water

MDPI

Article

Assessment of Heavy Metal Contamination in Beach Sediments of Eastern St. Martin's Island, Bangladesh: Implications for Environmental and Human Health Risks

Md. Simul Bhuyan [1,2,*], Sayeed Mahmood Belal Haider [1], Gowhar Meraj [3], Muhammad Abu Bakar [4], Md. Tarikul Islam [1], Mrityunjoy Kunda [2], Md. Abu Bakar Siddique [5], Mir Mohammad Ali [6], Sobnom Mustary [7], Istiak Ahamed Mojumder [8] and Mohd Aadil Bhat [9,*]

1 Bangladesh Oceanographic Research Institute, Cox's Bazar 4730, Bangladesh; belal_13th@yahoo.com (S.M.B.H.); taru@bori.gov.bd (M.T.I.)
2 Department of Aquatic Resource Management, Sylhet Agricultural University, Sylhet 3100, Bangladesh; kunda.arm@sau.ac.bd
3 Graduate School of Agricultural and Life Sciences, The University of Tokyo, 1-1-1 Yayoi, Tokyo 113-8654, Japan; gowharmeraj@g.ecc.u-tokyo.ac.jp
4 Bangladesh Council of Scientific and Industrial Research, Chittagong 4220, Bangladesh; bakar1012@gmail.com
5 Institute of National Analytical Research and Service (INARS), Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhanmondi, Dhaka 1205, Bangladesh; sagor.bcsir@gmail.com
6 Department of Aquaculture, Sher-e-Bangla Agricultural University, Dhaka 1207, Bangladesh; mir.ali@sau.edu.bd
7 Department of Biological Sciences, Birkbeck, University of London, Bloomsbury, London WC1E 7HX, UK; sobnom99@gmail.com
8 Department of Zoology, University of Chittagong, Chittagong 4331, Bangladesh; amed.himu108@gmail.com
9 State Key Laboratory of Marine Geology, Tongji University, 1239 Siping Road, Shanghai 200092, China
* Correspondence: simul@bori.gov.bd (M.S.B.); aadilgeo@tongji.edu.cn (M.A.B.)

Abstract: Heavy metal pollution in marine ecosystems is an escalating environmental concern, largely driven by anthropogenic activities, and poses potential threats to ecological health and human well-being. This study embarked on a comprehensive investigation into the concentrations of heavy metals in sediment samples and evaluated their potential ecological and health risks with a focus on Eastern St. Martin's Island (SMI), Bangladesh. Sediment samples were meticulously collected from 12 distinct sites around the island, and the concentrations of heavy metals, including Mn, Fe, Ni, Zn, Cr, Pb, and Cu, were quantified utilizing atomic absorption spectrometry (AAS). The results revealed that the average concentrations of the metals, in descending order, were Mn (269.5 ± 33.0 mg/kg), Fe (143.8 ± 21.7 mg/kg), Ni (29.6 ± 44.0 mg/kg), Zn (27.2 ± 4.34 mg/kg), Cr (8.09 ± 1.67 mg/kg), Pb (5.88 ± 0.45 mg/kg), and Cu (3.76 ± 0.60 mg/kg). Intriguingly, the concentrations of all the measured metals were found to be within permissible limits and comparatively lower than those documented in various national and international contexts. The ecological risk assessment, based on multiple sediment quality indices such as the geoaccumulation index, contamination factor, and pollution load index, indicated a moderate risk to the aquatic ecosystem but no significant adverse impact on sediment quality. Additionally, the human health risk assessment, encompassing non-carcinogenic hazard indices for different age groups, was considerably below the threshold, signifying no immediate health risk. The total carcinogenic risk was also found to be below acceptable levels. These findings underscore the current state of heavy metal pollution in Eastern St. Martin's Island, providing valuable insights for environmental monitoring and management. While the immediate risks were not alarming, the study highlights the imperative need for sustained monitoring and the implementation of rigorous regulations to curb heavy metal pollution in order to safeguard both ecological and human health. This warrants the development of policies that are both adaptive and preemptive to ensure the sustainable utilization and conservation of marine resources.

