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Ecological risk assessment of microplastics and heavy metals in Northern Vietnam's estuarine sediments: A case study of Ba Lat and Bach Dang

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ABSTRACT

Estuarine environments are highly productive and biodiverse ecosystems that are particularly vulnerable to environmental pollution. This study assessed the presence and ecological risks of microplastics (MPs) and ten heavy metals in surface sediments from two major estuaries of the Red-Thai Binh River system in northern Vietnam: Ba Lat and Bach Dang. Sediment samples were collected during the rainy season (July 2024) under low tide conditions. The average concentrations of heavy metals followed the order: Hg < Cd < As < Ni < Cu < Cr < Pb < Zn < Mn < Fe. While most metal concentrations, except for Fe, were below Vietnamese regulatory limits (QCVN 43:2025/BTNMT), several samples exceeded the U.S. EPA (1997) Threshold Effects Level (TEL), particularly for As, Pb, Hg, Cu, and Ni. The geo-accumulation index identified Pb as the most enriched element, followed by As and Zn. Despite localized exceedances, the overall ecological risk associated with heavy metals was classified as low.

In contrast, microplastic contamination posed a more prominent ecological threat. MP concentrations ranged from 3,600 to 9,000 items/kg (mean: 5,908±1,790) in Ba Lat and from 1,900 to 4,800 items/kg (mean: 3,858.3±832.8) in Bach Dang, surpassing levels reported in previous regional studies. The dominant particle types were small-sized fibers (< 2 mm) and fragments (0.05–0.2 mm^2), which are likely to have greater bioavailability and ecological impact. A Potential Ecological Risk Index (PERI), incorporating MP abundance, polymer types, and hazard scores, indicated high-to-dangerous risk levels in Bach Dang and medium-to-high risk levels in Ba Lat. These findings highlight the urgent need for effective mitigation strategies, including improved plastic waste management and routine MP monitoring, particularly in ecologically sensitive areas such as aquaculture zones, coastal habitats, and salt production sites.

Keywords: Microplastic, heavy metals, estuary, surface sediment, ecological risk, Vietnam.

1. Introduction

Estuarine ecosystems are among the most productive and ecologically important habitats on Earth, providing critical services such as nutrient cycling, nursery grounds for fisheries, and water filtration (Fortune et al., 2023).

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Estuaries are globally recognized as pollution hotspots due to the cumulative impacts of urbanization, industrialization, and agricultural runoff (Freeman et al., 2019). These dynamic systems act as sinks for pollutants transported from upstream watersheds and coastal activities, with heavy metals and microplastics emerging as two particularly concerning contaminants in estuarine sediments (Vibhatabandhu et al., 2025). As a result, many estuaries have been severely degraded by the accumulation of these substances, which now rank among the most pervasive pollutants in estuarine environments.

Heavy metals (such as lead, mercury, cadmium, arsenic, and chromium) are naturally occurring elements, but they have become widespread pollutants in estuarine areas due to anthropogenic activities (Niu et al., 2021; El-Sharkawy et al., 2025). These metals are persistent (non-biodegradable) and can remain in sediments for decades, where they accumulate and continuously cycle within the environment, posing significant ecological and human health risks. Studies have documented elevated metal concentrations in estuary sediments across Asia and Europe. Research in the Changhua River estuary (China) found that concentrations of cadmium (Cd) and mercury (Hg) in inshore sediments exceeded background values by 417.9% and 187.3%, respectively (Hu et al, 2013). A study of the Medway and Thames estuaries in England found that sediments near areas of intense industrial activity contained elevated levels of metals such as Cu, Ni, Pb, and Zn, frequently surpassing environmental guideline limits; these concentrations were linked to both historical and ongoing human discharges (Spencer and MacLeod, 2002).

Microplastic (MP) contamination has also emerged in recent decades as a global environmental issue in estuarine and coastal sediments. MPs are usually defined as plastic particles smaller than 5 mm (Andrady, 2011; Arthur et al., 2009) arising from the fragmentation of larger plastics under mechanical (erosion), chemical (photodegradation), or biological degradation (via microorganisms) (Andrady, 2011; Wagner et al., 2014; Zettler et al., 2013) or direct release of small particles (e.g., microbeads in cosmetics, fibers from laundering). Due to the massive production and poor disposal of plastics globally, microplastics have become widespread pollutants present in almost every environmental compartment, including oceans, rivers, soils, and even the atmosphere (Mendes et al., 2024; Nguyen et al., 2024; Le et al., 2023a; Truong et al., 2021). Studies report MP contamination in the sediments of highly urbanized estuaries in China, India, and the United States (Prapanchan et al., 2023). The abundance of MPs in estuarine waters and sediments tends to correlate with human population density and urban development in the watershed (Mendes et al., 2024).

Although to date there is no comprehensive systematic research, several studies have provided data and an overview of heavy metal pollution in surface sediments of Vietnam's estuarine and coastal areas. Heavy metal concentrations were compared with the CCME (Canadian Council of Ministers of the Environment) ISQG (Interim Sediment Quality Guidelines). In northern Vietnam, tidal sediments of the Cam and Van Uc Rivers exhibited contamination by Cu, As, Pb, and Cd; the Ba Lat estuary by Cu, Pb, Zn, and Cr. In central region, Thanh Hoa coastal area was contaminated by Cr, Pb, Cu, As, and Zn; Tam Giang-Cau Hai Lagoon by Pb, Cr, As, and Bi; nine coastal lagoons from Thua Thien Hue to Ninh Thuan provinces by Cr, As, Pb, and Cu; and the Cai River estuary (Nha Trang) by As, Cu, and Cr. In southern Vietnam, the Thi Vai River estuary and the Can Gio mangrove forest were contaminated with Cu and Cr. These studies suggest that pollution sources may be natural (weathering processes) or anthropogenic, including agricultural chemical use and inland mineral exploitation (Nguyen et al., 2025).

Vietnam has a 3,260 km coastline and about 114 river mouths that discharge into the sea (Le et al., 2011). In addition to other pollutants, estuarine and coastal areas are currently facing microplastic pollution from riverine sources. Studies on microplastic pollution in Vietnam's estuarine and coastal regions have only been conducted in recent years and have not yet been systematically conducted nationwide. Microplastics are widely distributed in estuarine sediments, with densities ranging from a few hundred to tens of thousands of particles per kg. Some typical studies include the Red River estuary (Le et al., 2023a), the Day River estuary (Nga et al., 2025), and the Thuan An estuary, Thua Thien Hue (Y et al., 2023). Among them, fiber and fragment shapes dominate. The predominant size is usually under 1 mm. The main components are PE (polyethylene), PP (polypropylene), PET (polyethylene terephthalate), and PS (polystyrene), which are derived from common everyday plastic products such as packaging, bottles, nylon bags, and especially single-use plastics.

The co-occurrence of heavy metals and microplastics in estuarine sediments raises serious concerns for ecosystem and human health. Heavy metals are well known for their toxicity to aquatic life: they can disrupt metabolic and reproductive processes in fish, shellfish, and benthic invertebrates, often at trace concentrations (Santos et al., 2023). MPs can adsorb persistent pollutants, heavy metals, and toxins, acting as vectors that bioaccumulate and biomagnify through food webs (Nguyen et al., 2023). They may induce oxidative stress, inflammation, immunotoxicity, hormonal disruption, changes in gut microbiota, and genetic damage, posing risks to wildlife and humans (Aliya et al., 2025).

