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Interactions Between Heavy Metals and Microplastics in Surface Marine Sediments, Chanthaburi River Mouth, Eastern Gulf of Thailand

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ABSTRACT

Sediment quality in global estuaries was reported by assessing the degree of anthropogenic input and the corresponding ecological risks. This research intended to categorize the quantities of marine pollution at the mouth of the Chanthaburi River, on the Eastern Gulf of Thailand, by examining the interactions amongst the heavy metals (Pb, Cd, Cu, Zn) and microplastics (MPs) in surface marine sediments. Marine pollution severity was classified using the Geo-accumulation Index (I_{geo}), Sediment Enrichment Factor (SEF), and Pollution Load Index (PLI). Spatial distribution of pollutants and geostatistical covariance were examined via Geographic Information System (GIS) and Principal Component Analysis (PCA). The average concentrations determined in sediment samples were as follows: Pb, 0.369 ± 0.022 ppm; Cd, 0.0042 ± 0.0004 ppm; Cu, 5.424 ± 0.007 ppm; Zn, 33.756 ± 0.182 ppm; and microplastics, 1.36 ± 0.06 particles/g. All metal levels were below the WASV, CCV, and TRV reference thresholds. I_{geo} and SEF indicated that Zn was moderately accumulated

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with minor enrichment, while other metals were unpolluted. PCA explained 90.85% of the variance, mainly reflecting Zn accumulation in downstream sites. We also found an inconspicuous correlation between heavy metals and MPs, which may be caused by distinct sources, physicochemical properties, and potential biological synergistic effects that remain unclear. A key originality of this study lies in the integration of GIS-based spatial interpolation with the PLI data to visualize and distinguish site-specific accumulation zones. The study did not assess biological uptake or biomarkers, limiting insight into actual bioavailability and toxicity to marine species. These findings provide spatially explicit evidence for targeted estuarine management and highlight the need for future studies on bioavailability and ecological risks.

Keywords: Heavy Metals; Microplastics; SEF; I_{geo}; PLI; Chanthaburi River Mouth

1. Introduction

To manage the biogeochemical cycling of ecological developments, the marine environment is an important topic. Besides stimulating biogeochemical processes in other environments by linking upstream and downstream areas, estuary and coastal regions are vibrant ecosystems for many marine species, contributing nourishment and habitats [1]. Estuarine ecosystems, situated in proximity to anthropogenic development areas, are more significantly contaminated by terrestrial run-off containing trace pollutants, including original MPs and heavy metals in both dissolved and particulate forms that subsequently settle within these environments [2–5]. The level between chemical release and precipitation in the sediment-pore water is altered by sediment dynamics [6,7]. Being an influential aspect disturbing the mineral equilibrium, biogeochemical processes may result in mobilization and bioavailability variations [8]. For instance, Higher-speed water flow, thermolysis and microbial degradation contribute to the fragmentation of MPs [9,10]. Other processes influencing the dynamics of trace pollutants at the river mouth include their adsorption onto suspended particulates, which can decelerate the rate of photodegradation and hydrolysis, potentially enhancing their bioaccumulation [11]. Moreover, metal accumulation rates are regulated by sediment geochemical properties, including pH, redox potential and grain size [12,13]. Additionally, a layer of iron-manganese oxyhydroxide can form on the surface of suspended solids, which significantly adsorbs heavy metals [14].

The extensive manufacturing and widespread utilization of plastic products have resulted in the pervasive presence of plastic debris in marine environments [15]. Based on prior reports, approximately 80% of the plastic waste found on the coast is produced from terrestrial ecosystems, with predominant microplastic polymers (PE, PP, PS) originating from their extensive use in Styrofoam, packaging, and textiles [16–18]. This plastic contamination pollutes from several sources, including land-derived pathways such as insufficient solid waste management, industrial effluents, household products, urban dust, and riverine inputs, as well as sea-based operations like commercial fisheries and maritime transportation [19,20]. The eco-toxicological impacts on marine species were related with the accumulation rates based on plastic pollution levels at intertidal habitats [21,22]. Currently, the prevalence of microplastics is increasing in different marine environments along the eastern coastal regions and the Gulf of Thailand (GoT) as reported by various monitoring studies [17,23,24]. The Gulf of Thailand (GoT) sediments demonstrate potential threats from microplastic pollution, containing a moderate abundance of fragment and fiber shapes [21,25–27].

Heavy metals are recognized as critical marine toxicants owing to their persistence, biological magnification and toxic properties [28]. Heavy metal contamination can lead to the bioconcentration and bioaccumulation of non-essential elements in marine species, resulting in long-term adverse effects on both human health and ecological food chains [29]. Heavy metal contamination exerts profound effects on the physiological processes of various aquatic organisms, markedly disrupts hemato-biochemical parameters, induces genetic anomalies, and severely impairs the reproductive capacity of marine animals [30]. Motivated by the distinctive anthropogenic events in Thailand, including the constant industrialization and urbanization on its east coast, which considerably enhances the threat of heavy metal pollution to marine ecosystems, heavy metal pollution in Thai fauna is a serious problem [31,32].