Keywords: trace metals; coastal island; coastal sediments; ecological risk; human health risk

check for updates

Citation: Bhuyan, M.S.; Haider, S.M.B.; Meraj, G.; Bakar, M.A.; Islam, M.T.; Kunda, M.; Siddique, M.A.B.; Ali, M.M.; Mustary, S.; Mojumder, I.A.; et al. Assessment of Heavy Metal Contamination in Beach Sediments of Eastern St. Martin's Island, Bangladesh: Implications for Environmental and Human Health Risks. *Water* **2023**, *15*, 2494. https://doi.org/10.3390/w15132494

Academic Editor: Dimitrios E. Alexakis

Received: 26 May 2023
Revised: 4 July 2023
Accepted: 5 July 2023
Published: 7 July 2023

1. Introduction

Heavy metals (HMs)are widely regarded as some of the most dangerous pollutants in the natural environment, owing to their toxicity, persistence, and propensity to accumulate within living organisms. These contaminants pose significant risks to ecosystems and can lead to severe repercussions [1–3]. Both geogenic and human-made sources of HMs are found in marine sediments. Domestic and mining waste disposal are the main anthropogenic inputs due to rising industrialization, urbanization, and related activities like agriculture [4,5]. Uncommon activities can release heavy metals into aquatic ecosystems where they are transported by the water column, settle in sediment, and become increasingly concentrated as they move up the food chain through bio-magnification. This poses a significant danger to both aquatic life and humans [6–8]. While lower concentrations of HMs are essential for organism survival, higher concentrations are harmful and negatively affect living things.

Heavy metal contamination is very severe in coastal sediments. Aquatic species living in seawater and sediments can accumulate HMs [2]. These can build up in sediments and are typically present in aquatic environments as dissolved or particulate matter. Heavy metals are far more prevalent in the sediment than in the water column, as they tend to be deposited in the lowest layers of water bodies. As a result, contaminants like heavy metals may sink into the sediments [9]. In aquatic environments, sediments on the seafloor are regarded as potential sources and transporters of contaminants [1,7,10]. To comprehend the contamination in the marine environment, it is helpful to investigate the distribution of HMs in surface sediments. Important factors affecting the accretion and availability of HMs in the sediment include sediment characteristics, metal features, pH, organic matter, and redox potential [11].

Environmental contamination assessment requires the analysis of hazardous components in sea sand [12]. Monitoring sediment yields useful data on a range of contamination indicators. Understanding the pollutant source in the sediments of aquatic ecosystems is essential for pollution control. Various methods have been utilized thus far to determine the ecological risks related to heavy metals (HMs) [13]. A considerable body of research has focused on evaluating heavy metal contamination in sediment by applying multi-variate statistical techniques such as Pearson correlation analysis, principal component analysis (PCA), and cluster analysis, effectively identifying the pollution sources [14]. Consequently, the metal pollution evaluation in sediment was carried out using indices such as contamination degree (Cd), pollution load index (PLI), potential ecological risk (PER), and geoaccumulation index (Igeo). These indices facilitated the determination of contamination levels and associated potential hazards.

Bangladesh's SMI is a distinctive feature. But either purposely or accidentally, the island is being poisoned. The majority of effluents from the tanning, electroplating, textile, mining, printing, dyeing, photo, and pharmaceutical industries are dumped straight into rivers [7]. River water that has been discharged and contains toxins contaminates coastal waterways. These impurities combine with seawater and contaminate the water (both coastal and offshore). Infected aquatic life includes fish, crabs, turtles, corals, and benthic organisms. Prolonged exposure to health risks is linked to the consumption of seafood and marine fish from these waters. The commercial fishing industries functioning along the coastline employ approximately five million people. Coastal communities primarily rely on fish and crustaceans as essential sources of protein and income.