Vietnam's estuarine and coastal zones exemplify these global pollution challenges. Rapid industrialization, urbanization, and intensive agriculture, combined with inadequate waste management, have led to accelerated inputs of heavy metals and microplastics into estuaries (Le et al., 2025; Duong et al., 2023b). While nutrient pollution in estuaries has been widely studied, investigations of heavy metal and MP contamination in Vietnamese estuaries and coastal zones remain limited. Yet, studies remain fragmented and primarily restricted to Northern and Southern hotspots. In addition to microplastics, heavy metal pollution remains a significant environmental concern. Therefore, this study aims to provide additional data and an assessment of contamination levels and ecological risks associated with microplastics and heavy metals in sediments of estuarine areas in northern Vietnam. The results will provide scientific information on microplastic and heavy metal pollution and their associated ecological risks, thereby supporting future research directions and environmental management efforts targeting emerging pollutants in typical estuary systems across Asia.

2. Materials and Methods

2.1. Study area and sample collection

The study was conducted in two estuaries in northern Vietnam, the Bach Dang estuary in Hai Phong and the Ba Lat estuary (the Red River mouth) in Nam Dinh province. These areas represent distinct coastal zones subject to varied anthropogenic pressures, such as intense industrial activity, port operations, and tourism in Hai Phong, and extensive aquaculture in Nam Dinh.

The Bach Dang River, part of the Thai Binh river system, forms the natural boundary between Quang Yen town (Quang Ninh province) and Thuy Nguyen district (Hai Phong city). It stretches 32 km and discharges into the sea via the Bach Dang estuary. Quang Yen has 12,300 hectares of tidal flats and lagoons (37.1% of Quang Yen's total area), primarily located in the Bach Dang estuary. Of this, 8,700 hectares are used for aquaculture, yielding approximately 14,500 tons of molluscs annually. The aquaculture zone in the Bach Dang estuary covers 3,700 hectares, accounting for 42.5% of Quang Yen's total aquaculture area (Ngo, 2023). Moreover, the Bach Dang estuary is home to major seaports in northern Vietnam. Hai Phong's port system currently includes 50 ports, of which 15 are located on the Dinh Vu Peninsula (Bach Dang estuary), according to Decision No. 323/QD-BGTVT dated March 29, 2024, announcing the list of port terminals under Vietnam's seaport system.

The Ba Lat estuary, situated at the downstream of the Red - Thai Binh river system, forms the natural border between Nam Dinh and Thai Binh provinces. It lies between Giao Thien commune (Giao Thuy district, Nam Dinh) and Nam Phu commune (Tien Hai district, Thai Binh). The Red - Thai Binh river basin spans 88,680 km² and supports 30 million residents across 25 provinces and cities, serving as the principal water source for both domestic and agricultural use in 16 northern provinces (Tran, 2024). The estuary areas feature rich biodiversity, with the Xuan Thuy National Park and the Tien Hai Wetland Nature Reserve. Aquaculture is also well developed in this region. In 2024, aquaculture in Tien Hai occupied 5,142 hectares, including 2,086 hectares of brackish-water farming and 2,024 hectares of clam farming (Manh, 2024). According to media sources from early 2025, over 1,500 oyster farming rafts were operating in the estuary area, doubling in number within one year. Of these, 30% were for commercial oyster production and the remainder for seed oyster cultivation. Notably, some households in the Ba Lat estuary have adopted rope-hanging oyster farming techniques, demonstrating significant economic potential. Given the ecological and economic importance of these estuary areas, coupled with their exposure to anthropogenic inputs, it is necessary to evaluate the pollution status and associated ecological risks of microplastics and heavy metals.

2.2. Sampling campaigns

The sampling campaign was conducted during the rainy season in July 2024, targeting the Ba Lat estuary (the Red River mouth) and the Bach Dang estuary during low tide. In the Bach Dang estuary, sampling sites labeled BD1 to BD6 were located along the main Bach Dang River and its tributary - the Rut River, representing the riverine estuary. In comparison, sites BD7 to BD12 reflected the seaward estuary. For the Ba Lat estuary, 12 sampling sites were designated. These included riverine sites: BL1 to BL4 (within the Red River) and BL8 and BL9 (tidal creek sites), and seaward estuary sites BL5 to BL7 and BL10 to BL12. The longest distance between sampling points was about 12 km (Fig. 1).

Sediment samples were collected following the national standard TCVN-6663-19:2015 (ISO 5667-19:2004), Water Quality - Sampling - Part 19: Guidance on Sampling in Marine Sediments. 24 sediment samples were collected using a stainless steel Ponar grab sampler, with a sampling area of 522 cm^2. Surface sediment samples at 0–5 cm depth were collected at three different points each. 5 meters apart at each sampling site. The Sub-samples were then mixed to obtain one composite sample of 100g for laboratory analysis. The samples for metals analysis were stored in polyethylene bags, while others for MP were wrapped in aluminum foil and preserved in an insulated ice box until analysis.

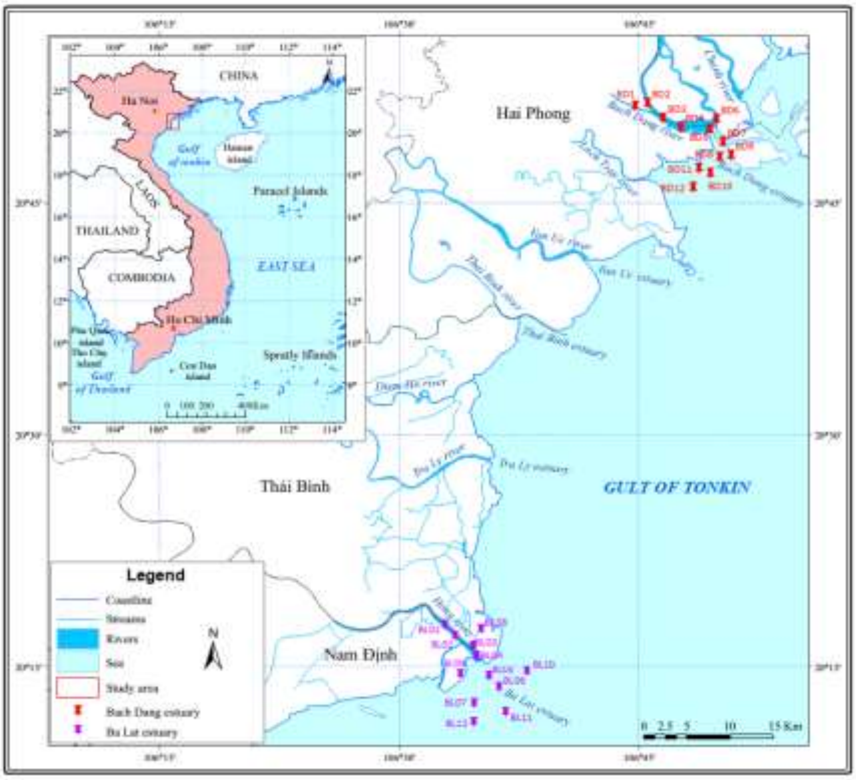

Figure 1. Sampling sites in the Bach Dang and Ba Lat estuaries

2.3 Laboratory analysis

2.3.1 Metal samples preparation

Sediment samples designated for heavy metal analysis were air-dried and subsequently oven-dried at 105°C until constant weight. The dried samples were then ground and sieved through a 1 mm mesh. Ten elements were selected for analysis: Cu, Pb, Zn, Cr, Cd, Hg, Fe, Ni, Mn, and As. The inorganic phase of 10 heavy metals was obtained by digesting 0.2 g of the sample with 5 ml of HNO_3 65%. The samples were analysed using an Agilent 8900 ICP-QQQ in MS/MS mode (Agilent Technologies 2019). Analytical quality control was evaluated based on the recovery percentage of spike samples prepared by adding a 10 $\mu g.L^{-1}$ certified reference material (CRM) for target metals (ICP-MS Calibration Standard (XXI), CPA Chem, Bulgaria) to the analysis samples. The analytical method demonstrated acceptable accuracy and precision, with recovery percentages ranging from 90.5% to 112.5% for the CRM. All samples, standards, and blanks were measured in triplicate, with the relative percent difference among triplicates less than 10%. The data are reported as the mean values of the triplicate measurements

2.3.2 Microplastic extraction, identification, and characterization

All the sediment samples were oven-dried at 40°C for 72 hours until a constant weight. The large particles in the samples were then removed using a 1mm mesh sieve. Three steps of the MP density separation process were done according to Strady et al. (2021) and Duong et al. (2022). Firstly, organic matters in the samples were removed by digesting in a 30% H_2O_2 solution (Merck, Germany) at 40°C for three hours; secondly, MP particles were flooded with a saturated NaCl solution (1.18 $g.cm^{-3}$) Finally, the supernatant was filtered through a GF/A glass microfiber filter (Whatman, 47 mm diameter and 1.6 µm pore size) using a glassware filtration unit.