In marine sediments, the potential toxicity of pollution

depends largely on the various phases that are activated in the environment. Given the rising severity of marine sediment pollution, identifying potentially risky areas is essential for the implementation of accurate and effective environmental protection measures. Sediment pollution indices are critical tools for accurately assessing contamination levels, evaluating environmental risk and degradation, and separating between natural and anthropogenic sources of accumulated areas [33]. Assessing trace contamination in the marine ambient is a widely used approach for evaluating estuarine pollution and its associated risks. The major pollution indices, including the Geo-accumulation Index (I_{geo}), Sediment Enrichment Factor (SEF), and Pollution Load Index (PLI), were used to classify accumulation levels, modified from Shafie et al. [34]. To this end, marine sediment indices serve a crucial function in translating complex technical data into accessible and interpretable assessments of environmental pollution.

The majority of the Chanthaburi coastal area is primarily used for tourism purposes, such as tourist hotels, recreational zones, commercial shipping routes, fisheries, and local seafood restaurants. However, they also put substantial pressure on the environmental safety of the estuarine area due to marine pollution. This study aimed to assess the levels of anthropogenic pollution in the surface sediments along the Chanthaburi River mouth, Eastern Gulf of Thailand. Accordingly, it is essential to consider the key factors, including spatial distribution, sediment quality, and concentrations of heavy metals and microplastics, which were critically investigated within the study area.

2. Materials and Methods

2.1. Study Area

The current study assesses coastal pollution along the southern river mouth area of the Chanthaburi Province, situated roughly 245 km to the southeast of Bangkok. Chanthaburi River Basin (CRB, area = 1,722 km^2), as a significant domestic river in the eastern coastal area, is the major river responsible for agriculture and transportation of Chanthaburi Province since 1948. The Chanthaburi River (approximately 120 km in length) originates in the northern mountain (Khao Khitchakut National Park), flows through the urban community of Chanthaburi, and ultimately discharges into the Gulf of Thailand at Laem Sing District. Meanwhile, the downstream area of Chanthaburi estuary receives runoff from the river, which transports heavy metals and MPs into the surface sediments. Sediment sampling was carried out in six stations around the mouth of the Chanthaburi River presently impacted by upstream activities and natural watershed erosion (Lam Phaen-1, Samet Ngam-2, Bang Sa Kao-3, Phlio-S4, Laem Pradu-5, and Pak Nam Laem Sing-6) from February to April 2025. The coordinates for each sampling site were recorded using the Global Positioning System (GPS), as illustrated in **Figure 1**. In most of the sampling sites, multiple samples were collected and merged to obtain a comprehensive sample indicative of the study area.

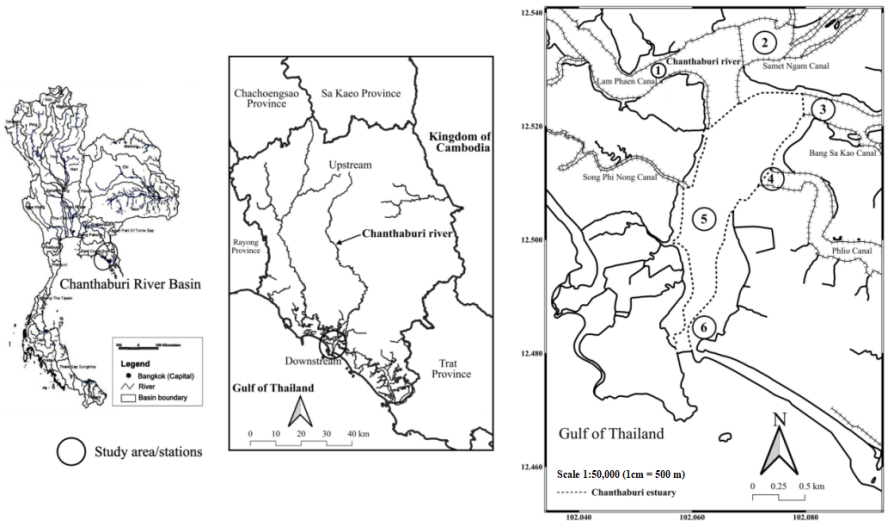

Figure 1. Sediment Sampling Locations Along the Chanthaburi River Mouth.

2.2. Sampling of Marine Sediments

Samples of surface sediment were randomly collected using an Ekman grab sampler (41×19×20 cm) with a larger sample area of 225 cm^2 and a volume of 5 L (**Figure 2**), obtaining sediment layers with a depth of approximately 10 cm. Aluminum foil was used to cover the samples, after which they were protected with cotton fabric, and kept in an icebox at 4 °C until MPs analysis. All sampling processes were carefully protected the contamination, with a specific attention given to avoiding the use of plastic materials.

Plastic tubes were utilized for heavy metals analysis due to their potential to reduce metal contamination, as well as their lightweight, durable, and inexpensive nature [35]. A PVC core sampling cylinder (Ø 5.08 cm) equipped with a vacuum valve was engaged to experimentally collect sediment samples (**Figure 2a** and **b**). Moreover, we stored the sediment samples in acid-rinsed polyethylene plastic bags to prevent heavy metal leaching. Triplicate samples were randomly collected at the study sites to analyse the contamination of MPs and heavy metals.