The world is recognized for its immaculate environments, including coral islands and ecosystems, that must be protected from heavy metal contamination [15]. Saint Martin's Island, situated in the Bay of Bengal and known for its living coral reefs, has experienced rapid growth due to the unforeseen tourism industry in Bangladesh. Yet, the island can be significantly impacted by increased tourist traffic. During peak season, over 3000 tourists are transported daily from Teknaf to Saint Martin's Island by six large ships and numerous small local boats. During the holidays, this number increases to over 5000 tourists. [16] On a small island like this, they frequently choose to spend the night. If there are more tourists, the level of environmental contamination increases [17]

Other potential metal pollution sources in seawater include domestic and municipal waste, painted fishing boats, and agricultural runoff. Tourism activities in various parts of the world can cause the leaching of heavy metals, which can have dangerous effects on coral and coral ecosystems [15]. The island's development efforts in response to rising visitor numbers could manifest in greater concentrations of contaminants like heavy metals in the water [18]. As a result, the island's aquatic ecosystem has been getting worse due to the constant infiltration of heavy metals from both anthropogenic and natural sources [19]. Heavy metals and other contaminants were discovered by [15] in the sediment and water of Saint Martin's Island. Additionally, the sediments around the island have not yet been carefully examined. It is essential to improve our understanding of the current levels of heavy metal concentration in the sediment of this marine habitat. If the island is contaminated with metals, it is very dangerous for living organisms, island people, and tourists. This study aims to assess the concentration of heavy metals present in sediment and evaluate the potential risk to human health due to these contaminants.

2. Materials and Methods

2.1. Study Area

This study was carried out in twelve sampling locations in the southernmost part of Bangladesh and the northeastern part of the Bay of Bengal, focusing on Saint Martin's Island (Figure 1). The Teknaf peninsula, at around 9 km north of the island, used to extend onto the island millennia ago, but subsequently, some of this peninsula became submerged, resulting in the southernmost part of this peninsula becoming an island with an area of 3 km^2 and being cut off from the Bangladesh mainland. The island was first inhabited 250 years ago, in the 18th century, by Arabian traders who gave it the name "Jazira". The majority or most of the residents (~3700) of the island depend heavily on fishing. The other major food sources are coconut and rice [20].

SMI is abundant with algae, which are generally gathered, dried, and shipped to Myanmar. The island is home to a variety of ecosystems, including rocky areas, mangroves, lagoons, and coral-rich regions. Many animal species find refuge on the island. In 2010, the island was home to 153 species of seaweeds, 187 species of oysters, 66 species of coral, 240 species of fish, 29 species of reptiles, 120 species of birds, and 29 species of mammals [21]. In 2022, the region nearby was designated as a marine protected area [22,23].

The northeastern corner of the Indian Ocean is home to the Bay of Bengal, which is the biggest semi-enclosed tropical bay in the world and roughly triangular in shape. It is a small island that makes up the southernmost region of Bangladesh and is located in the northeastern Bay of Bengal, roughly 9 km south of the peninsular point of Cox's Bazar-Teknaf. At the mouth of the Naf River, it is located about 8 km to the west of Myanmar's northwest coast. This island is located between latitudes 20°34′ and 20°39′ N and longitudes 92°18′ and 92°21′ E. It is locally referred to as Narikel Jinjira and is 3.6 m above the average sea level with a nearly flat shape. The open sea southwest of the island is substantially deeper than the 9.66 km wide canal that connects it to the mainland. Reefs can be found 10 to 15 km to the west-northwest [24].

An anticlinal rise symbolizes the island's straightforward geological structure. The west shore of Dakshinpara contains a small portion of the anticline's axis. The exposed part of the axis runs roughly parallel to the island from north-northeast (NNW) to south-southeast (SSE). A fault with a trend that is almost parallel to the axis runs along the northwest coast. Coral clumps and molluscan coquina horizons make up Saint Martin's limestone. Wherever they occur beneath the alluvium, the shelly limestone acts as a good aquifer due to its high porosity and permeability. The main supply of fresh water comes from recent coastal sands and shelly limestone [24].