MPs were then classified by shape into fiber, pellet, and fragment using a Leica S9i stereomicroscope equipped with a camera. MPs with a size range of 300 to 5,000 µm were measured using LAS software® according to the GESAMP (2019) protocol. The particle size observation range of 300–5,000 µm was determined based on the applied protocol and the GESAMP (2019) guidelines, which apply when a systematic or representative particle analysis is not feasible. This range includes explicitly fragment areas from 45,000 µm² (300 × 150 µm) to 25,000,000 µm² (5,000 × 5,000 µm), ensuring appropriate size coverage for the analysis. The polymer characteristic of MP was identified by using a microscope coupled with a µFTIR spectrometer (NICOLET iN 10 MX infrared imaging microscope, Thermo Scientific).

2.3.3. Quality control for microplastic analysis

All sampling equipment and laboratory glassware were pre-cleaned using filtered deionized water and wrapped in aluminum foil to prevent cross-site contamination. Laboratory personnel wore cotton lab coats and nitrile gloves, and all working surfaces were disinfected daily with ethanol. Reagents used in sample processing were filtered through 1.6 µm glass fiber filters (Whatman GF/A) and stored in clean glass containers. Procedural blanks were analyzed alongside actual samples to monitor potential background contamination during laboratory procedures. The average blank contained approximately two fibers per sample, which was considered negligible in comparison to the microplastic (MP) concentrations found in field sediment samples.

2.4. Pollution level and potential ecological risk assessment

2.4.1. For heavy metals

Three indices were applied to assess the accumulated degree (Igeo), potential sources (EF), and potential ecological risk (RI) of heavy metals in surface sediment.

The Geoaccumulation Index (Igeo) and Enrichment Factor (EF) are widely used to assess the presence and degree of anthropogenic metal deposition in surface soil. While Igeo is used to determine the degree of heavy metal accumulation relative to its natural concentration, EF, on the other hand, provides information on the source of heavy metal enrichment, natural or anthropogenic. The geoaccumulation index (I_{geo}) was first introduced by Muller (1969) as:

$$I_{geo} = \ln (C_n/1.5\ B_n) \quad (1)$$

Where: C_n is the concentration of the metal (n) in the sediment sample ($mg.kg^{1}$); The background value 1.5 B_n of metal (n) presents for natural fluctuations and even very low anthropogenic contamination, the respective background concentration (B_n) is multiplied by a factor of 1.5 to obtain the upper limit of the lowest contamination. The Bn values (Turekian and Wedepohl, 1961) are listed in Table 3, and the Igeo classification was presented in Table 1 (Muller, 1969).

Table 1. The I_{geo} classification

Level	Igeo value	Accumulation degree
0	Igeo ≤ 0	Practically unharmed
1	0 < Igeo ≤ 1	Unloaded to moderately loaded
2	1 < Igeo ≤ 2	Moderately loaded
3	2 < Igeo ≤ 3	Moderately - heavily loaded
4	3 < Igeo ≤ 4	Heavily loaded
5	4 < Igeo ≤ 5	Heavily - excessively stressed
6	Igeo > 5	Excessively stressed

The Enrichment Factor (EF) is calculated following (Sinex and Helz, 1981)

$$EF = (X/Fe)\ sediment\ /(X/Fe)\ Earth's\ crust \quad (2)$$

Where: (X/Fe) sediment is the concentration ratio of metal (X) to Fe in the samples; (X/Fe) Earth's crust is the concentration ratio of metal (X) to Fe in the Earth's crust. This study used average shale values from Turekian and Wedepohl (1961) as the elemental concentrations in the Earth's crust, instead of those proposed for the upper continental crust by Taylor and McLennan (1995). The EF value of 0.5 < EF < 1.5 indicates crustal contribution, such as weathering product, EF > 1.5 indicates that metals are derived from non-crustal sources, such as biota and/or pollution drainage; EF < 0.5 may indicate that a sorting mechanism for minerals is involved in the erosion of particulate trace metals during weathering of the crust and subsequent transport in the river (Zhang and Liu, 2002).

The potential ecological risk index (RI) proposed by Hakanson (1980) was applied to assess the ecological risks posed by different metals in sediment.

$$\text{RI}= \sum_{i=1}^{n} E_r^i = \sum_{i=1}^{n} T_r^i \ x \ C_f^i \quad (3)$$

Where: E^i_r is the potential ecological risk factor of metal (i); T^i_r is the toxicity coefficient of metal (i). T^i_r were defined as: 10 for As, Cd = 30, Pb = 5, Zn = 1, Hg = 40, Cr = 2 and Cu = 5. C^i_f is the contamination factor of the metal i: $C_f^i = C_s^i / C_n^i$ Where: C^i_s is the concentration of metal (i) in the sediment sample, C^i_n: background concentration (B_n) of the metal (i) (Table 3). The classification of ecological risk based on the E_r^i and RI values was given as follows: low ecological risk (E_r^i < 40, RI < 150); moderate ecological risk (40 ≤ E_r^i < 80, 150 ≤ RI ≤ 300); considerable ecological risk (80 ≤ E_r^i < 160, 300 ≤ RI < 600); high ecological risk (160 ≤ E_r^i < 320); very high ecological risk (E_r^i ≥ 320; RI ≥ 600).

2.4.2 For microplastic

To assess pollution levels and potential ecological risk, the Pollution load index (PLI), Polymer hazard index (PHI), and Potential ecological risk index (PERI) were used in the study. In which PLI, PHI, and PERI were adopted from Tomlinson et al. (1980), Hakanson (1980), and Xu et al. (2018**)**, respectively. The equations used to calculate the indices are as follows:

Pollution load index (PLI) is defined as:

$$CF_i = \frac{C_i}{C_o} \quad (4)$$

$$PLI = CF_i \quad (5)$$

$$PLI_{zone} = \sqrt[n]{PLI_1 PLI_2 \dots PLI_n} \quad (6)$$

Where: CF_i is the microplastic contamination factor; C_i is the MP concentration (mg.kg^{-1} dry weight) in sample (i); C_o is the minimum MP concentration in reference to available publications for these studied areas. In this research, the concentrations of 800 items kg$^{−1}$ dry weight (Le et al., 2023a) for Ba Lat estuary and 1,700 items kg$^{−1}$ dry weight (Duong et al.,2020) for Bach Dang estuary were selected. Since MPs at each site are considered as a whole, PLI at each sample site equals CF_i (Picó et al., 2021). An integrated index, PLI_{zone}, for the studied area was also determined using the PLI indices of the 12 sampling sites (n = 12). The PLI index is then classified as follows (Nguyen et al., 2024): Low degree contaminant (CF < 1); moderate degree (1 < CF < 3); considerable degree (3 < CF < 6); very high degree (CF > 6).