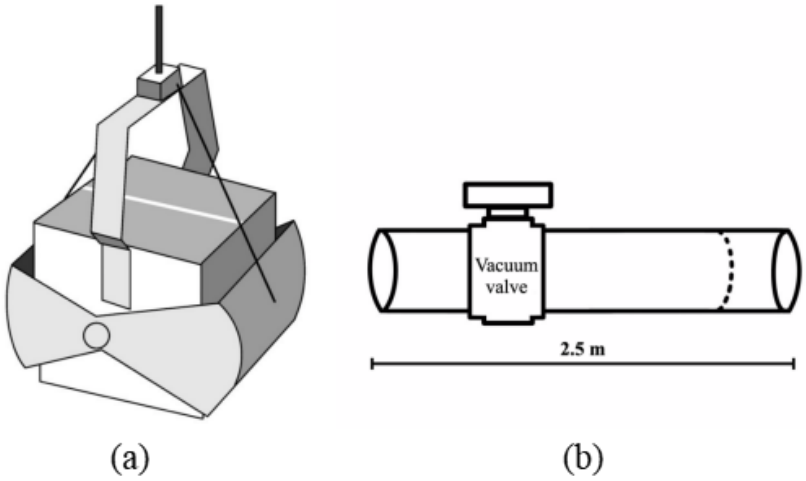

Figure 2. Ekman Grab (**a**) and PVC Cylinder (**b**) Sampling for Analysis of MPs and Heavy Metals, Respectively.

Physicochemical indicators, including pH, temperature, salinity and dissolved oxygen, were examined directly at the sampling site. The pH values were recorded using an electrometric method on a sediment-water mixture prepared at a 1:2 (w/v) ratio. Temperature and salinity levels were recorded using a Conductivity-Temperature-Depth (CTD) probe capable of multiple measurements (Waterproof Tester, Model 7200). Dissolved oxygen was examined by Winkler titration method.

2.3. Marine Pollution Analysis

The techniques of floatation and filtration were chosen for microplastic analysis from previous reports with slight modification [36]. Heavy metals in sediments were analyzed using standardized scientific methods. The sediment samples were prepared by subsampling, homogenizing and storing prior to aqua regia digestion. Specifically, 5 grams of each sample were digested with analytical grade reagents: 7 mL of 65% HNO_3 (Ajax Finechem, Australia) and 3 mL of 37% HCl (QRëC, New Zealand), followed by heating at 60°C for 30 minutes [37]. After digestion, the samples were maintained at room temperature after cooling and then filtered through Whatman No.5 filter paper. The filtrate was consequently diluted with distilled water to a final volume of 25 mL. Covering Pb, Cd, Zn, and Cu, heavy metal examination was done on the filtrate from the sediment samples. Inductively coupled plasma mass spectrometry (ICP-MS, Plasma Quant MS Elite, Analytikjena) was used to detect Pb and Cd, while a Flame Atomic Absorption Spectrophotometer (FAAS 3110, Perkin Elmer) was used to examine Zn and Cu. The Marine Sediment Reference Materials (MESS-3), National Research Council Canada (NRCC), was similarly analyzed to validate the precision of the analytical process, confirming results within 90% of the certified values.

2.4. Assessment of Sediment Pollution Levels

Marine pollution in the Chanthaburi estuary, Eastern Gulf of Thailand, originating from both natural and anthropogenic activities, was assessed through a critical analysis of sediment samples collected from the study sites. Three sediment pollution indices, specifically the Geo-accumulation index (I_{geo}), Sediment Enrichment Factor (SEF) and Pollution Load Index (PLI), were used to ascertain the relative accumulation levels based on sediment quality criteria (**Table 1**)[38–40].

Table 1. Classification Criteria for the Degrees of Marine Pollution in This Study[38–40].

Index	Objective and Function	Criteria of Sediment Pollution Degrees
I_{geo}	I_{geo} serves as a tool for assessing metal accumulation in sediments by comparing it with the geochemical background.	< 0: Practically unpolluted 0–1: Unpolluted to moderately polluted 1–2: Moderately polluted 2–3: Moderately to strongly polluted 3–4: Strongly polluted 4–5: Strongly to extremely polluted > 5: Extremely polluted[38]
SEF	SEF was widely applied to assess the anthropogenic input on metal load in marine sediments.	< 1: No enrichment 1–5: Minor enrichment 5–10: Moderately severe enrichment 10–25: Severe enrichment 25–50: Very severe enrichment > 50: Extremely severe enrichment[39]
PLI	In this study, PLI was used to evaluate total contamination by accounting for all pollutants across different stations.	PLI < 1: Unpolluted PLI > 1: Polluted[40]

2.4.1. Geo-Accumulation Index (I_{geo})

The I_{geo} was designed to assess the levels of environmental pollution in the marine sediment[41], and is calculated using

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5 \times B_n} \right) \quad (1)$$

where C_n is the determined concentration of heavy metal (n) in the surface sediment, B_n denotes its corresponding geochemical background values, and the constant 1.5 is a correction factor to account for natural lithogenic variability in uncontaminated sediment. In this study, the baseline data originated from average crustal values as proposed by Taylor[42], which include 2.5 μg/g for Pb, 0.2 μg/g for Cd, 55 μg/g for Cu, and 70 μg/g for Zn.