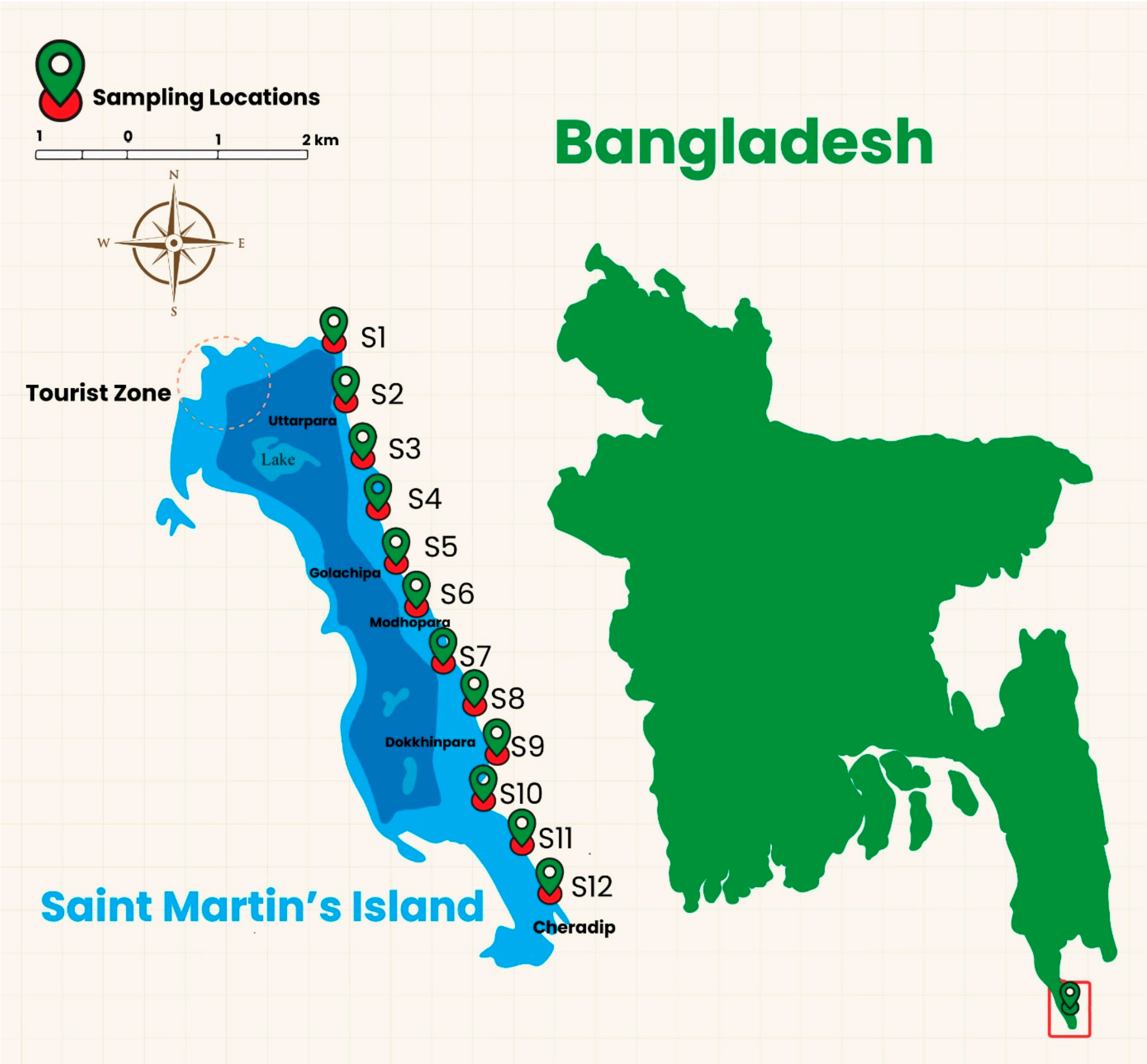

Figure 1. Map showing the eastern side of St. Martin's Island. S1 to S12 are locations of the sampling sites.