The Polymer hazard index (PHI): The hazard posed by microplastic (MP) contamination was assessed based on two factors: the chemical composition of MPs and their hazard scores, as referenced in (Lithner et al., 2011):

$$PHI = \sum P_n \times S_n \quad (7)$$

Where: P_n is the percentage of specific polymer of a sample; Sn represents the hazard score (Table 5) of different polymer types proposed by Lithner et al. (2011). Hazard levels derived from PHI values are given in Table 2 (Emmanuel and Rajaram, 2024; Pan et al., 2021; Ranjani et al., 2021).

The Potential Ecological Risk Index (PERI) was applied to assess the combined effects of microplastic pollution levels and polymer hazards on the ecology. PERI can be calculated for a single sampling site and $PERI_{zone}$ for a geographical area (Peng et al., 2018).

$$PERI = CF_i \times PHI \quad (8)$$

$$PERI_{zone} = \sqrt[n]{PERI_1 PERI_2 \ldots PERI_n} \quad (9)$$

Where: $PERI_{zone}$ is an integrated index calculated from PERI indices of the twelve sampling sites (n = 12). The potential ecological risk classification based on PERI values is summarized in Table 2 (Emmanuel and Rajaram, 2024; Pan et al., 2021; Ranjani et al., 2021).

Table 2. Hazard category levels for PHI and PERI

Polymer hazard index	
PHI value	Hazard category
0–1	Minor
1–10	Medium
10–100	High
100–1,000	Danger
> 1,000	Extreme danger
Potential ecological risk index	
PERI value	Potential ecological risk category
< 150	Low
150–300	Moderate
300–600	Considerable
600–1200	Danger
> 1200	Severe

2.5. Statistical analysis

Data series were first checked for normal distribution. Then apply the appropriate statistical analysis to compare heavy metal and MP concentrations in sediment across sites. All statistical analyses were performed using SPSS (Statistical Package for the Social Sciences) 15.0 for Windows.

3. Results and discussions

3.1. Heavy metals in sediment

3.1.1. Heavy metal concentration

Heavy metals persist in coastal sediment environments, can be released into the water column, undergo bioaccumulation and biomagnification through the food chain, and thus can cause adverse effects on benthic and aquatic biota and human health. Typically, the assessment of heavy metal contamination levels in sediment is conducted by comparing concentrations with standard levels, such as QCVN-43:2025/BTNMT, as in this study. Additionally, concentrations are compared with threshold effect levels (TELs), below which adverse biological effects rarely occur, and probable effect levels (PELs), above which adverse biological effects frequently occur (Table 3) (Macdonald et al., 1996). Heavy metal concentrations in the sediment of research areas were reported in Table 3. The average concentrations of both Bach Dang and Ba Lat estuary were in ascending order: Hg < Cd < As < Ni < Cu < Cr < Pb < Zn < Mn < Fe.

Table 3. Heavy metal concentrations (mg. kg^{-1}) in sediments of the Ba Lat and Bach Dang estuaries, min-max (mean ±SD)

Study areas	**Concentration: min-max (mean ±SD)**									
	Hg	**Cd**	**As**	**Ni**	**Cu**	**Cr**	**Pb**	**Zn**	**Mn**	**Fe**
Ba Lat estuary (2024)	0.0001-0.1456 (0.0371±0.0423)	0.03-0.25 (0.12±0.08)	5.5-23.3 (14.4±6.1)	12.3-44.3 (21.8±9.8)	5.8-40.5 (23.7±13.4)	12.5-46.2 (24.5±10.8)	12.7-64.7 (33.9±17.5)	29.0-97.8 (64.6±24.1)	240.4-1112.4 (556.0±292.7)	12,722-44,500 (22,068±10,012)
Bach Dang estuary (2024)	0.0001-0.0042 (0.0006±0.0012)	0.07-0.37 (0.15±0.09)	10.7-26.2 (15.1±5.3)	15.5-41.1 (21.7±8.2)	15.9-50.7 (27.4±11.2)	19.5-53.6 (28.1±10.9)	18.6-63.2 (31.3±13.1)	50.7-148.6 (81.3±30.3)	396.2-1145.3 (645.6±286.3)	17,188-40,857 (24,498±8,075)
QCVN-43:2025/BTNMT	0.7	4.2	41.6		108	160	112	271		20,000
TEL[a]	0.13	0.68	7.24	15.9	18.7	52.3	30.2	124		
PEL[a]	0.70	4.21	41.6	42.8	108	160	112	271		
Upper continental crust[b]	-	0.098	1.5	20	25	35	20	71	600	35,000
Average shale[c]	0.4	0.3	13	68	45	90	20	95	850	47,200

TEL: Threshold effects level; PEL: Probable effects level: a: Macdonald et al., 1996; b: Taylor and McLennan, 1995; c: Turekian and Wedepohl, 1961

Statistical analysis shows that there is no difference in the mean value of most heavy metals in Ba Lat and Bach Dang estuaries ($p>0.05$), except for Hg, which was higher in the Ba Lat estuary than in the Bach Dang estuary. The mean concentrations of Hg, Cd, As, Cu, Cr, Pb, and Zn were lower than the allowed values of the Vietnam technical regulation on Sediment Quality QCVN-43:2025/BTNMT. Ni, Mn, and Fe are not regulated in the QCVN-43:2025/BTNMT. However, in Ba Lat estuary, 11 out of 12 samples of As, 7/10 of Pb, 1/12 of Hg, 6/12 of Cu, and 7/12 of Ni exceeded the TELs, but none of them were over the PELs. In comparison, the average concentrations of As, Ni, Cu, and Pb were 1.99, 1.37, 1.27, and 1.12-fold higher than the TEL, respectively. For the Bach Dang estuary, the average concentration of 4 metals (Cd, Zn, Hg, and Cr) was lower than the TEL; other metals, such as As, however, were 2.08 times higher than the TEL; Pb, 1.04 times; Cu, 1.47 times; and Ni, 1.37 times. In detail, 12/12 samples of As; 4/12 of Pb; 2/12 of Zn; 1/12 of Cr; 10/12 of Cu; and 11/12 of Ni have concentrations higher than TEL.

Statistical analysis indicated that, in the Bach Dang estuary, there were no significant differences ($p>0.05$) in heavy metal concentrations between riverine and seaward sampling sites. It can be explained by two main reasons: with the maximum distance between sampling points being 12 km, the entire study area was subject to similar influences from the estuary's hydrodynamic regime. Additionally, port and shipping activities were consistently present throughout the sampling transect. In contrast, in the Ba Lat estuary, concentrations of Zn, Ni, Fe, and Cr at riverine sites were significantly higher than those at seaward sites ($p<0.05$). Notably, tidal creeks within the mangrove forests appeared capable of retaining pollutants in sediments, as reflected by elevated concentrations of most heavy metals at these locations compared to other sites.

3.1.2 Pollution level and potential ecological risk assessment of heavy metals in the sediment environment

The degree of heavy metal accumulation relative to their natural concentrations in the studied areas is indicated by the geoaccumulation index (Igeo), which shows that most are at level 0, suggesting they are practically unharmed. The mean Igeo values for ten heavy metals were <0, ranging from –11.76 (Hg) to –0.03 (Pb) in the Bach Dang estuary and from –5.67 to –0.001 in the Ba Lat area. The Igeo of As indicates that 83.3% samples in the Bach Dang area and 75% samples in the Ba Lat area are at level 0, the rest were at level 1- unloaded to moderately loaded, BD3 (0.39), BD6 (0.43), BL4 (0.23), BL6 (0.26), and BL9 (0.09) in detail. The Igeo of Zn at level 1 was 8.3% in the Bach Dang area only, whereas the other sediment samples were at level 0. The Igeo of Pb was highest in both areas, showing 8.3% at level 2 - moderately loaded, 25% at level 1, 66.7% at level 0 in Bach Dang, and 16.6% at level 2, 41.7% at level 1, and 41.7% at level 0 in Ba Lat.

