



# Assessment of heavy metals of the mangrove flats over the largest delta, Beibu Gulf in China: coastal ecological risk with management strategies

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## ABSTRACT

Heavy metals in mangrove tidal flats poses a significant threat to vegetation growth and adversely affect benthic fauna. However, little information is related about how changes of heavy metals beneath mangrove with associated coastal countermeasures. In this study, we collected 56 sediment samples along a transect from creek mudflat zone (CMZ) and fringe mangrove zone (FMZ) toward the interior mangrove zone (IMZ) in the Nanliu River Delta, the largest delta in the Beibu Gulf. The median concentrations of heavy metals followed the order: Fe ( $21731.84 \text{ mg kg}^{-1}$ ) > Cr ( $244.20 \text{ mg kg}^{-1}$ ) > Mn ( $5.01 \text{ mg kg}^{-1}$ ) > Zn ( $36.71 \text{ mg kg}^{-1}$ ) > Pb ( $20.61 \text{ mg kg}^{-1}$ ) > Cu ( $13.19 \text{ mg kg}^{-1}$ ) > Ni ( $31.08 \text{ mg kg}^{-1}$ ) > Cd ( $0.05 \text{ mg kg}^{-1}$ ). Results revealed a clear increasing gradient in heavy metal concentrations from CMZ and FMZ toward IMZ, highlighting the capacity of even early-stage mangroves to sequester metallic pollutants. The spatial variation was primarily attributed to sediment texture, which transitioned from coarser sediments in the CMZ to progressively finer sediments in the FMZ and IMZ, enhancing heavy metal adsorption.

We assessed the heavy metal risk in tidal flat mangroves and found that natural sources predominated in the CMZ and FMZ, while minor anthropogenic enrichment occurred for Cr, Pb and Cd in the IMZ. Multi-index evaluations reflected mild pollution at certain sampling points but overall low comprehensive pollution levels across the area. Both the Potential Ecological Risk Index (PERI) and Toxicity Risk Index (TRI) further confirmed low ecological risk, despite a slight increasing trend from CMZ to IMZ. Continuous monitoring is recommended to track long-term ecological risks as mangrove ecosystems develop and metal bioavailability changes. Management strategies should include zoning regulations to minimize anthropogenic input in sensitive areas, coupled with regular sediment quality assessments. These results underscore the role of mangroves in mitigating coastal metal pollution and provide critical insights for managing contamination in vulnerable estuarine and coastal zones.

## 1. Introduction

Mangrove forests are unique ecosystems predominantly found in the intertidal zones of tropical and subtropical coastlines across the global, providing various valued ecological services in coastal protection, water quality, wildlife and fisheries habitats (Duke et al., 2007; Lin et al., 2019; Sandilyan and Kathiresan, 2014). Despite their ecological importance, mangrove forests have faced severe degradation and loss over the recent 60 years with an alarming rate due to anthropogenic activities such as urbanization and industrialization (Abeywardhana et al., 2022; Hamilton and Casey, 2016). Additionally, mangroves are

increasingly exposed to pollutants from terrigenous sources, such as heavy metals and persistent organic compounds, which accumulate in sediments and biota, threatening these ecosystems and the species that depend on them.

Heavy metals in mangrove ecosystems exhibit complex and heterogeneous spatial distribution patterns, influenced by a combination of sedimentary processes, hydrological conditions and biological activities. The distribution can be highly site-specific, with metals like Mn and Pb showing opposing trends in different reserves or under varying hydrological conditions (Jiang et al., 2020). A well-documented zonation pattern showed that concentrations of Cu and Ni often increased

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significantly from the low to the high intertidal zones (Wang et al., 2024). Previous studies found that mangrove ecosystems declined the concentration of Hg and accumulate Cu in the sediments (Hu et al., 2018). When compared to adjacent unvegetated mudflats, mangrove sediments often function as significant sinks for various heavy metals (Bastakoti et al., 2018; Wang et al., 2026).

The considerable heterogeneity in heavy metal distribution across multiple scales is governed by a complex interplay of physicochemical, biological and anthropogenic factors (Abeywardhana et al., 2022; Rashidifard et al., 2025). The unique anaerobic and reducing environment of mangrove sediments, characterized by fine-grained compositions and high organic matter content, promotes the formation of reduced inorganic sulfur compounds. These compounds play a critical role in immobilizing heavy metals through the formation of highly insoluble metal sulfides (Chai et al., 2017a). The complex interplay of tidal hydrology and seasonal fluctuations further modulates metal mobility. The role of mangroves in metal processing evolves significantly over time with forest development. During early stages of mangrove or upon initial exposure to metal contamination, accumulation within sediments driven largely by sedimentation, adsorption, and sulfide formation (Rahman et al., 2021). In contrast, in mature stands with well-developed root systems, biological uptake by plants often become more significant, with certain species demonstrating a pronounced ability to absorb, translocate and sequester metals in their tissues (Sandilyan and Kathiresan, 2014; Serrano et al., 2019). Furthermore, different mangrove species can influence their immediate sediment environment differently through root oxygen release, organic acid excretion and litter decomposition. For example, some species (e.g., *Avicennia marina*) release oxygen from their roots, which can alter local redox conditions, suppress the formation of acid-volatile sulfide (AVS), consequently enhance the bioavailability and potential toxicity of metals such as Cd and Pb (Ma et al., 2025a). Other species, like *Acanthus ilicifolius*, exhibit strong phytoextraction capabilities, accumulating metals in leaves at concentrations higher than in roots, indicating their potential use in phytoremediation (Tanjin et al., 2024). While some studies have documented the efficient bioaccumulation of heavy metals in natural and aged mangrove forests, there remains a notable lack of information regarding these dynamics in newly restored or developed mangrove forests with short-term reclamation histories (Temminck et al., 2022; Van Santen et al., 2007).

The ecological risk assessment of heavy metals in mangrove ecosystems is essential for evaluating environmental impacts and guiding management and restoration strategies. These metals may subsequently transfer and amplify through the food chain, posing potential threats to higher trophic levels and human health (Partani et al., 2024). Regional studies have documented varying levels of ecological risk. For example, in the Aojiang Estuary, Hg and Cd were identified as the primary risk factors, with the potential ecological risk index (RI) indicating a moderate overall risk level (Ma et al., 2025b). Similarly, in the Greater Bay Area, Cd exhibited high concentrations in the exchangeable fraction, resulting in elevated ecological risk values (Guan et al., 2023). In the Maowei Sea mangrove reserve, Cd was also the dominant contributor to potential ecological risk (Jiang et al., 2020). However, ecological risk assessments for heavy metals in newly developed mangrove forests are relatively scarce, such assessments are of crucial guidance for the later growth and development of these mangrove ecosystems.

Current researches on heavy metals in mangrove sediments have predominantly focused on tropical regions and mature mangrove ecosystems, whereas studies on subtropical areas, particularly young mangroves, remain limited. This study focused on the natural new-developed mangrove ecosystem in the Beibu Gulf, the second-largest mangrove region in China. Despite the ecological significance of these mangroves, the spatial distribution and ecological risks associated with sedimentary heavy metals in this area remain poorly understood. To address this knowledge gap, we analyzed the concentrations of eight heavy metals (Cr, Ni, Cu, Zn, Pb, Cd, Mn, Fe) and sulfur in both

mangrove and adjacent mudflat sediments. The objectives of this work were to: (1) determine the spatial distribution patterns of heavy metals across different tidal zones in mangrove sediments; (2) characterize the sources of sedimentary heavy metals; (3) evaluate the ecological risk using different assessment indicators. This research aims to provide scientifically-grounded data to support the formulation of effective management and restoration policies for coastal ecosystems.