2.2. Sample Collection and Preservation

To investigate the heavy metal contamination in the sediments of SMI, 12 composite sediment samples were collected randomly from the eastern 12 sites of the island based on the probable contamination level in 2022. Using an Ekman dredge, samples of about 500 g were taken from each location and stored in airtight polyethylene plastic bags. The samples collected were shipped to the laboratory of the Bangladesh Council of Scientific and Industrial Research (BCSIR), Chittagong, Bangladesh, for heavy metals analysis. The samples were dried in an oven for 48 h at a temperature of 45 °C. After being air dried, the samples were ground into a fine powder utilizing mortar and pestle, then sieved utilizing a 106 m mesh and placed in a polycarbonate vial. The vial was marked with an identification label and stored in a desiccator for metal analysis.

2.3. Sample Digestion, Analysis, and Quality Control

Digestion of about 2 g of the sediment sample was carried out with 10 mL of concentrated HNO_3 and 5 mL concentrated $HClO_4$ in a 100 mL glass beaker at 130 °C for 5 h to almost dryness. After complete digestion was indicated by a transparent solution, the mixture was passed through Whatman filter paper (No. 41), washed with a 1/10 M concentrated HNO_3 solution, and raised to a volume of 100 mL in a calibrated volumetric flask for metal analysis.

In this study, the sediment samples were analyzed for concentrations of chromium (Cr), nickel (Ni), copper (Cu), lead (Pb), manganese (Mn), zinc (Zn), and iron (Fe) using an atomic absorption spectrophotometer (AAS, Model No. ZEEnit700P#150Z7P0110 from Analytikjena, Germany) in an air/acetylene flame. The choice to focus on these specific metals was informed by several factors that are crucial for a comprehensive assessment of heavy metal pollution in marine sediments. Primarily, these metals are prevalent contaminants in marine environments, often emanating from anthropogenic sources such as industrial activities, agricultural practices, and maritime operations. Monitoring these metals is essential for gauging the overall extent of heavy metal pollution in marine environments. Furthermore, certain metals among the selected ones, like lead and chromium, are notorious for their potential toxicity to both aquatic organisms and humans. Evaluating the concentrations of these metals is indispensable for assessing the potential ecological risks and human health implications associated with their presence in the sediments. In addition, metals such as copper, zinc, manganese, and iron are trace elements that are vital for the physiological functions of aquatic life. However, their toxicity escalates with increased concentrations. Therefore, assessing these metals helps in deciphering their role in the marine ecosystem and ensuring that their levels remain within non-hazardous ranges. Further, the selection aligns with international norms and guidelines for heavy metal pollution assessment and draws from precedent in the literature. This alignment facilitates meaningful comparisons with other studies and aids in contributing to the global dialogue and understanding of trends in marine heavy metal pollution. By analyzing these specific metals, the study aims to provide a robust and informed evaluation of heavy metal pollution, its potential ecological impacts, and the implications for human health in Eastern St. Martin's Island. In-house validation of each technique was performed as per the guidelines of EC567/2002. All the requirements for analyzing heavy metals in the samples using atomic absorption spectroscopy are listed in Table 1.

Table 1. Analytical requirements for heavy metals analysis utilizing AAS.

Heavy Metals	Wave Length (nm)	Lamp Current (mA)	Slit (nm)	Detection Limit (mg/L)	Calibration Range (mg/L)
Cr	357.9	12	0.5	0.25–2.0	Flame-AAS
Cu	324.8	5	0.5	0.25–2.0	Flame-AAS
Ni	232.0	15	0.2	0.25–2.0	Flame-AAS
Mn	279.5	12	0.2	0.25–2.0	Flame-AAS
Zn	213.9	10	0.2	0.25–2.0	Flame-AAS
Pb	217.0	10	0.5	0.25–2.0	Flame-AAS
Fe	248.3	15	0.2	0.25–2.0	Flame-AAS

Sigma Aldrich's (Buchs, Switzerland) standard material was used to establish the instrument's calibration curve for metal analysis. Deionized water was utilized throughout the experiment for the sample and standard preparations. All analytical glassware containers had to be cleaned thoroughly with 20% HNO_3 before being washed many times using deionized water and dried in the oven.