The EF calculated results show that the mean EF values range from 0.002 to 3.03 and from 0.19 to 3.78 in Bach Dang and Ba Lat, respectively. The EF values for Hg were lowest, and those for Pb were highest, in the following order: Pb > As > Zn > Mn > Cu > Cd > Ni > Cr > Hg in both studied estuaries. The mean EF values of Pb, As, and Zn in both areas were greater than 1.5, suggesting that their sources are non-crustal materials, biota, and/or pollution drainage. Industrial effluents, port operations and navigation, and agricultural runoff are considered among the main sources of metal pollution in the environment. The elevated levels of As, Zn, and Cd in the environment were attributed to industries such as mechanical engineering, textiles, leather and rubber processing, tobacco, paper, and plastics (Le et al., 2024). Excess feed from aquaculture can cause nutrient and heavy-metal pollution, including Zn, Fe, Cu, Co, I, and Se (Kong et al., 2020). Port operations and navigation release heavy metals into the surrounding environment through antifouling paint leaching, ship maintenance waste, cargo spills, fuel emissions, ballast water discharge, and dredging activities. The agricultural sector, on the other hand, can release heavy metals through fertilization, pesticides, livestock manure, and wastewater (Alengebawy et al., 2021). Thus, it can be considered that these are the primary pollution sources of heavy metals in the study areas, particularly in the context that the Ba Lat and Bach Dang estuaries are the endpoints receiving pollution from rivers that run through the key economic region in northern Vietnam with highly industrial activities, extensive agriculture in the Red River Delta, the most significant port operations in Hai Phong Province, and aquaculture activities taking place in these two estuarine areas. Meanwhile, EF values for Hg were lower than 0.5, suggesting its origin from the erosion of a weathering crust containing Hg. The remaining heavy metals all have EF values in the range from 0.5 to 1.5, demonstrating the crustal contribution, such as weathering products. Potential ecological risk factors for each metal (Eri) and the Potential ecological risk index (RI) for each sampling point were calculated (Fig. 2). Based on the categories of Hakanson (1980), the heavy metals pose low ecological risks. ($E_r^i < 40$, RI < 150) in both studied estuaries (RI ranged from 15.9 to 79.4, average: 39.5±18.8). A study on heavy metals (Fe, Mn, Zn, Pb, Cu, Cr, V, As, Co, Cd, and Mo) in surface sediments along the coast of Vietnam, with 43 sampling points covering estuaries, seagrasses, coastal lagoons, embayments, and coral reefs, was conducted (Nguyen et al., 2025). The results revealed that most heavy metals had average Igeo values < 0, except for Zn, As, and Cd, which ranged from 0 to 1. These results were consistent with our findings, except for Pb. In a potential ecological risk assessment, only Cd showed a moderate potential ecological risk. However, overall, the RI values ranged from 2.35 to 211.83, with an average of 44.97, also indicating low risk.

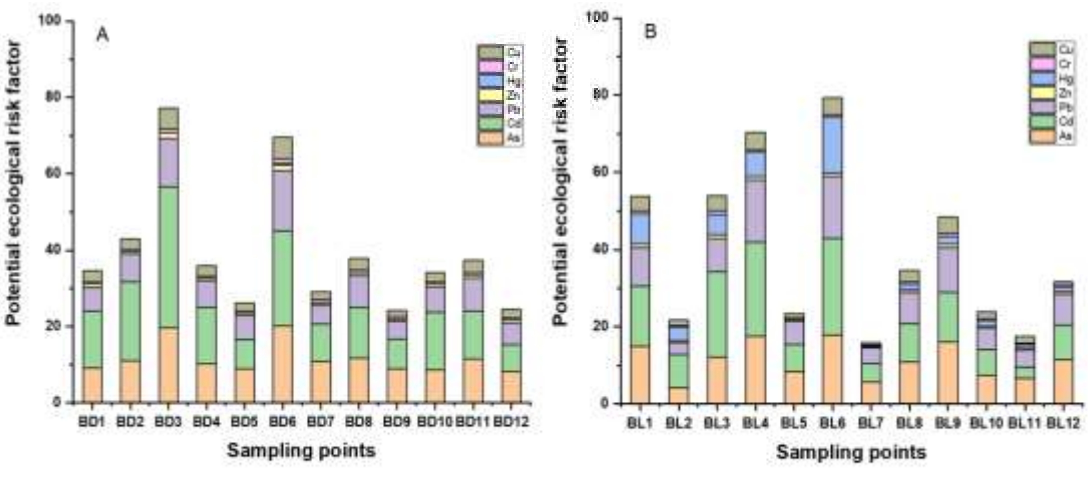

Figure 2. Potential ecological risk factor of each metal (in different colours) and Potential ecological risk index (the whole column) in Bach Dang estuary (A) and Ba Lat estuary (B)

3.2. Microplastics in sediment

3.2.1. Microplastic abundance

The concentration of MP in surface sediment of the Ba Lat estuary area was significantly higher than in the Bach Dang ($p<0.05$), which were from 3,600 to 9,000 (average of 5,908±1,790) and 1,900 to 4,800 (3,858.3±832,8) items/kg, respectively. (Fig. 3). The above results may be due to Ba Lat being the primary outlet of the Red River system, receiving a substantial load of microplastics from a large basin with high population and industrial density upstream (Le et al., 2023a; Nguyen et al., 2024). The Ba Lat area features alluvial terrain and mangrove forests, characterized by low flow velocities, which help retain and accumulate microplastics in sediments (Long et al., 2021; Vermeiren et al., 2023; Viet Dung et al., 2021). In contrast, the Bach Dang estuary is strongly influenced by tidal interference, which increases the transport and dispersion of microplastics into the sea rather than depositing them in place (Lefebvre et al., 2012; Le et al., 2022). The abundance of MP in both Ba Lat and Bach Dang estuaries was higher than that in the Guangdong Coastal Areas, South China (Li et al., 2021) or the coast of southeast India (Emmanuel and Rajaram, 2024), Black Sea and Caspian Sea (D'Hont et al., 2021), Cowichan and K'omoks estuaries in Canada (Zoveidadianpour et al., 2025), or other estuaries in Vietnam, such as Tien Yen Bay, Quang Ninh, Vietnam (Duong et al., 2023a). On the other hand, MPs abundance in our study areas was lower than that reported for Jakarta Bay, Indonesia (Manalu et al., 2017), and the North East Arabian Sea, India (Gurjar et al., 2023), and much lower than the concentrations found in river sediment samples. In comparison, microplastic concentrations in the Red River range from 990 to 21,610 items/kg (Nguyen et al., 2024). In urbanized rivers in the Red River Delta of Vietnam, such as the To Lich, Nhue, and Day rivers, MP concentrations have been reported to range from 1,600 to 94,300 items/kg (Duong et al., 2023b) (Table 4).