## 2. Materials and methods

### 2.1. Study area

The short-term developed mangrove forest located in Nanliu River Delta, the largest tropical delta of the Beibu Gulf in Southwest China. The delta is a tide-dominated delta subject to strong tidal action. The hydrodynamics of the study area are mainly controlled by waves (Long et al., 2022). The selected mangrove area is located on Qixing Island, which is the largest fluvial island of the Nanliu River Delta (Fig. 1). Mangrove species are dominated by *Aegiceras corniculatum* (L) Blano within the five-year growth period.

### 2.2. Field samplings and laboratory analysis

The sampling design of this study encompassed various zones and selected typical transects perpendicular to the shoreline and tidal direction as the sampling belts. The transect was approximately 600 m long and comprised a creek mudflat zone (CMZ, S1-S25), a fringe mangrove zone (FMZ, S26-S40) and an interior mangrove zone (IMZ, S41-S56). Sample collection was conducted at the lowest tide level on July 22, 2020. The locations are shown in Fig. 1. Sediment samples were packed in labeled polyethylene bags and then transported to the laboratory and stored at -20 °C until analyzed.

Size fraction, TOC were determined by a Beckman laser particle size analyzer (LS13320, Coulter) and an elemental analyzer (TOC-V, Shimadzu), in accordance with the procedures described in previous studies (Li et al., 2024). For sedimentary metal (Cr, Ni, Cu, Zn, Pb, Cd, Mn, Fe) and Sulfur analysis, microwave digestion system (Antor Parr, PRO) Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES, Thermo Fisher, icap 7400) and Atomic Absorption Spectrometer (AAS, PerkinElmer, 800) were employed, following previously established methods (Shetaia et al., 2025). All the heavy metal were measured based on dry weight. Details were shown in supporting information.

### 2.3. Comprehensive ecological risk assessment

To thoroughly evaluate the contamination status, spatial distribution, and potential ecological risks of heavy metals in the sediments, a multi-index approach was adopted, such as Enrichment Factor (EF), Modified contamination factor (*mCd*), Pollution Load Index (PLI), Nemerow Pollution Index (NPI), Modified Pollution Index (MPI), Potential Ecological Risk Index (PERI) and Toxic Risk Index (TRI). This integrated assessment framework covers source identification, pollution level quantification, and ecological risk interpretation, providing a holistic view of the environmental impact. The definitions, formulas, and classification criteria for all applied indices are systematically summarized in Table 1 (Hakanson, 1980; Kumar et al., 2019; Tomlinson et al., 1980; Zoller et al., 1974). Detail information of the index was shown in Text S2. The background metal values were selected the Chinese soil background values and the Sediment Quality Guidelines was the TEL developed by MacDonald (MacDonald et al., 2000; Wei and Chen, 1991).

### 2.4. Statistical analysis

One-way analysis of variance (ANOVA) was performed to assess the significance of differences. Statistical significance was evaluated at the

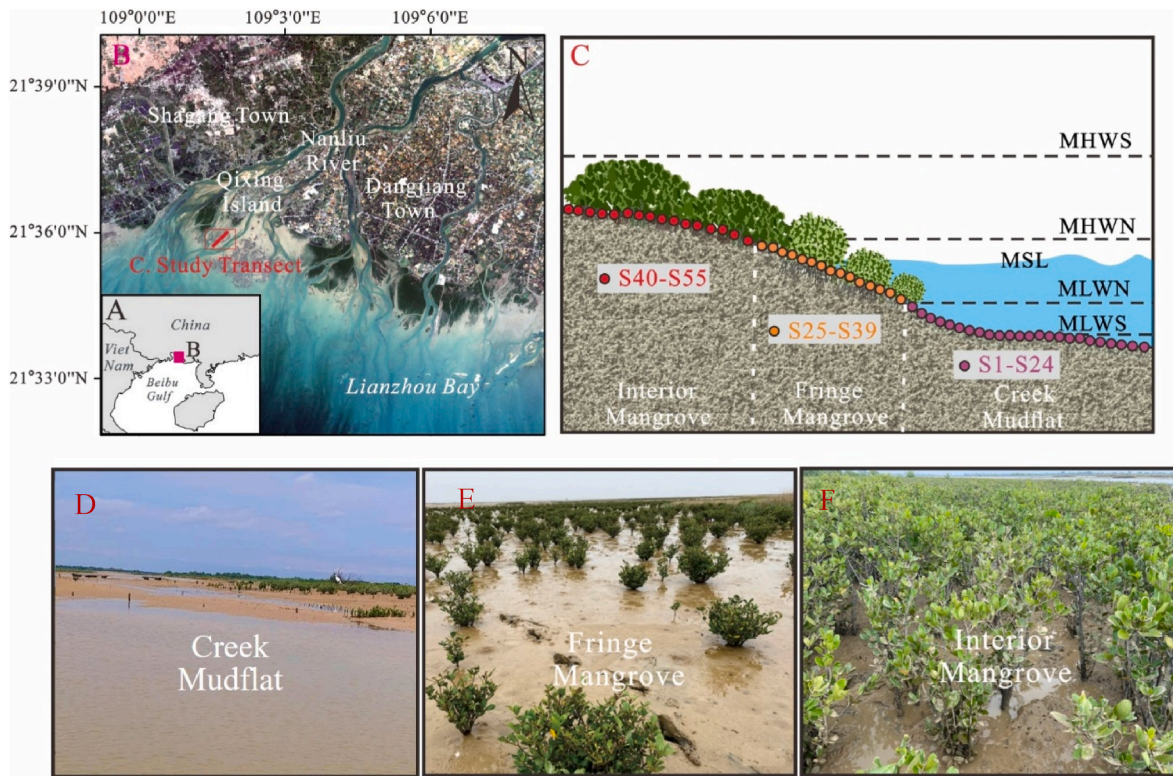


Fig. 1. The study area (B) and sampling sites (C) in Beibu Gulf, China (A); (D): the Creek Mudflat Zone; (E): the Fringe Mangrove; (F): the Interior Mangrove.