2.4.2. Sediment Enrichment Factor

Generally, the Enrichment Factor (EF) is ordinarily recommended to distinguish lithogenic sources of natural elements, with its effectiveness demonstrated in several studies[39,43,44]. However, this study focuses on the sediment behavior by using the Sediment Enrichment Factor (SEF) approach; the classification of metal pollution was assessed by comparing the ratio of metal concentrations in sediment samples to those in the Earth's upper continental crust[45]. Elements such as Al, Ti, Fe, and Sc are considered preservative and geochemically stable in the context of continental crust composition. In this study, Fe was selected as the lithogenic-origin metal for normalizing the SEF. The SEF for Fe-normalization is defined using

$$\mathrm{SEF_{Heavy\ metals}} = (\mathrm{M_x/Fe_x})_{\mathrm{sample}} \div (\mathrm{M_c/Fe_c})_{\mathrm{shale}} \quad (2)$$

where M_x and Fe_x are the concentrations of heavy metals and Fe in the examined sample, respectively, and M_c and Fe_c are their respective in average shale or undisturbed sediment.

2.4.3. Pollution Load Index

The pollution load index (PLI) is directly related to marine pollution at a specific location, as described by Tomlinson[40]. This tool is used to assess the contamination of heavy metals and microplastics[46,47], which is calculated using

$$\mathrm{PLI\ for\ a\ station} = \sqrt[n]{\mathrm{CF1} \times \mathrm{CF2} \times \mathrm{CF3} \ldots \mathrm{CFn}} \quad (3)$$

where n is the number of pollutants, CF is $C_{pollution}/C_{background}$, $C_{pollution}$ corresponds to the concentrations of metals and microplastics of the sediment samples,

and $C_{background}$ represents the background pollution. The lowest pollution values detected in the sediment samples were designated as a background value.

2.5. Statistical Approaches and Pollution Spatial Distribution Analysis

For establishing the links between the microcontaminants in the sediment and their potential sources, Principal Component Analysis (PCA) was applied, with statistical analyses done by IBM SPSS software (version 20.0).

The Inverse Distance Weighted (IDW) interpolation technique, implemented using functions available in Quantum GIS (QGIS) (http://www.qgis.org/), was activated to analyze and visualize the spatial variability of marine pollution across surface sediments.

3. Results and Discussion

3.1. Physicochemical Data and Concentrations of Heavy Metals and MPs

In the study area, sediment pH values ranged from 7.01 to 8.35. In situ measurements of physicochemical parameters, which varied with depth, revealed an average temperature of 30.89 °C (ranging from 29.28 to 33.36 °C), an average salinity of 16.62 % (ranging from 15.14 to 17.37 %) and an average dissolved oxygen concentration of 7.76 mg/L (ranging from 7.16 to 8.36 mg/L).

The levels of marine pollution contamination along various sediment sampling stations at the Chanthaburi River mouth, Eastern Gulf of Thailand, are given in **Table 2**[48–50]. Based on the investigation across all locations, the mean values of heavy metals were measured at 0.369 ± 0.022 ppm for Pb, 0.0042 ± 0.0004 ppm for Cd, 5.424 ± 0.0071 ppm for Cu, and 33.756 ± 0.182 ppm for Zn. When comparing the average metal concentrations to reference datasets, including the Worldwide Average Shale Values (WASV), Continental Crust Values (CCV), and Toxicity Reference Values (TRV), it was found that the concentrations were lower than all reference criteria. The ultratrace concentrations of Pb and Cd may be attributed to biogeochemical processes such as weathering, erosion, dissolution, ion exchange, and phytoplankton uptake, which can result in localized enrichment or depletion of specific metals[51,52]. In contrast, Cu and Zn are essential biological elements, yet their elevated concentrations in the environment are often associated with anthropogenic inputs such as agrochemicals, inorganic fertilizers, animal manure and sewage sludge[53].

Table 2. Estuarine Area Data for Heavy Metal Concentrations in Surface Sediment[48–50].

Metals (ppm)	The Metals Content of the Present Study						Reference Values		
	S1	S2	S3	S4	S5	S6	WASV[1]	CCV[2]	TRV[3]
Pb	0.360 ± 0.053	0.325 ± 0.027	0.308 ± 0.012	0.298 ± 0.046	0.447 ± 0.049	0.477 ± 0.041	20	12.5	31
Cd	0.0065 ± 0.0005	0.0032 ± 0.0009	0.0023 ± 0.0008	0.0044 ± 0.0007	0.0045 ± 0.0005	0.0044 ± 0.0010	0.3	0.09	0.6
Cu	5.549 ± 0.382	5.124 ± 0.324	4.329 ± 0.232	3.567 ± 0.374	6.847 ± 0.264	7.127 ± 0.136	45	55	16
Zn	32.357 ± 0.904	30.478 ± 1.096	29.207 ± 1.154	26.417 ± 1.140	43.691 ± 1.667	40.386 ± 0.789	95	70	120

WASV[1] worldwide average shale values[48], CCV[2] continental crust values[49], TRV[3] toxicity reference values[50].