2.4. Sediment Contamination Level Assessment

2.4.1. Evaluating Geoaccumulation Index (Igeo)

The geoaccumulation index or Igeo is a crucial ecological measure for separating naturally occurring metals from artificial sources of metal and assessing the contamination degree in the samples of sediment. The following equation defines the geoaccumulation index (I_{geo}):

$$Igeo = \log_2\left(\frac{Cn}{1.5\ BAn}\right) \tag{1}$$

where Cn is the metal concentration in sediment samples and BAn is the background geochemical metal concentration (n). The background matrix correction factor, which accounts for lithospheric effects, is 1.5. Seven categories were established by Müller (1981) [25] for the geoaccumulation index (Table 2).

Table 2. Geoaccumulation Index Categories for Assessing Sediment Quality.

Classification	Contamination Degree
Igeo less than 0	Practically uncontaminated
0 less than or equivalent Igeo less than 1	Uncontaminated to moderately contaminated
1 less than or equivalent Igeo less than 2	Moderately contaminated
2 less than or equivalent Igeo less than 3	Moderately to heavily contaminated
3 less than or equivalent Igeo less than 4	Heavily contaminated
4 less than or equivalent Igeo less than 5	Heavily to extremely contaminated
Igeo greater than or equivalent to 5	Extremely contaminated

Note: Source: [25].

2.4.2. Evaluating Contamination Factor (CF) and Pollution Load Index (PLI)

Contamination factor (CF) is utilized to evaluate contamination in the area of interest. The pollution load index (PLI) was utilized to quickly assess sediment quality in the study area.

$$CF = Cn_{(Sample)}/Bn_{(Shale)} \quad (2)$$

$$\text{PLI} = (\text{CF1} \times \text{CF2} \times \text{CF3} \times \ldots \times \text{CFn})^{1/n} \quad (3)$$

To calculate the contamination factor (CF) value [26], the conc. of each metal in the sediment is divided by its respective background level. In terms of PLI, "n" denotes the total number of elements being assessed. A CF value of less than 1 signifies low contamination, while a CF value between 1 and 3 indicates moderate contamination. A CF value between 3 and 6 suggests considerable contamination, and a CF value of 6 or greater points to extremely high pollution levels. For PLI, a value of 0 represents ideal quality, a value below 1 signifies no pollution, and a value greater than 1 denotes the presence of pollution.

2.5. Evaluation of Potential Ecological Risk

For assessing ecological risks, a method was developed by Hakanson related to heavy metal pollution in 1980 [26]. This approach can be applied to estimate the productivity of an aquatic environment, which is an aspect of its assumed sensitivity. The potential ecological risk index (PERI) was also established to measure the pollution degree in sediments. This index allows for a more accurate assessment of the potential ecological risk factor (PERF) tied to contamination by heavy metals by integrating environmental and ecological consequences with toxicological considerations [27]. Following are the equations used for its calculation:

$$E_r^i = T_r^i \times CF \quad (4)$$

$$C_f^i = C_n^i / C_o^i \quad (5)$$

$$RI = \sum_{i=1}^{n} E_r^i \quad (6)$$

In this context, RI represents the cumulative risk of all heavy metals present in the sediment, while E_r^i denotes the individual PERF. The toxic response factor (TRF) for specific elements accountable for toxicity and sensitivity is represented by T_r^i). The individual contamination factor (CF) is symbolized by C_f^i, while C_n^i and C_o^i represent the sediment metal content and the background value for each element, respectively. The PERI for the sediment can be categorized as follows: $E_r^i < 30$, $R_I < 100$—low risk; $30 \leq E_r^i < 50$, $100 \leq R_I < 150$—moderate risk; $50 \leq E_r^i < 100$, $150 \leq R_I < 250$—significant risk; $100 \leq E_r^i < 150$, $200 \leq R_I < 350$—very high risk; and $E_r^i > 150$, $R_I > 350$—disastrous risk [27,28].