**Table 1**  
The definitions, formulas and classification criteria for ecological risk assessment indices.

Index	Formula	Parameters	Contamination or risk degree
Enrichment Factor (EF)	$EF = \frac{(C_i/C_{ref})_{sample}}{(B_i/B_{ref})_{background}}$	$C_i$ : metal concentration; $C_{ref}$ : reference element (e.g., Al) concentration; $B_i$ : background metal value, $B_{ref}$ : background reference element value	$EF \leq 1$ : No enrichment; $1 < EF \leq 3$ : Minor enrichment; $3 < EF \leq 5$ : Moderate enrichment; $5 < EF \leq 10$ : Moderately severe enrichment; $EF > 10$ : Severe enrichment
Modified contamination factor (mCd)	$mCd = \frac{\sum_{i=1}^n CF_i}{n}$	$CF_i$ : contamination factor of metal $i$ ; $n$ : number of metals	$mCd < 1.5$ : Nil to very low degree of contamination; $1.5 \leq mCd < 2$ : Low degree of contamination; $2 \leq mCd < 4$ : Moderate degree of contamination; $4 \leq mCd < 8$ : High degree of contamination; $mCd \geq 8$ : Very high degree of contamination;
Pollution Load Index (PLI)	$PLI = \sqrt[n]{CF_1 \times CF_2 \times \dots \times CF_n}$	$CF_n$ : contamination factor of metal $n$	$PLI = 0$ : No contamination; $0 < PLI \leq 1$ : Baseline contamination; $PLI > 1$ : High contamination
Nemerow Pollution Index (NPI)	$P_N = \frac{\sqrt{(CF_{avg})^2 + (CF_{max})^2}}{2}$	$CF_{avg}$ : maximum contamination factor; $CF_{max}$ : average contamination factor	$NPI \leq 1$ : Unpolluted; $1 < NPI \leq 2.5$ : Low polluted; $2.5 < NPI \leq 7$ : Moderately polluted; $NPI > 7$ : Strongly polluted
Modified Pollution Index (MPI)	$MPI = \frac{\sqrt{(EF_{avg})^2 + (EF_{max})^2}}{2}$	$EF_{avg}$ : mean value of the $EF_i$ of all the metals studied $EF_{max}$ : maximum value of the $EF_i$ of all the metals studied	$MPI \leq 1$ : Unpolluted; $1 < MPI \leq 2$ : Slightly polluted; $2 < MPI \leq 3$ : Moderately polluted; $3 < MPI \leq 5$ : Moderately polluted-heavily polluted; $5 < MPI \leq 10$ : Heavily polluted; $10 > MPI$ : Severely polluted
Potential Ecological Risk Index (PERI)	$PERI = \sum E_r^i; E_r^i = T_r^i \times CF^i; CF = \frac{C_i}{C_b}$	$E_r^i$ : monomial ecological risk; $T_r^i$ : toxic response factor; $CF$ : contamination factor; $C_s$ : measured concentration; $C_b$ : background reference value	For PERI: $PERI < 150$ : Low risk; $150 \leq PERI < 300$ : Moderate risk; $300 \leq PERI < 600$ : Considerable risk; $PERI \geq 600$ : Very high risk
Toxic Risk Index (TRI)	$TRI = \sqrt{\sum \left(\frac{C_i}{SQG_i}\right)^2}$	$C_i$ : measured concentration; $SQG_i$ : Sediment Quality Guideline (eg., PEL, TEL)	$TRI \leq 5$ : No toxic risk; $5 < TRI \leq 10$ : Low toxic risk; $10 < TRI \leq 15$ : Moderate toxic risk; $15 < TRI \leq 20$ : Considerable toxic risk; $TRI > 20$ : Very high toxic risk

$p < 0.05$  level. Principal component analysis (PCA) was applied to identify the multivariate relationships between geochemical variables.

All statistical analyses were performed with SPSS software (Ver 23.0), Origin software (Ver 9.1).

### 3. Results

#### 3.1. Characteristics of sediment geochemical composition

The sediments predominantly consisted of clay (<4 μm), silt (4-63 μm) and sand (>63 μm). Sand was the dominant fraction across all zones, ranging from 46.66% to 98.65% (Fig. 2), with its proportion in the CMZ and FMZ significantly higher than that of clay and silt (Fig. S1). In contrast, the IMZ exhibited a substantially lower sand content but higher fine-particle (clay and silt) fractions compared to the CMZ and FMZ. Specifically, clay and silt contents ranged from 0.10% to 13.75% and 1.25% to 43.29%, respectively.

The TOC contents varied from 0.2 to 6.6 g kg<sup>-1</sup> (Fig. 2). The mean TOC value in the IMZ was significantly higher than those in the CMZ and FMZ (p < 0.01). A similar spatial trend was identified for sulfur, which displayed its highest values in the IMZ and increased markedly from the CMZ/FMZ to the IMZ, paralleling the distribution pattern of TOC.

#### 3.2. Heavy metal contents in sediments

The concentrations of eight heavy metals (Fe, Mn, Cr, Ni, Cu, Zn, Pb, and Cd) in surface sediments across different sampling zones are summarized in Fig. 3. The median concentrations followed the order: Fe (21731.84 mg kg<sup>-1</sup>) > Cr (244.20 mg kg<sup>-1</sup>) > Mn (5.01 mg kg<sup>-1</sup>) > Zn (36.71 mg kg<sup>-1</sup>) > Pb (20.61 mg kg<sup>-1</sup>) > Cu (13.19 mg kg<sup>-1</sup>) > Ni (31.08 mg kg<sup>-1</sup>) > Cd (0.05 mg kg<sup>-1</sup>). Among these, Fe was the most abundant element, consistent with its natural dominance in mineral sediments and role as a key adsorbent for other metals. Notably, the highest concentrations of most metals (Cr, Ni, Cu, Zn, Cd) were observed in IMZ, suggesting strong retention and accumulation mechanisms in vegetated sediments. In contrast, the highest Pb value was recorded at Site 12 within CMZ, possibly indicative of localized anthropogenic input or physical transport processes. Based on the spatial distribution patterns, the heavy metals were categorized into three distinct groups. Cd

exhibited a statistically significant increasing trend (p < 0.05) from CMZ through FMZ to IMZ. Concentrations of Cr, Cu, Ni and Zn were significantly higher in the IMZ compared to both CMZ and FMZ (p < 0.05), indicating clear enrichment within the mangrove interior. Pb, Fe, and Mn displayed no significant differences across zones, implying relatively uniform distribution or common geological sources.

Sediment quality guidelines (threshold effect limit: TEL) established by MacDonald and Grade I marine sediment quality standards from China (GB, 18668-2002) were used to assess the potential biological effects of heavy metal (Hübner et al., 2009; MacDonald et al., 2000). The concentrations of Zn and Cd were well below both the TEL and Grade I thresholds, indicating a low risk of adverse ecological impacts for these metals. By contrast, all samples from the IMZ exceeded the TEL for Cr, with some also surpassing the Grade I limit. Additionally, less than 10% of samples showed TEL exceedances for Cu, Ni, and Pb, which were predominantly concentrated within the IMZ.

#### 3.3. Ecological risks

The Enrichment Factor (EF) is utilized to discriminate between natural and anthropogenic sources of heavy metals. In this study, the EF values for both CMZ and FMZ were below 1 (with the exception of Pb), indicating that the heavy metals in these zones predominantly originate from natural sources, with no significant enrichment observed (Fig. 4). In contrast, within the IMZ area, EF values for Cr, Pb and Cd exceeded 1, demonstrating a state of minor enrichment.