Additionally, the abundance of microplastics was detected at an average value of 1.36 ± 0.06 particles/g, and MPs accumulate in the environment due to their chemical inertness[15]. In marine ecosystems, plastics may also adsorb or accumulate various chemical compounds due to their hydrophobic properties[54]. The form of reaction, involving partitioning, Van der Waals forces, electrostatic interaction, π-π interaction, and hydrogen bonding, highly influences the sorption capacity of microplastics for micropollutants, hydrophobic and hydrophilic compounds, along with heavy metals[55]. The impact of MPs on quality of life has garnered significant scholarly attention. MPs can damage tissues and organs throughout the digestive, nervous, respiratory, reproductive, and cardiovascular systems, as suggested by data, impacting the growth of certain diseases and interfering with human health[56].

The marine pollution exhibited significantly different levels in sediment sampling stations (**Figure 3**). In all cases, pollutant concentrations did not differ significantly among the stations (Tukey HSD, $p > 0.05$), except for Pb, Cu, and Zn, which showed significantly higher levels at stations S5 and S6, and for Cd and microplastics, which increased at station S1 (Tukey HSD, $p < 0.05$). Our data were plotted as bivariate scattergrams comparing the mean and standard deviation (SD) values of pollutant concentrations, thereby revealing distinct distribution patterns between essential and non-essential heavy metals, as shown in **Figure 4**. In addition, Principal Component Analysis (PCA) biplot was analyzed to confirm the patterns observed in the mean-SD scattergrams, providing further distinction in the distribution of heavy metals (**Figure 5**). All analyzed pollutants contributed significantly to the variation along the principal component 1 (PC_1), which accounted for 90.85% of the total variance. In contrast, the variation along principal component 2 (PC_2), representing 9.15% of the variance, was primarily influenced by location of the sampling sites.

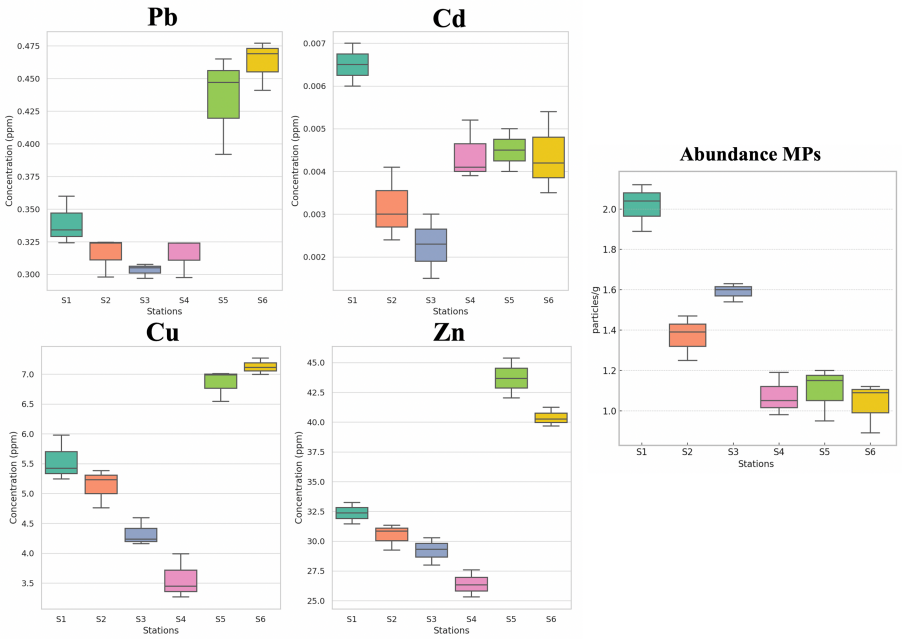

Figure 3. Comparison of Marine Pollution in the Box Plot Indicating Statistically Significant Differences Based on Tukey HSD ($p < 0.05$).

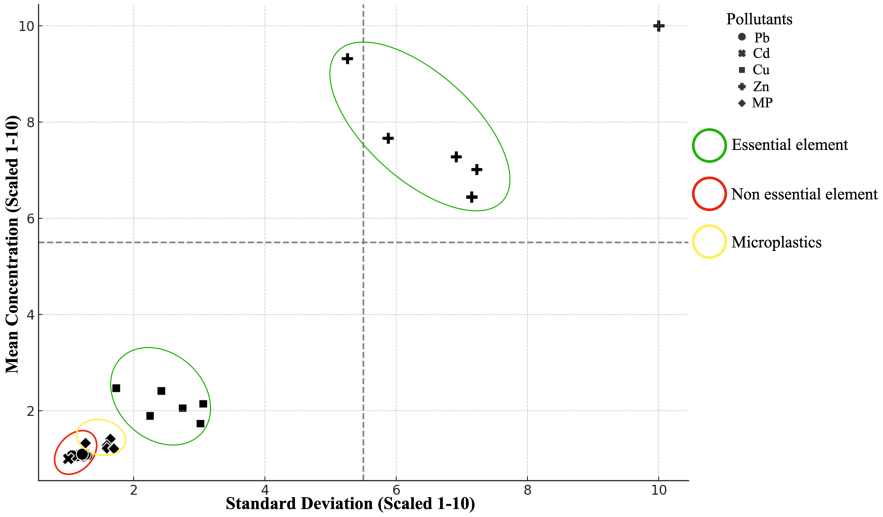

Figure 4. Comparison of Mean and SD Values of Marine Pollution in This Study.