2.6. Assessing Human Health Risk

To evaluate the danger to human health as a result of exposure to the trace metals contained in soil, chronic daily intake (CDI) was utilized. Since humans use three different techniques to absorb metal contents, CDIs can be assessed for these routes: cutaneous, inhalation, and ingestion) [29–31]

$$CDI\ (for\ inhalation) = \frac{PM \times CS \times ET \times EF \times IR_{air} \times ED}{BW \times PEF \times AT} \quad (7)$$

$$CDI\ (for\ dermal\ contact) = \frac{CS \times SA \times AF \times EF \times ED \times ABS}{BW \times AT \times 10^6} \quad (8)$$

$$CDI\ (for\ ingestion) = \frac{CS \times EF \times ED \times IRS}{BW \times AT \times 10^6} \quad (9)$$

In this equation, CS represents the soil trace metal concentration. At the same time, PM refers to the ambient concentration of particulate matter in the target area (0.146 mg/kg). In contrast, ET corresponds to the 24-h daily exposure frequency, and EF signifies the 350-day annual exposure frequency. IR_{air} denotes the inhalation rate of air (20 m^3/d), and ED refers to the 30-year exposure duration [31,32]. Body weight is indicated by BW, with adults being 70 kg and children being 15 kg [32]. Particle emission factor or PEF is 1.36×10^9 m^3/kg according to [32] guidelines. For non-carcinogenic substances, the average time is calculated as 365 × ED days, while for carcinogenic substances, it is 365 × 70 days. The skin surface area is denoted by SA for soil contact exposure, being 5700 cm^2/d for adults and 2800 cm^2/d for children. The adherence factor of soil is indicated by AF: 0.07 mg/cm^2 for adults and 0.2 mg/cm^2 for children, according to [31]—a conversion factor of 10^6 to convert from kg to mg. ABS corresponds to the fraction of dermal absorption at 0.001 for other elements and 0.03 for arsenic (As), while IRS represents the ingestion rate of 100 mg/d according to the guidelines of [31].

2.6.1. Assessing Non-Carcinogenic Risk

Due to varying levels of exposure to heavy metal concentrations, the hazard quotient (HQ) was used to evaluate the non-carcinogenic risk associated with a specific metal. The ratio of chronic daily intake (CDI, mg/kg/d) to the reference dose (mg/kg/day) was employed to calculate the hazard quotient (HQ) [33]. The following equations were used to assess the hazard quotient (HQ) and hazard index (HI) [34]:

$$HI = \sum_{i=1}^{n} HQ_k = HQ_{inhalation} + HQ_{dermal} + HQ_{ingestion} \quad (10)$$

RfD values (in mg/kg/day) and exposure pathways for various elements are as follows: Pb (3.5×10^{-3}), Cr (3×10^{-3}), Cd (1×10^{-3}), and Hg (3×10^{-4}). If the HI is greater than 1, it depicts no option to alleviate the non-carcinogenic effect, indicating that there is a higher likelihood of human exposure [35].

2.6.2. Assessing Carcinogenic Risk

By employing the cancer slope factor (CSF) for the specific metal content for each pathway, the lifetime cancer risk (CR) exposure was evaluated. As per [31], the CSF value is 0.5 mg/kg/day for chromium (Cr). To determine the CR, the following formula was utilized:

$$CR_i = CSF_i \times CDI_i \quad (11)$$

$$CR = \sum_{i=1}^{n} CR_i \quad (12)$$

The lifetime permissible CR limit ranges from 10^{-6} to 10^{-4}. A number $>10^{-5}$ suggests a higher likelihood of somebody developing malignancy than 1 in 100,000 [36–40].