In the multi-index risk assessment system, the Pollution Load Index (PLI) values of some samples in the IMZ area exceeded 1, indicating mild pollution at individual points (Fig. 5). However, both the modified Contamination Degree (mCd) and the Nemerow Pollution Index (NPI) remained at low levels, suggesting an overall low comprehensive pollution level by multiple heavy metals in this area. Some sites in the IMZ area showed moderate pollution by the Modified Pollution Index (MPI). This may be due to MPI heavily weighted more toxic metals like

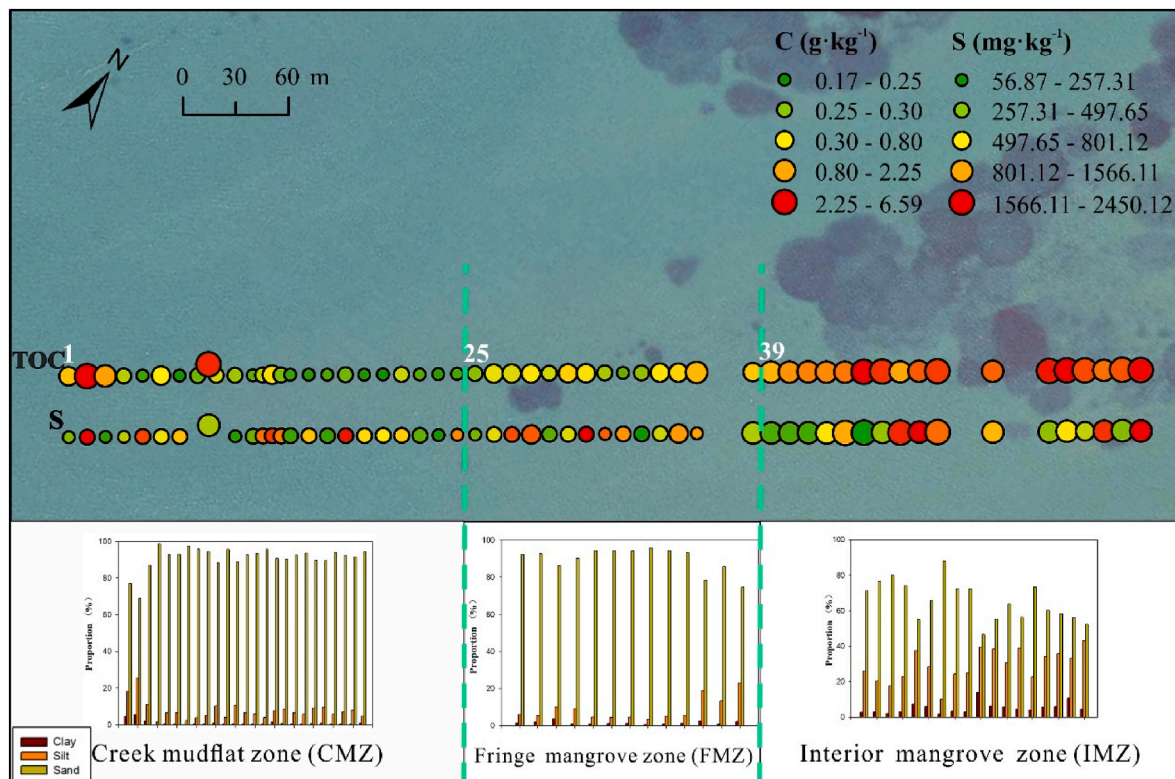
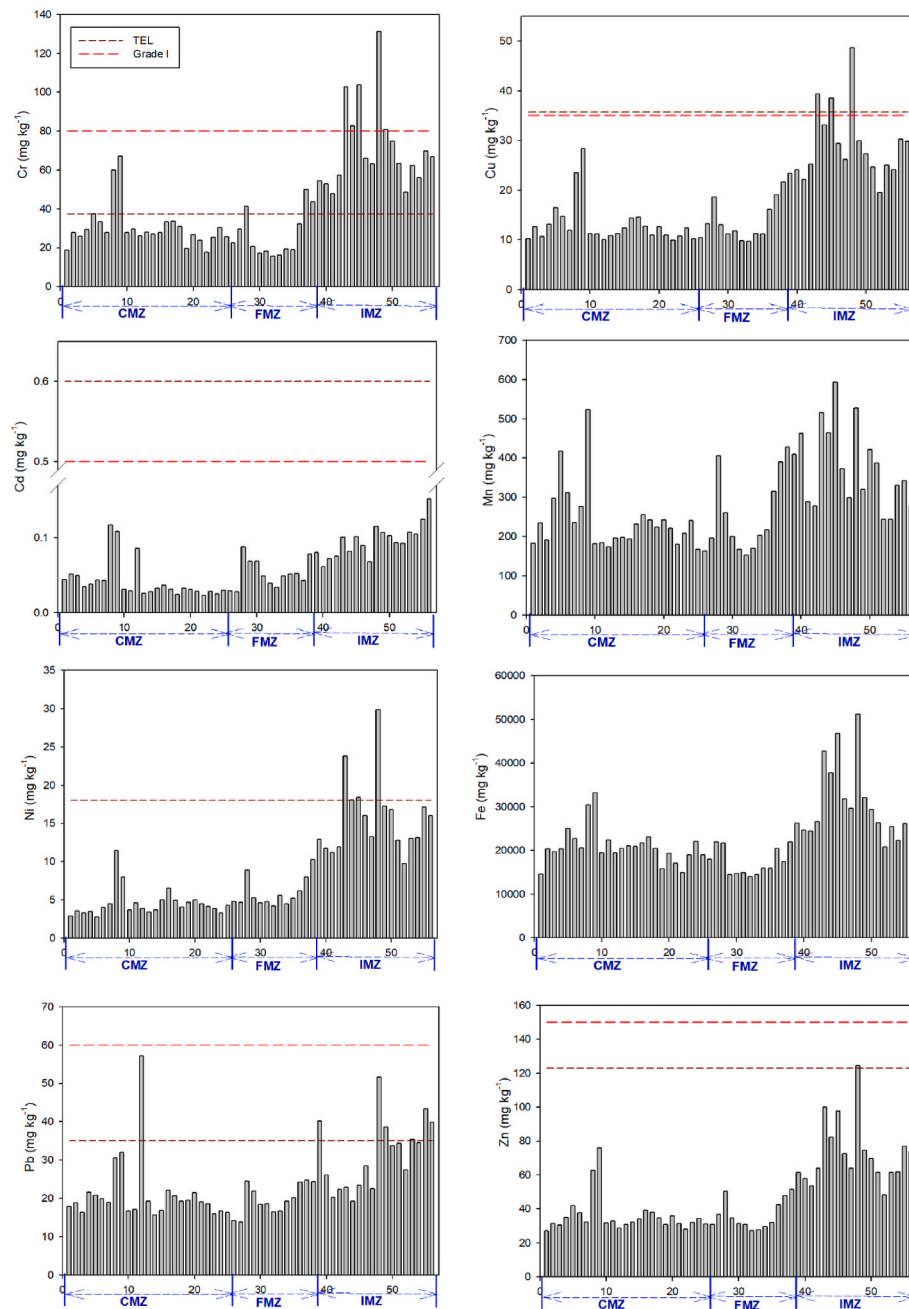


Fig. 2. The values of sedimentary composition, TOC and Sulfur contents in different zones.



**Fig. 3.** The contents of heavy metals in sediments of mangrove forests. TEL was the sediment quality guidelines (threshold effect limit) developed by MacDonald. Grade I was marine sediment quality standards in China.

Cd, which had a higher hazard index than other common heavy metals. Thus, even at relatively low absolute concentrations, their high toxicity disproportionately amplified their contribution to the overall assessment, resulting in an elevated composite index value.

Furthermore, the results of the Potential Ecological Risk Index (*PERI*) and the Toxicity Risk Index (*TRI*) both demonstrated a low comprehensive ecological risk in the region. Although no statistically significant differences were observed among the three areas (CMZ, FMZ, and IMZ), the values of these comprehensive indices generally exhibited an increasing trend: CMZ < FMZ < IMZ.

