one hand, the sampling, pretreatment and identification methods of microplastics were inconsistent among studies, contributing partly to the variation in abundance and composition. Developing a unified methodology consisting of sampling, drying, digestion, density separation, filtration and identification steps could enhance the comparability of microplastic data from different studies (Fig. 8), thereby improving our understanding for the distribution and morphology of microplastics in bays. In particular, surface sediments should be collected from the same depth, ideally from top 5 cm. To reduce the influence of humidity and organic matter on quantitative results, sediment samples should be dried and digested. Digested samples should be processed by the density separation and followed by the filtration, and the combination of separation of NaCl and NaI could achieve high recovery of microplastics. Microplastics retained in the filter are recommended to be identified by Fourier transform infrared spectroscopy or Raman spectroscopy, which are able to detect smaller-sized particles. Our suggested methodologies need modification if the research field evolves, for example, when separation methods with higher recoveries become available.

On the other hand, although the environmental risk of microplastics was quantified with the proposed assessment system using the current available dataset, several barriers still remain. First, a well-defined thresholds for safe abundance of sedimental microplastics is lacking. Secondly, the microplastic bioavailability depends not only on abundance but also on their size and density. Finally, microplastics tend to adsorb harmful chemicals from the surrounding environment, enhancing their toxicity. To provide a more reliable estimation of

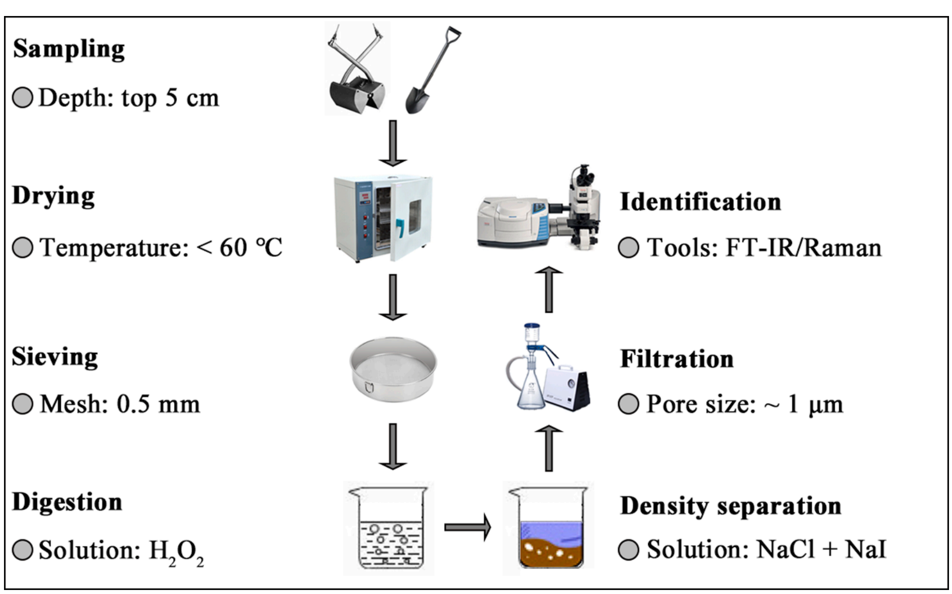

Fig. 8. Suggested sampling and analysis methods for sedimental microplastics.

environmental risk, we recommend optimizing the proposed assessment system by updating the safe abundance of sedimental microplastics, highlighting the influence of size and density on microplastic bioavailability and considering the combined toxicogenic effects of microplastics and other pollutants. Moreover, sedimental microplastics have primarily been studied in Asia and Europe, with little data from other continents. The uneven data distribution might limit our understanding for the distribution and risks of microplastics, highlighting the need for data sharing in microplastic research.

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CRediT authorship contribution statement

Dong Liu: Conceptualization, Data curation, Methodology, Visualization, Writing – original draft. **Zhao-Feng Guo:** Methodology, Writing – review & editing. **Yao-Yang Xu:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Faith Ka Shun Chan:** Writing – review & editing. **Yu-Yao Xu:** Writing – review & editing. **Matthew Johnson:** Writing – review & editing. **Yong-Guan Zhu:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2022.107483.

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