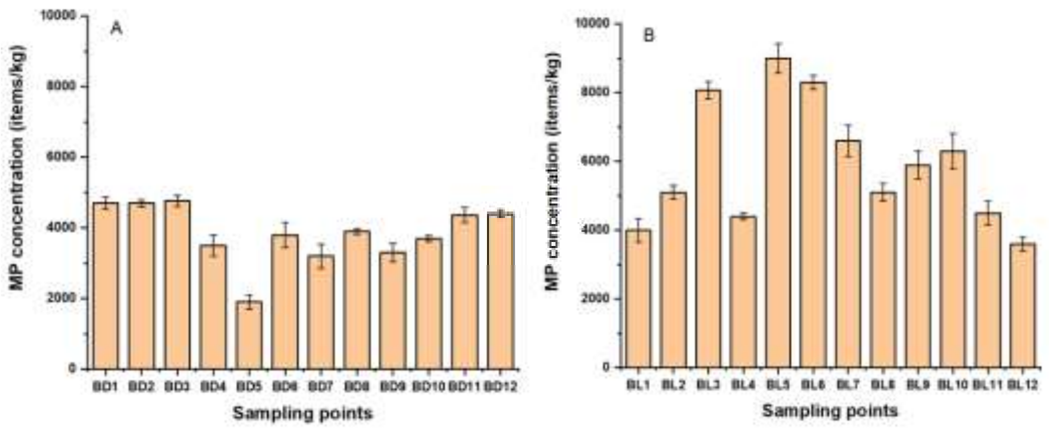

Figure 3. Microplastic abundance in Bach Dang estuary (A) and Ba Lat estuary (B)

There were insignificant statistical differences ($p>0.05$) between MP abundance in the riverine site and seaward sites of both estuaries. Studies on microplastic pollution in surface sediments have been conducted in the Ba Lat estuary (Le et al., 2023a) and the Bach Dang estuary (Duong et al., 2020). Sampling locations were at the river mouths; sampling campaigns were conducted in July and August 2019 for the Bach Dang estuary and in August, September, November, and December 2020 for the Ba Lat estuary. The sampling methods and microplastics analysis procedures were consistent with those applied in this study. Therefore, the comparison used to determine the temporal trends of microplastic pollution in the studied areas is considered unbiased and reliable. Temporally, the distribution of MP concentration in the Ba Lat estuary has increased since previous studies, reaching 2.7 times higher than reported in Le et al. (2023a). The MP concentration in the Bach Dang estuary showed a slight increase, 1.03 times higher than previous results (Duong et al., 2020).

Table 4. MP abundance (mg. kg^{-1}) in sediments of the Ba Lat, Bach Dang, and other estuaries, min-max (mean ±SD)

Areas	Sampling time	In sediment items/kg range (mean)	References
Ba Lat estuary	2020	800–3,817 (2,188±1,499)	Le et al., 2023a
Ba Lat estuary	2024	3,600 to 9,000 (5,908±1,790)	This study
Bach Dang estuary	2019	1,700–6,500 (3,730±1,675)	Duong et al., 2020
Bach Dang estuary	2024	1,900–4,800 (3,858±833)	This study
The Red River from Hanoi to Ba Lat river mouth	2023	Dry season: 653–8,069 Rainy season: 990–21,610	Nguyen et al., 2024
Tonkin Bay, North Vietnam	2020–2021	63–955	Phuong et al., 2024
Tien Yen Bay, Quang Ninh, Vietnam	2019	236–1,324 (664±68)	Truong et al., 2020
Guangdong Coastal Areas, South China	2018	433.3–4,166.3 (1444 ± 28)	Li et al., 2021
Jakarta bay, Indonesia	2015, 2016	18,405–38,790	Manalu et al., 2017
North east Arabian Sea, India	September 2018 to March 2020	4,400–15,300	Gurjar et al., 2023
Coastal of Southeast India	October 2020 to September 2021	Monsoon season: 84.3±24.2 to 325.4±113.9 Post-monsoon: 75.5±32.5 to 325.4±113.9 Summer season: 59.7±17.2 to 209.7±47.4 Pre-monsoon season: 85.7±5.0 to 246.0±46.2	Emmanuel and Rajaram, 2024
Black Sea and Caspian Sea		Black Sea: 140–7,360 (1,599±1,469) Caspian Sea: 80–2,095 (862±545)	D'Hont et al., 2021
British Columbia, Canada		Cowichan Estuary: 14.37±11.57 K'omoks' Estuary: 30.96±14.58	Zoveidadianpour et al., 2025

3.2.2 Microplastics shape, size, and color

MP found in sediment are diverse in shape, size, and colour. The shapes can be fiber, pellet, foam, fragment, film, bead, or random. In this study, MP in the samples exhibited fiber- and fragmented-shaped forms. In both areas, fibers dominated, 77.3–100% in the Bach Dang area and 97.7–100% in Ba Lat area (Fig. 4). Our results are also consistent with the previous studies, including 94% fibers in the Ba Lat estuary (Le et al., 2023a), 75.5% in the Red River from Hanoi to the Ba Lat estuary (Nguyen et al., 2024), 66–92% in southeastern India (Emmanuel and Rajaram, 2024): 95.1% in the Black Sea and Caspian Sea (D'Hont et al., 2021) and 77.3% in the coastal region of Guangdong, southern China (Li et al., 2021). According to Duong et al. (2023a) and Phuong et al. (2024), fibers dominate the sediment of Northern coastal Vietnam. Potential sources of fiber include fisheries (e.g., the breakdown of fishing nets and ropes), waterway transport, domestic wastewater, and textile fibers (e.g., clothing fibers discharged during washing).

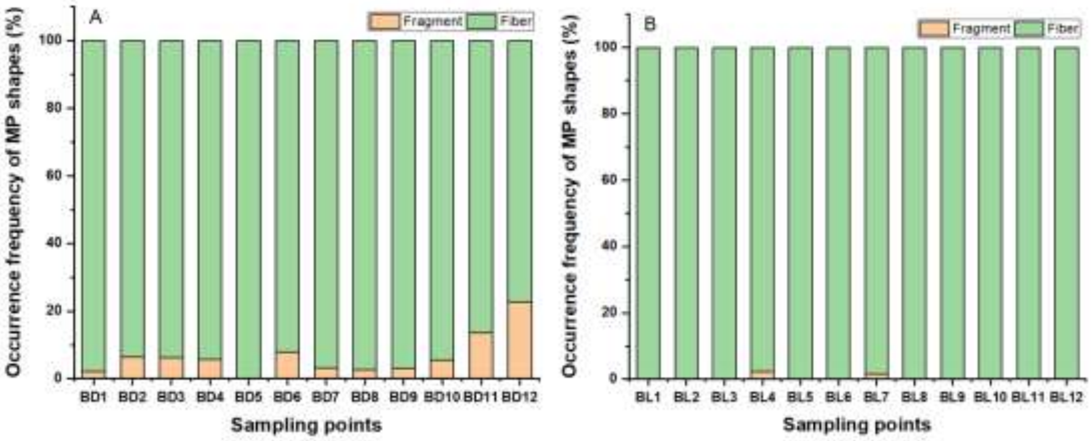

Figure 4. Types of microplastics in the surface sediments from Bach Dang (A) and Ba Lat (B) estuaries

The fibers were categorized into five levels: 0.3–1.0 mm, 1–2 mm, 2–3 mm, 3–4 mm, and 4–5 mm. In both areas, MPs were found mainly in small size (< 2 mm), 79.47–99.44% in the Ba Lat area and 78.95–94.74% in the Bach Dang area (Fig. 5). In which the items of 0.3–1.0 mm occupied 39.22–67.80% and 42.11–73.68% in Ba Lat and Bach Dang estuary, respectively. The fragments were mainly found in the Bach Dang area, which occupied 94.3%. Most items were 0,05–0,2 mm^2 in size. Our finding is consistent with the previous results in the Ba Lat estuary (Le et al., 2023a), Bach Dang estuary (Duong et al., 2023a), Guangdong Coastal Areas, South China (Li et al., 2021), Cowichan and K'omoks estuaries in Canada (Zoveidadianpour et al., 2025**.** The small items found indicate that MP particles have split into smaller particles. Thus, posing a greater potential impact on aquatic animals, as noted in the small-sized MP found in a variety of animals, as reviewed by Jeong et al. (2024). On the other hand, smaller MPs are more easily ingested and more difficult to egest by biota (Liu et al., 2020). Moreover, microplastics present a chemical risk in addition to the physical consequences they have. They contain toxic additives (e.g., plasticizers, flame retardants) that can leach into the environment and be absorbed by organisms. Furthermore, due to their large surface area and hydrophobic properties, microplastics can adsorb persistent organic pollutants (POPs) and heavy metals from the surrounding environment, acting as a medium for transporting these toxins into organisms, potentially increasing their toxicity and risks to the ecosystem (Tursi et al., 2022).