## 4. Discussion

### 4.1. Impacts from sediments factors

Analysis revealed significant variations in sedimentary fractions and organic matter content across different zones. Owing to the efficient trapping capacity of mangrove roots, fine-grained particles (clay and silt) are more readily captured within mangrove forests (IMZ) compared to creek mudflat areas (CMZ/FMZ). These particles, characterized by their large specific surface area and abundant functional groups, effectively adsorb and immobilize heavy metals (Bastakoti et al., 2018). This process directly resulted in elevated heavy metal concentrations (e.g., Cr, Pb, Cd) in the IMZ, demonstrating the role of mangroves as a sink for metallic contaminants.

The physicochemical environment within mangrove sediments

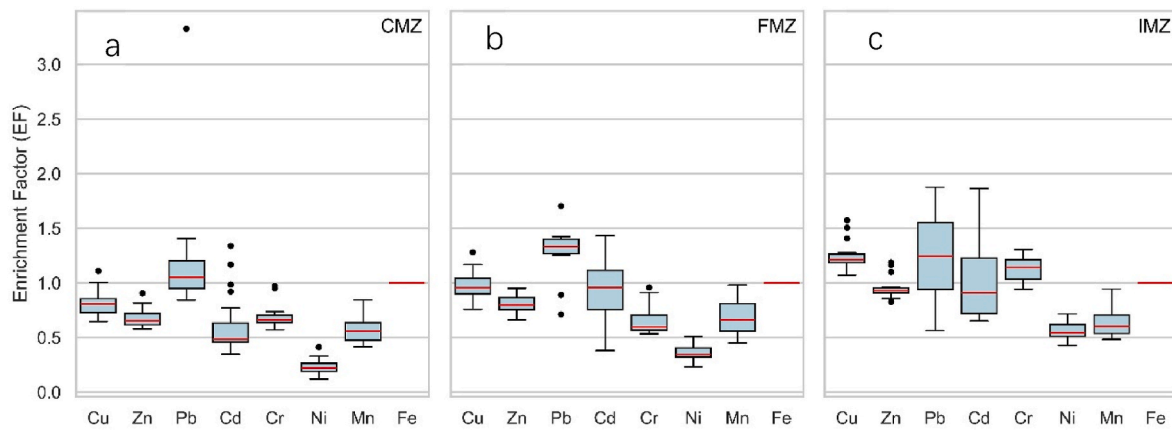


Fig. 4. The values of Enrichment Factor (EF) in mangrove forest: a. creek mudflat zone (CMZ); b. fringe mangrove zone (FMZ); c. interior mangrove zone (IMZ).

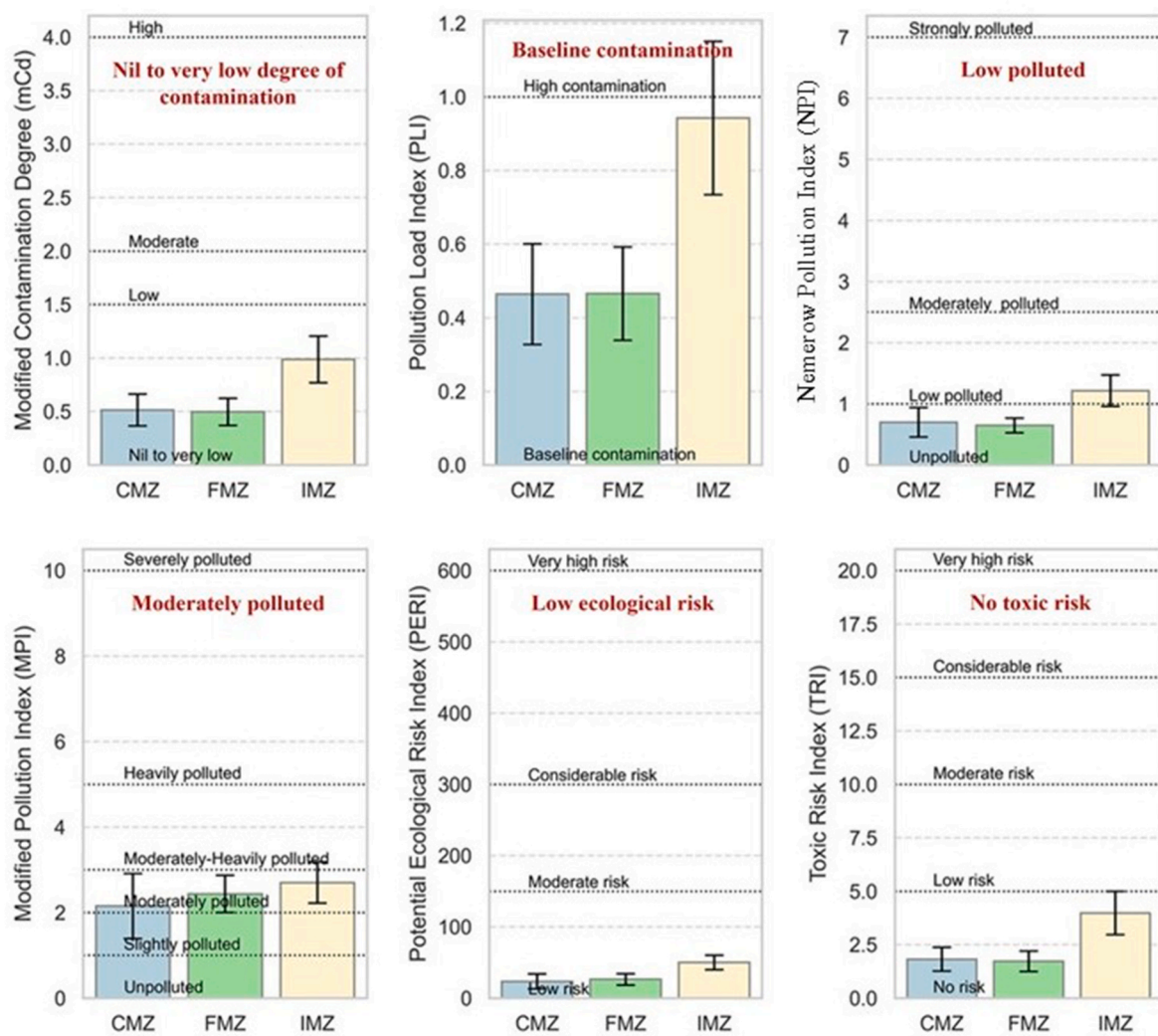


Fig. 5. A comprehensive assessment of sediment pollution levels and potential ecological risks using multiple indices in different zones of mangrove forests.

further modulates metal behavior. Redox conditions, influenced by root activity (e.g., radial oxygen loss), can oxidize sediments in the rhizosphere, potentially altering metal speciation and bioavailability. Furthermore, the prevalent anoxic conditions and higher concentrations of sulfur in the IMZ promote the formation of stable metal-sulfide complexes, which significantly enhances the sequestration and

retention of trace metals, contributing to the long-term burial of heavy metals within the mangrove zone.