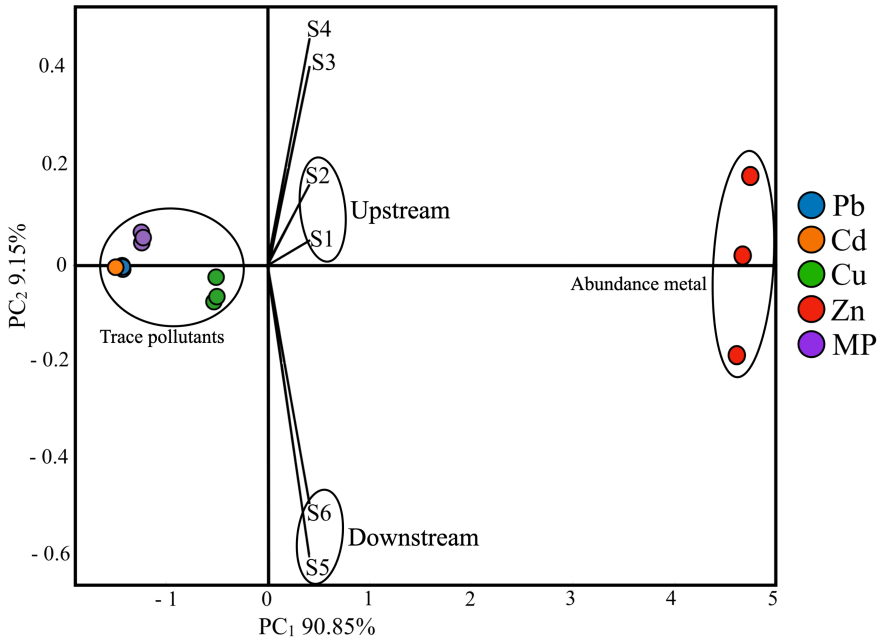

Figure 5. The Principal Component Analysis (PCA) Biplot Visually Illustrating the Segregation of Pollution Concentrations at Different Sampling Stations.

3.2. Assessment of Sediment Pollution Indices

Environmental indices such as I_{geo} and SEF are widely adopted for assessing and classifying sediment quality and pollution severity in marine environments, respectively [57]. The means of I_{geo} and SEF followed the sequence: Zn > Cu > Pb > Cd (**Figure 6**), and the corresponding violin plot of these averages is illustrated in **Figure 6a** and **b**.

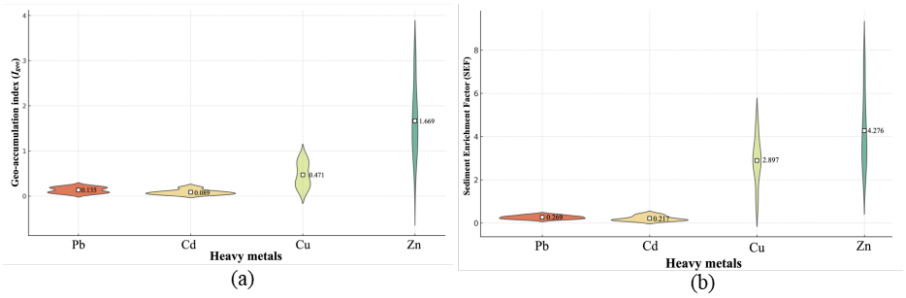

Figure 6. The Violin Plot for Mean Values of I_{geo} (**a**) and SEF (**b**).

The sediment samples collected from the Chanthaburi River mouth had I_{geo} values within the unpolluted to moderately polluted category, except for Zn, which was classified as moderately polluted. This may indicate anthropogenic influence from terrestrial activities occurring in the upstream region of this river. The marine sediments at the Chanthaburi and Welu River mouths in Chanthaburi Province are affected by strong hydrodynamic forces such as runoff, tidal flows, and coastal currents [58]. Moreover, during the rainy season, the Gulf of Thailand is influenced by the Asian monsoon system, leading to the influx of heavy metals into the estuarine ecosystem and influencing the transport and resuspension behavior of marine sediments [59]. Besides, several anthropogenic activities have linked the point sources of heavy metals, with PCA findings suggesting that industrial wastewater and mineral mining were sources of Cd and As, while natural erosion and agricultural areas were sources of Cr, and Zn and Cu were from both [60].

According to Pekey [61], SEF values below 10.0 are not considered significant, as such low levels of enrichment may result from geological differences at the study site or from variations in the baseline data incorporated into the SEF equations. On this basis, we found no substantial enrichment

of heavy metals at the study sites. However, Zn exhibited minor enrichment based on degrees of sediment pollution, as suggested by Naji and Ismail [39]. Overall, the marine pollution levels were assessed using I_{geo} and SEF, and comparatively plotted based on mean values, as illustrated the relative pollution indices in **Figure 7**.