The MP in the study areas appeared in 8 colors: red, blue, gray, white, black, yellow, green, and purple. The primary colour was white, accounting for 37.8–59.6% in Bach Dang area and 30.6–58.7% in Ba Lat area, followed by black colour 20.5–32.4% and 19.1–40.0% in Bach Dang and Ba Lat respectively (Fig. 6). The abundance of black and white microplastics in the sediment corresponds to the findings of other publications (D'Hont et al., 2021; Emmanuel and Rajaram, 2024; Cao et al., 2025; Nguyen et al., 2024; Zoveidadianpour et al., 2025). White-coloured MPs can originate from plastic materials used at sea, such as fishing nets and lines, as well as daily-life plastic products. In contrast, black-coloured MPs pose greater ecological risks, as they may originate from industrial products or tire wear (Zoveidadianpour et al., 2025).

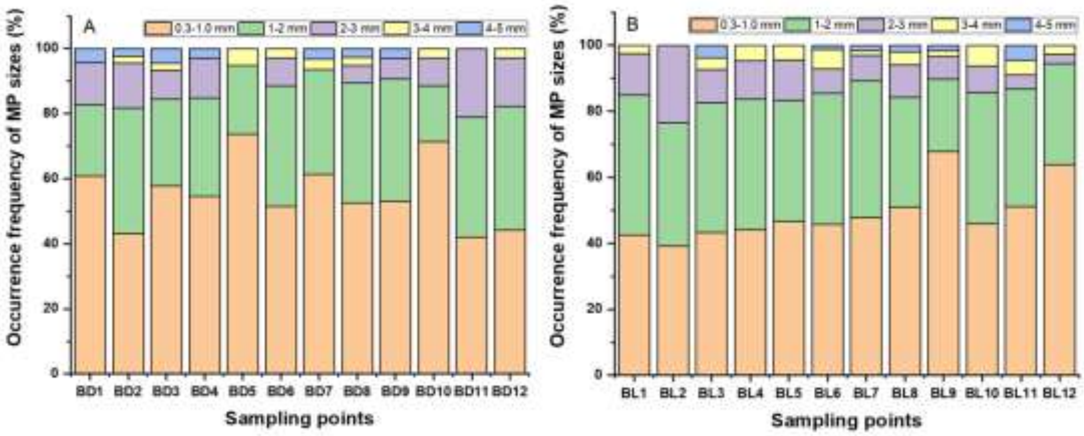

Figure 5. Size of microplastics in the surface sediments from Bach Dang (A) and Ba Lat (B) estuaries

In both areas, the least accounted colour was yellow, only 0–5.3% in Bach Dang and 0–2.2% in Ba Lat estuary. Yellowing, together with fragmentation, the formation of oxygen-containing groups, and biofilm, are MP physicochemical properties that are altered by weathering processes (Liu et al., 2020). The low abundance of yellow particles in the studied areas suggests that microplastic degradation is not evident, and most likely originates from surrounding areas (Li et al., 2021). This is consistent with the abundance of small particles in the study area, as larger, heavier items would settle during transport from the river to the sea.

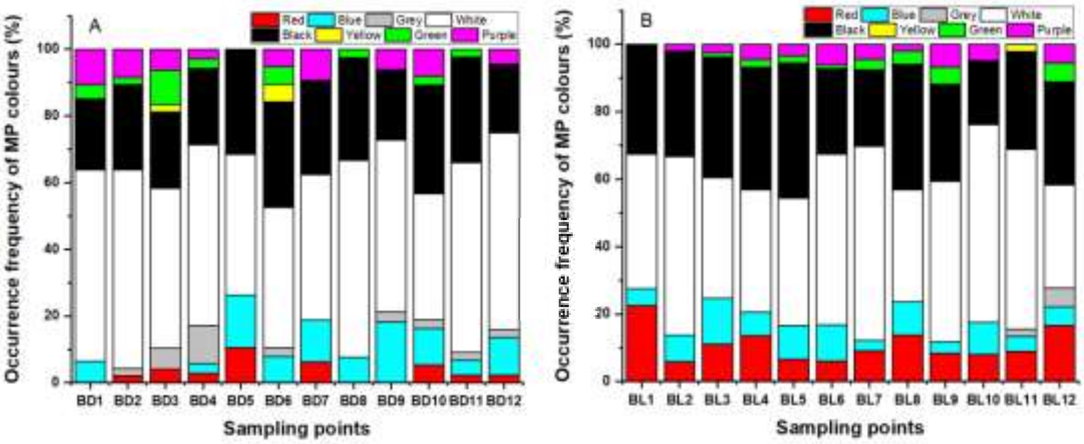

Figure 6. Microplastics colours, Bach Dang (A) and Ba Lat (B) estuaries

3.2.3 Polymer composition

Analysis results revealed seven main polymer types in the research areas, including polyethylene (PE), polypropylene (PP), polystyrene (PS), polyurethane (PU), polyvinyl chloride (PVC), polyamide (nylon) (PA), and polyester (Fig. 7 and Table 5). In Bach Dang, PE was the most abundant (67.9%), followed by polyester, PP, PS, and PU, with PVC having the lowest share (0.89%). Only PP and PS were found in the intertidal sediments of the Tonkin Bay Coast, North of Vietnam, including Van Don (Quang Ninh province), Lan Ha Bay-Cat Ba island (Hai Phong city), Thai Thuy (Thai Binh province), and Giao Thuy (Nam Dinh province) during 2020–2021, research by Phuong et al. (2024). In Ba Lat estuary, PE was also the main polymer (71.50%), followed by PP, PS, PA, and polyester (2.80%). PE, PP, PA, and PU were detected in previous studies conducted in the Ba Lat area (Le et al., 2023a). In which PE and PP were also the dominant polymers, while the PA proportion was similar to that of this study. A notable point is that some types of pollutants (e.g., polyester) with high toxicity levels were only detected during this period, not in the previous one.

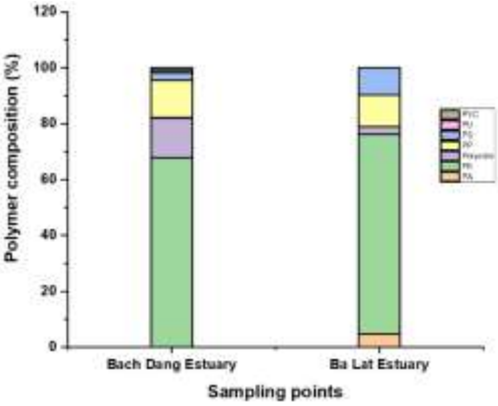

Figure 7. Polymer composition proportion (%)

Table 5. Polymer detection in Ba Lat and Bach Dang estuaries

Polymer	Main application[a]	Hazard score	Ba Lat estuary	Bach Dang estuary
Polyethylene (PE)	Toys, bottles, pipes, housewares, etc.	11 (II)	71.50%	67.86%
Polypropylene (PP)	Food packaging, microwave-proof containers, etc.	1 (I)	11.21%	13.39%
Polyvinyl chloride (PVC)	Pipes, cable insulation, garden hoses, etc.	10,551 (V)	-	0.89%
Polyamide (nylon) (PA)	Bearings, automotive applications, etc.	47 (III)	4.67%	-
Polyurethane (PU)	Upholstery, sports mats, packaging bags, etc.	7,384 (V)	-	0.89%
Polystyrene (PS)	Spectacle frames, plastic cups, packaging, etc.	30 (II)	9.81%	2.68%
Polyester	Textiles, plastic bottles, plastic-containing products and packaging, etc.	1,117 (IV)	2.8%	14,29%