Multivariate statistical analyses were pivotal in deciphering the sources and behavior of these metals. The cluster analysis illustrated that the eight heavy metals can be divided into two categories, Pb and Cd, the other category is Mn, Fe, Ni, Cr, Cu and Zn (Fig. 6). The majority

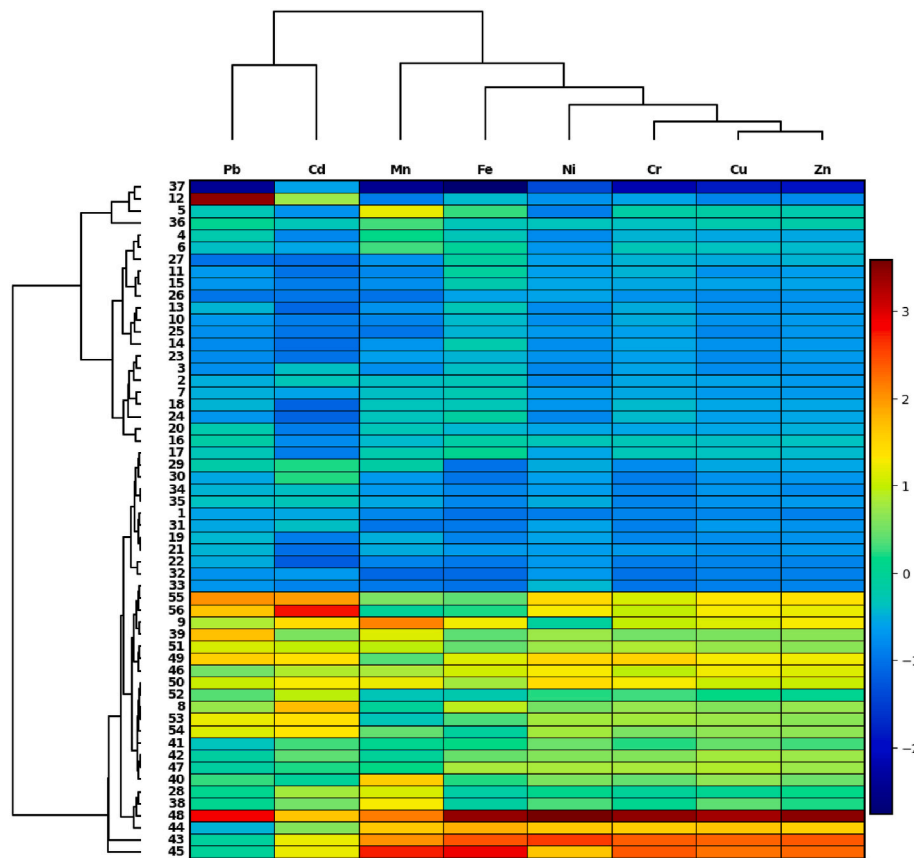


Fig. 6. Heavy metal distribution patterns of mangrove forests by heatmap and cluster analysis.

of samples from the IMZ area cluster within the same group. This effectively demonstrated that mangroves exert a more significant influence on the spatial distribution of these anthropogenic-sourced heavy metals Pb and Cd. The sources of Pb and Cd were primarily linked to agricultural activities, aquaculture and shipping. Studies have shown that Pb and Cd from ship coatings and fuel combustion can enter the mangrove environment through surface runoff or atmospheric deposition, ultimately accumulating in sediments (Deng et al., 2024).

The Principal Component Analysis (PCA) results showed that two principal components (PCs) explained 86.22% of the total variance (Table 2 and Fig. 7). The first PC1, explaining 75.63% of the total variance, was strongly and positively related to most heavy metals, fine fractions and sedimentary TOC. Cu and Zn exhibited the highest contribution for Factor 1, which may be attributed by aquaculture activities using bait and organic fertilizers. Mangroves in this study area

**Table 2**  
Component loadings of each variable obtained from PCA.

Variables	PC 1	PC 2
Cr	0.962	0.229
Fe	0.858	0.430
Ni	0.968	0.069
Mn	0.793	0.442
Cu	0.974	0.201
Zn	0.966	0.233
Pb	0.706	-0.093
Cd	0.852	-0.113
S	0.924	0.179
Clay	0.837	-0.372
Silt	0.846	-0.470
Sand	-0.864	0.463
TOC	0.695	-0.465
% variance	75.63%	10.59%

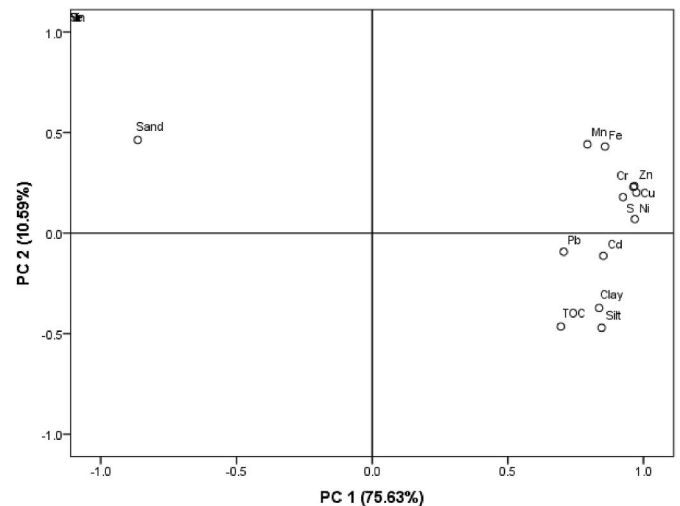


Fig. 7. Principal component analysis (PCA) plot showing the multivariate variation.

were influenced by adjacent shrimp and crab aquaculture. During each farming cycle, aquaculture tailwater was discharged, and pond sediments were cleared. These processes released heavy metals from the culture medium, which were then transported directly or indirectly into the mangrove zone, where they accumulated in the sediments. Therefore, Factor 1 can be identified as originating from aquaculture activities.

The second PC2, explaining 10.59% of the total variance, showed highly positive factor loadings on sand fraction. The principal

components exhibited distinct patterns in representing naturally sourced metal elements such as Fe and Mn. Therefore, Factor 2 can be interpreted as a natural source. Most metals showed positive correlation with factor 2, except for Pb and Cd. This indicated that Pb and Cd are influenced exclusively by anthropogenic sources, whereas the other elements are affected not only by external inputs such as aquaculture but also by natural background sources. These findings are consistent with the results of the cluster analysis mentioned above.

The results of Spearman correlation analysis conducted in this study are presented in Fig. 8. The remarkably positive correlation was found between all the heavy metals and sedimentary fine fractions. This indicated fine-grained sediment fraction retained the majority of heavy metals due to the physical adsorption (electrostatic attraction) on clay and silt particles. A positive correlation was also observed between all heavy metals and TOC, indicating that TOC plays a crucial role in the deposition of heavy metals as well. Strong correlations observed among heavy metals suggested a potential common origin and similar chemical behaviors during mobilization. Notably, Cr and Cu, as well as Zn ( $r > 0.98$ ,  $p < 0.01$ ) show significant correlations, suggesting they may originate from similar sources.

#### 4.2. Mangrove influences on heavy metal

Mangrove roots are effective in attenuating hydrodynamic energy. Although the mangroves in this study were in their early developmental stage, they still demonstrated a significant capacity to reduce hydrodynamic forces (Long et al., 2022; Zhou et al., 2022a). Studies have shown that mangroves can effectively regulate hydrodynamic conditions under different tidal regimes. Taking spring tide as an example, wave energy decreased from 7.44 J/m<sup>2</sup> on the bare flat to 0.12 J/m<sup>2</sup> inside the mangrove area, with an incident wave energy dissipation rate of approximately 98%. During middle tide, wave energy dropped from 6.86 J/m<sup>2</sup> to 0.08 J/m<sup>2</sup>, while under neap tide, wave energy on the bare

flat was extremely weak (Zhou et al., 2022b). Overall, in the seaward-to-landward direction, wave energy dissipation was most pronounced during spring tide, accompanied by significant sediment deposition, followed by middle tide. The reduced hydrodynamic energy facilitates the accumulation of fine-grained particles (e.g., clay and silt) and organic matter in this region, which exhibit high binding capacities for heavy metals due to their extensive surface area and functional groups. This promoted net landward sediment transport and the accumulation of metals in mangrove zones. Consequently, IMZ sediments exhibit notably higher clay-silt and OM content than CMZ/FMZ, directly correlating with heavy metal accumulation. For instance, studies in estuarine wetlands have demonstrated that Cu concentrations in mangrove sediments are significantly higher than in reference mudflat sites ( $p < 0.05$ ), while surface sediments within mangroves contain elevated levels of Cr, Co, Ni, Zn, Cd, and Pb relative to adjacent mudflats (Hu et al., 2018; Jiang et al., 2020).