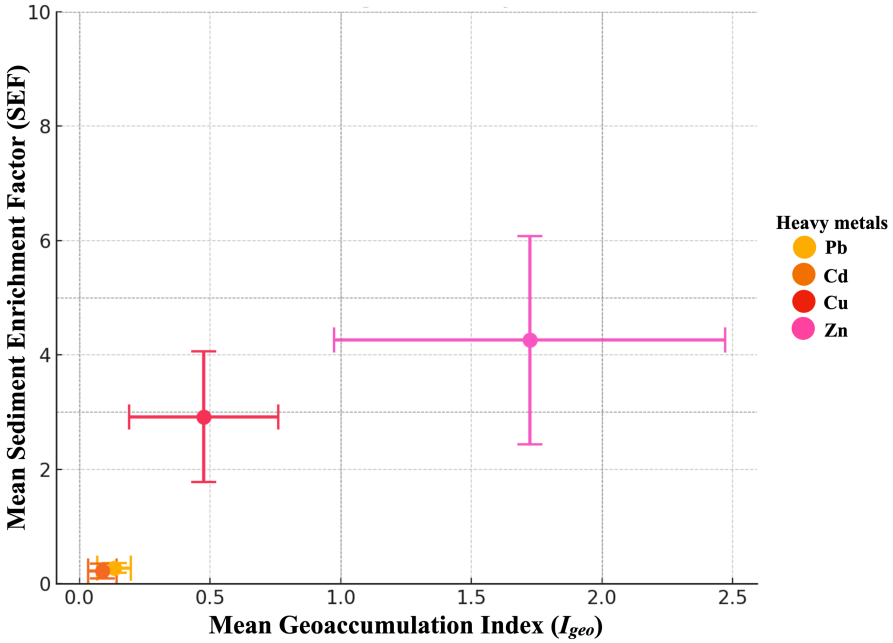

Figure 7. Comparative Plot of I_{geo} and SEF Showing Pollution Levels in Marine Sediments.

3.3. Interactions of Heavy Metals and MPs

The main finding of this study, which focuses on the coupling between heavy metals and MPs in marine sediments, indicated no significant relationships, with all metals showing negative correlations except Cd, which showed a low positive correlation, as shown in **Figure 8**. These findings align with those of Wang et al. [62], who reported that most adsorption of MPs onto lead (Pb) exhibited a strong inverse correlation when comparing river and marine sediments. Furthermore, the synergistic toxicity of MPs and heavy metals has been found to be inversely related to their adsorption capacity, indicating that heavy metals may continue to serve as the dominant contributor to the overall toxic effects on organisms [63]. Additionally, the differing accumulation behaviors of heavy metals and MPs in sediment particles are attributed to their distinct origins, with heavy metals derived from both anthropogenic activities and geological background levels, whereas plastics, as polymers developed within the past century, become increasingly prone to adsorption as they degrade into nano plastics [64]. In contrast, heavy metals, as micropollutants, can undergo both adsorption and absorption through biogeochemical processes, which serve as a primary mechanism controlling the behavior of pollution in estuarine environments [65].

Pollution Load Index (PLI) values of metals and their combinations with MPs were compiled as input data for spatial accumulation analysis. The range of PLI values was from 1.304 to 2.109 for the metals, and from 1.374 to 1.991 for combined metals and MPs, revealing that the marine sediments of the studied river mouth were polluted (PLI > 1). All sites showed PLI values greater than one, which indicates significant accumulation and highlights the sites as potential risk zones for marine pollution. Among these, sites 5 and 6 revealed elevated PLI values for metals, whereas site 1 displayed the highest combined pollution from metals and MPs. It can be inferred that upstream areas were impacted by Cd and MPs, while downstream sites require monitoring for Pb, Cu and Zn as indicated by marine pollution concentrations (**Figures 3** and **5**).

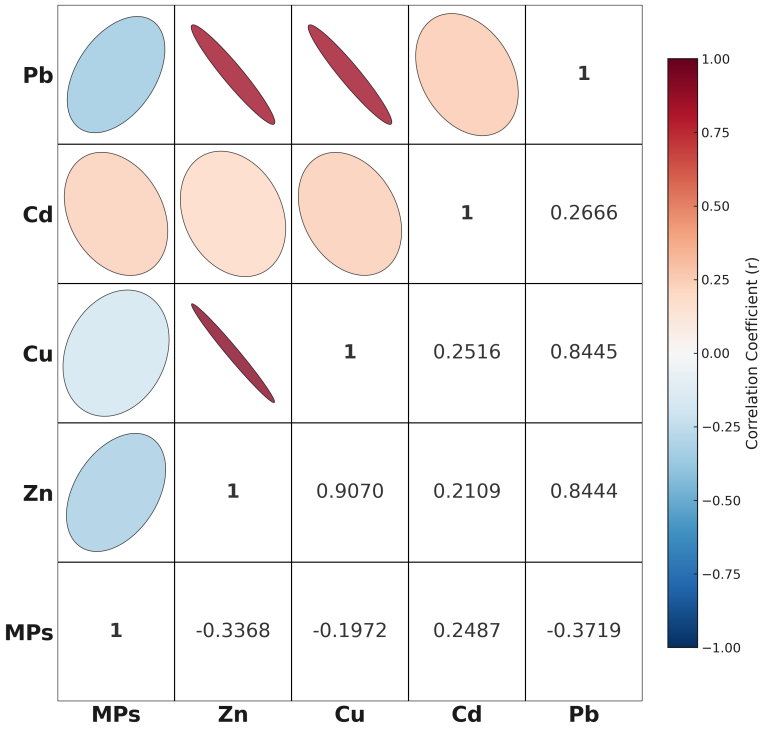

Figure 8. Correlation Between Heavy Metals Concentrations and Abundance of MPs in Marine Sediments.