[a]From Plastics Europe (2016); [b]From Lithner et al. (2011); Level V: might be carcinogenic; Level IV: can cause an allergic skin reaction; Level III: can be toxic if inhaled, swallowed, or in contact with skin; Level II: can cause respiratory irritation, skin irritation, serious eye irritation, severe skin burns, or eye damage; Level I: less harmful

The presence of very high-hazard-score polymers, such as PVC (Sn of 10,557), PU (Sn of 7,384), and polyester (Sn of 1,117), might pose risks to aquatic organisms. PVC is considered a potentially toxic polymer because it contains many additives, such as phthalates and chlorinated stabilizers, that can be released into the sediment environment, thereby causing toxicity to benthic organisms (Henkel et al., 2022; Kudzin, 2023). Similarly, polyurethane (PU) can be absorbed by aquatic organisms and cause acute toxicity, while PU degradation products can impair their physiological health (Dinani et al., 2021). Polyester fibers (microfibers) also have greater potential to penetrate the benthic ecosystem than fragmented polymers, thereby affecting sediment ecological functions, such as organic matter metabolism and community structure (Ladewig et al., 2024). In addition, polyester was considered to have a higher capacity to adsorb contaminants than other polymers (Llorca et al., 2020; Wang et al., 2021); thus, 14.3% of polyester in the Bach Dang area is notable for its potential to contribute to additional contamination. The high proportion of PE in sediment is consistent with numerous previous studies in Vietnam, including those in water and sediment environments of lakes, rivers, coastal areas, and aquatic animals (WWF, 2023). There are 4 major plastic product groups produced in Vietnam, including packaging plastics, of which 39% are made from PE, PP, and PET. PE raw material is in high demand in the plastic industry, accounting for 31% of total imported plastic raw materials (WWF, 2023), and in plastic packaging, especially single-use bags, which account for the most significant proportion of plastic waste in Vietnam (The World Bank, 2021). These are some of the reasons for the large abundance of PE in the environment.

3.2.4 Pollution level and potential ecological risk assessment of MPs in the sediment environment

As mentioned above, for PLI calculation, a critical factor is the baseline concentration, which can be the minimum concentration reported in available references or the lowest MPs abundance measurement in the study. In this research, the lowest MP concentrations reported in previous studies in both Bach Dang and Ba Lat estuaries were chosen as the baseline. Therefore, PLI results can temporally indicate MP pollution levels in these areas. PLI values in Bach Dang ranged from 1.12 to 2.82; the mean was 2.27, and the PLI_{zone} was 2.21, indicating a moderate pollution level. In contrast, PLI data from Ba Lat indicated a considerable to very high degree of MP pollution in this area, ranging from 5.0 to 11.75 (mean value: 7.99; PLI_{zone}: 7.68). The baseline MP concentrations in the Ba Lat and Bach Dang estuaries in this study are relatively high compared to those in other estuarine and coastal areas in Vietnam and worldwide. However, studies on microplastic pollution have only been conducted in recent years, and the research in the Bach Dang and Ba Lat estuaries, which this study used as references for baseline MP concentrations, is the earliest publication in these areas. Therefore, these baseline concentration values were still employed in the present study. Accordingly, our results likely underestimate the accurate cumulative anthropogenic input since the onset of pollution. The PLI_{zone} values in this study were relatively lower than those of Dongshan Bay, China (PLI_{zone} = 14.2; Pan et al., 2021), the Day River (PLI_{zone} = 10.53), and the To Lich River (PLI_{zone} = 17.3; Duong et al., 2023). However, the PLI_{zone} of the Bach Dang estuary was higher than that reported for the Red River (PLI_{zone} = 1.97; Nguyen et al., 2024). Meanwhile, the PLI_{zone} of the Balat estuary was higher than that of the Red River (Nguyen et al., 2024), the Le Thuy beach area in Quang Ngai province (PLI_{zone} = 3.15; Le et al., 2023b), and also the Nhue River (PLI_{zone} = 6.52; Duong et al., 2023).

Even though the PLI of Ba Lat was significantly higher than that of the Bach Dang area, the presence of more hazardous MP components, such as PVC and PU, led to a considerably higher PHI value in the Bach Dang estuary (385.79, indicating a dangerous hazard level, compared to the Ba Lat area (44.43), a high hazard level. No correlation between PLI and PHI of MPs has also been reported (Galloway et al., 2017; Vijayaprabhakaran et al., 2024). Based on PERI scores, the Bach Dang estuary sediment exhibited a high to dangerous ecological risk of MPs, with PERI values ranging from 431.2 to 1089.3, while the mean PERI value and $PERI_{zone}$ values were 875.6 and 852.6, respectively. Meanwhile, Ba Lat estuary sediment posed a medium to high ecological risk associated with MPs, with PERI ranging from 222.2 to 522.1, a mean value of 355.0, and a $PERI_{zone}$ of 341.1. The PERI index has been widely used to assess the potential ecological risk posed by MPs. This index integrates three factors: the pollution load of MPs (represented by the PLI value), the proportion of each polymer in the sample (represented by the Pn variable in eq. 7), and their toxicity (the Sn variable in eq. 7). Because the PERI index is used to assess potential ecological risks to organisms, the toxicity of polymers is a critical factor. For this reason, although polymers classified as carcinogenic (e.g., PVC and PU) were detected in very low proportions in this study, a high PERI value remains reasonable and is not an overestimation. In fact, numerous published studies have discussed and supported this conclusion (Emmanuel and Rajaram, 2024; Nguyet et al., 2024; Duong et al., 2023). A prior study in the Uppanar River, Gadilam River, and Cuddalore Coast, Cuddalore district, Bay of Bengal, Southeast India (Emmanuel and Rajaram, 2024) documented PHI values (9,554–18,931), which were much higher than those in our study areas. However, the PERI values in this area (80–1,125) were comparable to those in the Bach Dang estuary. The PERI values of both Bach Dang and Ba Lat estuaries, however, were substantially higher than that calculated for Dongshan Bay, China (21.5; Pan et al., 2021).

4. Conclusions

This study evaluated microplastic (MP) and heavy metal contamination in surface sediments from the Ba Lat and Bach Dang estuaries in northern Vietnam. Heavy metal concentrations were comparable between the two sites and generally below Vietnamese sediment quality standards (QCVN 43:2025/BTNMT). However, localized exceedances of As, Pb, Hg, Cu, and Ni relative to the U.S. EPA (1997) Threshold Effects Level (TEL) indicate potential ecological concern. Pb was the most enriched element, followed by As and Zn, though overall ecological risks remained low to moderate. In contrast, MP contamination represented a more critical and emerging threat. Concentrations were higher in Ba Lat than in Bach Dang, dominated by small-sized fibers and fragments (< 2 mm) with high bioavailability. The Potential Ecological Risk Index (PERI) revealed high-to-dangerous levels in Bach Dang and medium-to-high levels in Ba Lat, primarily linked to hazardous polymers and industrial black particles. Despite existing mitigation efforts, urgent and more comprehensive actions are needed. Reducing plastic emissions at the source, improving waste management, and phasing out single-use plastics are crucial. Developing integrated risk assessment frameworks that account for polymer mass and contaminant vectoring (e.g., heavy-metal adsorption) will enhance understanding of co-pollution dynamics and support sustainable management of estuarine ecosystems.

Acknowledgments

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