The capacity for metal enrichment varies markedly among mangrove species due to differences in root morphology, physiological adaptations and tolerance mechanisms (Shen et al., 2021; Wong et al., 2024). *Kandelia obovate* and *Aegiceras corniculatum* exhibited strong affinity for Cu, Zn and Pb, facilitated by root secretions and iron plaque formation on root surfaces, which effectively immobilize metals (Wu et al., 2016). Research found that Mn is bioconcentrated in every species, highest bioconcentration was found in *A. officinalis* than *S. apetala* and *E. agallocha*. It was reported that heavy metal concentrations varied significantly in the species-specific sediments of *A. marina*, *B. gymnorrhiza*, *R. mucronata* and *E. agallocha* in the Indian Sundarbans. The highest concentrations of As, Cd and Pb were observed in *E. agallocha* sites, Cu and Zn, in *B. gymnorrhiza* sites, followed by Co and Ni, in *A. marina* sites (Chanda et al., 2021). In this study, the enrichment effects of Cu and Pb were more pronounced in the dominant tree species, *Aegiceras corniculatum*, from the bare mudflat to the mangrove area.

The development stage of mangroves critically modulates their metal

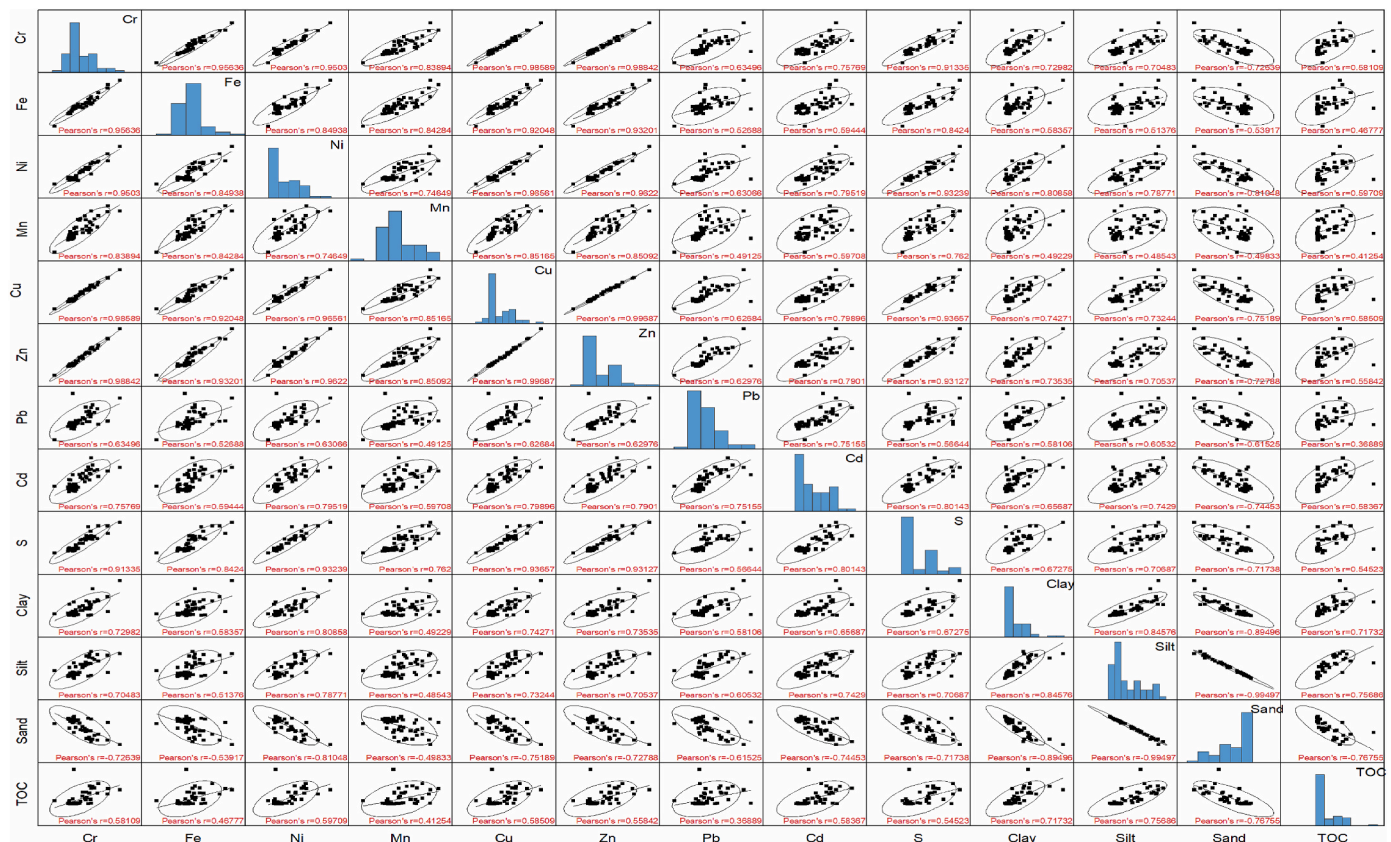


Fig. 8. Spearman correlation among heavy metals, size fractions and TOC in mangrove sediment.

accumulation capacity and sequestration efficiency. In young or restoring mangroves, despite their lower biomass, developing roots enhanced sediment trapping, rapidly increasing the content of fine particles and organic matter (OM). Restored mangroves in Shantou, for instance, demonstrated early efficacy in altering sediment properties and promoting metal fixation, though some young mangroves exhibited high translocation rates for certain elements (Zhao et al., 2022). In contrast, mature forests with developed root systems and greater biomass exhibited stronger sediment trapping and assimilation capacities (Bastakoti et al., 2018). The high degree of root lignification and suberization in mature mangroves enhanced long-term metal stabilization. Moreover, mature mangrove forests effectively remove heavy metals from sediments through plant uptake and bioaccumulation. Research on the world's largest mangrove forest, situated along the northern coast of the Bay of Bengal, demonstrates that *E. agallocha* functions as an effective phytostabiliser for Mn, thereby mitigating the risk of its erosion and leaching into adjacent water bodies (Hossain et al., 2022). Furthermore, for metal extraction, *A. officinalis* was found to be more suitable than *S. apetala* and *E. agallocha*.

Mangrove enhance the concentration of AVS by maintaining anaerobic conditions. These highly stable and water-insoluble sulfides effectively transform heavy metals from more bioavailable forms, such as exchangeable and carbonate-bound fractions, into the much less bioavailable sulfide-bound fraction, thereby promoting long-term immobilization of heavy metals in the sediments (Queiroz et al., 2018). However, the oxygen released by mangrove roots can influence the formation of AVS, and the root respiration of different mangrove species also exerts varying effects on this process. Research found that levels of AVS in mangrove forest sediments (dominated by *K. obovata* and *S. caseolaris*) were lower than in the mudflat (Chai et al., 2017b). Although this study did not specifically address acid-volatile sulfide (AVS), the observed high sulfur content suggests the need for further investigation into the influence of AVS on heavy metal speciation and ecological risk in this area.