The interaction studies also revealed the co-potential association between microplastics (MPs) and various metals—Lead (Pb), Cadmium (Cd), Copper (Cu) and Zinc (Zn) with the IDW technique applied to classify and geostatistically visualize their spatial distribution patterns in marine sediments. The spatial distribution maps (**Figure 9**) clearly demarcated zones of varying marine pollution intensities, using PLI values, as illustrated in **Figure 9a** and **b**. Currently, increasing attention has been directed toward MPs contamination and its interactions with heavy metals as a global concern [66], but the underlying mechanisms and their synergistic environmental effects remain limited in understanding. However, the application of Geographic Information System (GIS) techniques for spatial assessment is critical for understanding the dynamics of marine pollution, identifying environmentally sensitive areas, and revealing anthropogenic intensification [67].

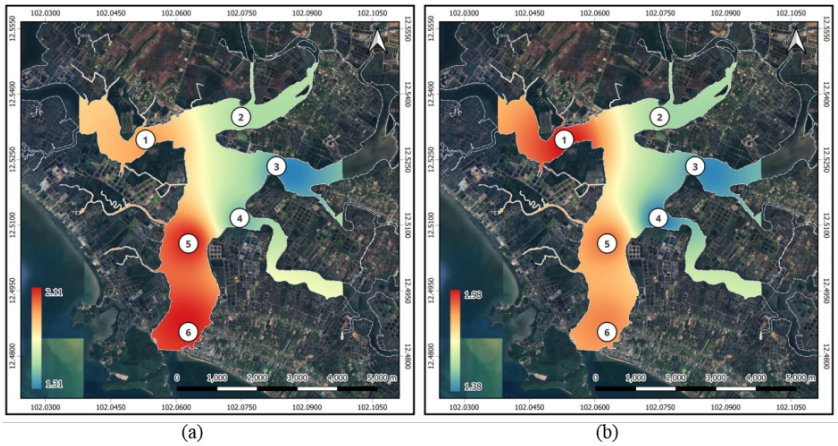

Figure 9. Spatial Distribution of Sediment Pollution at Chanthaburi River Mouth Based on Pollution Load Index (PLI): Heavy Metals (**a**); Combined Heavy Metals and MPs (**b**).

4. Conclusions

The study successfully identified the accumulation of pollution in surface sediment along the Chanthaburi River mouth, Gulf of Thailand. Subsequently, numerous sediment pollution indices, I_{geo}, SEF, and PLI, were employed as sediment quality guidelines to assess potential risks in the marine environment. The findings indicated that most metals were within unpolluted to moderately polluted levels and showed no significant enrichment, except for Zn, which was classified as moderately polluted and exhibited minor enrichment based on I_{geo} and SEF, respectively. Additionally, PLI values (> 1) confirmed widespread sediment pollution, with the highest metal distribution observed in downstream areas (sites 5 and 6). However, no strong correlation was observed between heavy metals and MPs, suggesting varied environmental dynamics and distinct origins. This research effectively fills a regional data gap on co-contamination by heavy metals and MPs in Thai estuarine sediments, where such integrative studies are limited. The comprehensive assessment of pollution indices and GIS-based analysis provides a spatial mapping approach for classifying pollution severity to support environmental restoration. According to Ntona and Morgera [68], the guidelines for sediment quality management and marine ecosystem services should incorporate Sustainable Development Goal (SDG 14: Life below water) alongside scientific monitoring. Future research should focus on biological indicators and bioaccumulation assessments to determine the actual ecological and toxicological risks of marine species. The methodology and findings of this study provide a foundation for combined approaches to estuarine investigations under anthropogenic effects, contributing to national marine environmental protection planning.

Author Contributions

For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, J.P. and T.R.; methodology, J.P., R.S. and T.R.; software, P.O.; validation, T.R. and P.O.; formal analysis, J.P. and R.S.; investigation, R.S. and T.R.; resources, J.P., R.S. and T.R.; data curation, P.O.; writing—original draft preparation, J.P. and P.O.; writing—review and editing, J.P., R.S., T.R. and P.O.; visualization, R.S. and P.O.; supervision, J.P. and T.R.; project administration, J.P. and T.R.; funding acquisition, J.P., R.S., T.R. and P.O. All authors have read and agreed to the published version of the manuscript." Authorship must be limited to those who have contributed substantially to the work reported.

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Not applicable.

Data Availability Statement

Data will be made available upon request.

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Conflicts of Interest

The authors declare no conflict of interest.

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