#### 4.3. Risk assessment of heavy metals

Spatial variability was observed in Enrichment Factor, pollution level (*mCd*, *PLI*, *NPI*, *MPI*) and ecological risk index, showing a slight increasing trend from the creek mudflat towards the interior mangrove forest. This distribution pattern aligned with findings in other developed mangrove ecosystems. Despite this gradient, the overall ecological risk in this newly developed mangrove system remained low. The potential ecological risk assessment of mangroves in Aojiang Estuary showed a moderated ecological risk level (with an average PERI value of 324.3) (Ma et al., 2025b). The PERI risks were considerable (301.6–538.6) between a depth of 0–10 cm and moderate (237.0–297.1) from 20 cm to the bottom layer in Maowei sea mangrove, China (Jiang et al., 2020). While the PERI values in this study were all below 150, indicating lower ecological risk compared with other mangroves. Moreover, significant disparities in risk levels exist globally: mangroves in Mangalavanam show moderate to significant metal enrichment, whereas sites like Nansha Mangrove and certain Central and South American mangroves face very high ecological risks, often driven by severe cadmium (Cd) contamination (Hülse et al., 2025; Kannankai et al., 2022; Wu et al., 2014). Similarly, Hong Kong's Deep Bay mangroves are heavily impacted by industrial discharge and poor hydrology (Zhang et al., 2023). Pore water was a key component of the mangrove ecosystem. The heavy metal concentrations in pore water were generally low. However, there existed a significant correlation among heavy metal levels in pore water and plant leaves, indicating that pore water as the primary source of heavy metal by mangrove plants (Ma et al., 2025a). Therefore, the potential ecological risks associated with heavy metals in pore water should be given attention in future research.

The enrichment and ecological risk of heavy metals in mangroves are influenced not only by the natural developmental stage of the mangrove

forest, but strongly influenced by the intensity and nature of surrounding anthropogenic activities (e.g., sediment properties, hydrodynamics) (Sumudumali et al., 2025). The minor anthropogenic enrichment of Cr, Pb and Cd in the IMZ may be related to the anthropogenic inputs. Study also found the moderate enrichment of Cd and a slight enrichment of Cr and Pb during the last ~81 year in Beibu Gulf (Xia et al., 2011). These anthropogenic inputs could be related to the intensive use of fertilizers in aquaculture and the coal and fuel combustion (Zhang and Shan, 2008; Zhao et al., 2025).

Although current comprehensive assessments indicate overall low pollution loads and ecological risk levels, the rapid development of coastal ports and navigation channels in the region significantly elevates environmental risks. Given the diversity and complexity of risk sources, the ecological risk management system should introduce zoned and classified management strategies. The heavy metal concentration gradient (CMZ < FMZ < IMZ) signifies the biological capture and enrichment effect within the mangrove ecosystem. Rather than merely acting as a “purifier,” mangroves function more like highly efficient “pollutant traps.” Consequently, the forest interior has become a zone of heavy metal accumulation and a potential “ecological risk hotspot.” Based on this, the core forest area should be explicitly designated as a “pollutant isolation and buffer zone”, with strict restrictions on any human activities that might disturb the sediments, such as aquaculture, fishing, tourist trampling and logging. The forest edge, as a transition area, can be utilized restrictively for low-interference ecological monitoring and educational activities. Utilization of the bare mudflat area may be considered following relatively stricter assessment, with pollutant input controlled. Crucially, ecological interception projects (e.g., constructed wetlands, vegetative buffer strips) should be established upstream (e.g., bare mudflats, estuaries, waterways) to protect the mangrove ecosystem itself. This would intercept and purify pollutants before they entered the highly efficient “sink”. Although heavy metals enriched in the forest interior were relatively stable, sediment resuspension caused by typhoons or human disturbance, could pose serious ecological risks. Therefore, it is essential to establish a dynamic monitoring system focused on preventing resuspension and biological exposure, develop a sediment stability assessment mechanism, monitor root system consolidation status, and guard against erosion.

Priority control and continuous monitoring must be implemented for key elements such as Cadmium (Cd), which was the dominant contributor of potential ecological risk. It exhibits significant biotoxicity and can pose high risks even at low concentrations due to its high toxic response factor and potential for biomagnification within food chains. This necessitates management strategies that are differentiated and precise. The establishment of a long-term, multi-dimensional monitoring network (covering water, sediments, vegetation, and biota) serves as the foundation for precise management and control. It is essential to implement zoned and classified management of pollution sources. For instance, in areas predominantly affected by industrial sources, the focus should be on strictly regulating the treatment and discharge of wastewater containing heavy metals. In regions where agricultural sources are dominant, promoting ecological agriculture and reducing the use of chemical fertilizers and pesticides is necessary. For areas already contaminated with cadmium (Cd), highly resilient remediation species could be selected. Mangrove plants with strongly lignified root systems can inhibit the absorption and translocation of heavy metals to a certain extent, thereby enhancing their tolerance to heavy metal stress. This significantly reduces the bioavailability of heavy metals in the soil and lowers ecological risks. Therefore, selecting such mangrove species with a high degree of lignification, such as *Kandelia obovata*, *Bruguiera gymnorhiza* and *Aegiceras corniculatum* can help mitigate the ecological risks posed by cadmium. By integrating the comprehensive measures (encompassing monitoring and early warning, source control, and natural remediation), the risk of cadmium pollution in mangrove ecosystems can be systematically reduced. Such a holistic and proactive governance framework will help maintain mangrove ecosystem

integrity and function, thereby supporting ecological security and sustainable regional development while strengthening the long-term resilience of these vital blue carbon sinks.

## 5. Conclusion

This study revealed a significantly increasing spatial gradient of heavy metals from CMZ/FMZ to IMZ. This enrichment process was primarily driven by fine-grained sediments (clay and silt) and total organic carbon (TOC), which strongly adsorbed and complexed metals due to their extensive surface area and abundant functional groups. The alteration of local hydrodynamics by mangrove vegetation, which reduces flow velocity and promotes the sedimentation of fine particles and organic matter, is a key physical process facilitating this enrichment. Although the young mangroves in this study exhibited a notable capacity for heavy metal enrichment, the associated ecological risk remained relatively low. As the mangrove ecosystem develops and its metal accumulation capacity further increases, coupled with the rapid development of coastal ports and navigation channels in the region, the ecological risks will be significantly heightened. It is essential to implement regular and continuous monitoring to assess ecological risks. Additionally, differentiated remediation and management measures should be implemented based on a zoned management strategy, targeting distinct areas such as the core forest interior, the transitional forest edges, and the bare mudflat zones.

## CRedit authorship contribution statement

**Yue Li:** Writing – original draft, Methodology, Data curation, Conceptualization. **Xiaowen Xie:** Formal analysis. **Chuqi Long:** Formal analysis, Investigation. **Yuan Xiong:** Formal analysis, Data curation. **Riming Wang:** Investigation, Resources. **Zhijun Dai:** Conceptualization, 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.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ocecoaman.2026.108137>.

## Data availability

Data will be made available on request.

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