2.7. Statistical Analyses

To address potential concerns related to data distribution, the Shapiro-Wilk and Kolmogorov-Smirnov tests were employed to assess whether the data followed a normal distribution. A statistical significance level of $p \leq 0.05$ was used for correlation analysis to evaluate the associations between the variables under investigation. Cluster analysis (CA) is an unsupervised pattern recognition technique that uncovers the underlying structure of a dataset without making any assumptions about the data. This enables the classification or grouping of the system's objects based on their closeness or similar pairing [41]. Hierarchical clustering is a widely used method in which clusters are incrementally formed, initially pairing the most similar items and then constructing larger clusters in a stepwise manner. Analytical measurements from both samples can be used to express a "distance", with the Euclidean distance typically indicating similarities between two samples [42]. In this study, the normalized dataset was subjected to hierarchical agglomerative CA using Ward's method and Euclidean distances as an index of similarity [43]. This approach seeks to minimize the sum of squares for any two clusters that can be formed at each step while evaluating cluster distances using analysis of variance. The linkage distance is presented as Dlink/Dmax to standardize its display on the y-axis. This ratio is the sum of the linkage distances for all cases divided by the maximum distance multiplied by a hundred.

3. Results and Discussion

3.1. Heavy Metals Concentrations in Sediment

Data from the measurement of heavy metals (Cr, Cu, Ni, Mn, Zn, Fe, and Pb) in the surface sediment of Saint Martin's Island are displayed in Figure 2. Due to decreased water flow, sediment has an average Mn and Fe concentration that is larger than that of other metals, likely contributing to the accumulation of heavy metals [44,45]. Metals in sediment can come from various sources, including trawlers, agricultural waste, gum boats, engine boats, and ships. Moreover, Cox's Bazar and Chittagong, two adjacent industries, can be the source of metals. The heavy metal average concentration in sediments was in the decreasing order of Mn > Fe > Ni > Zn > Cr > Pb > Cu in twelve sites (Figure 2).

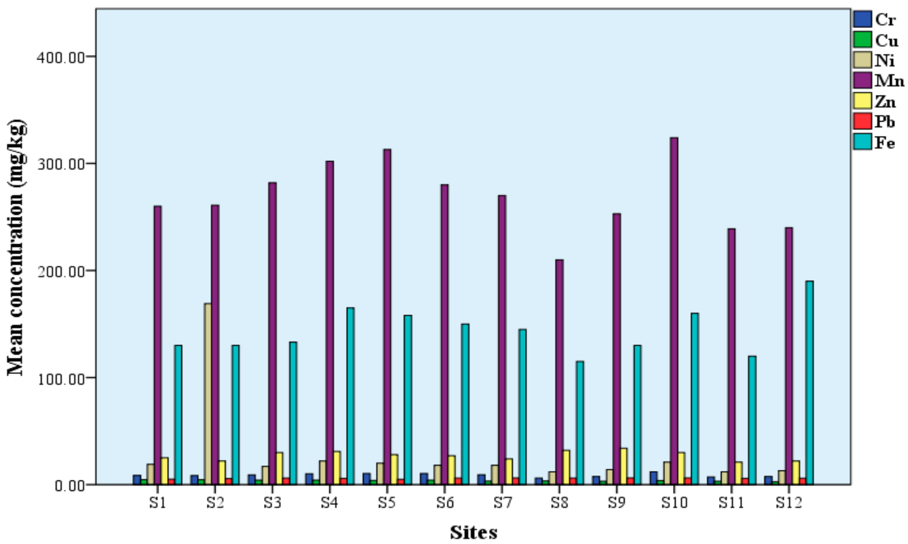

Figure 2. Heavy metals concentrations in the different site's sediment of Eastern Saint Martin's Island.

3.1.1. Chromium (Cr)

Cr is a multifaceted metal, abundantly present in the Earth's crust in various forms and found in deposits such as plants and ores [46]. Its presence is attributed to both natural sources and human activities, including industrial processes like shipbreaking, stainless steel production, and plating [47]. Notably, Cr compounds are known to bind with sediments, and their toxicity, especially Cr(VI), poses health risks, including liver and lung damage and respiratory issues [48,49]. This study observed an average Cr concentration of 8.91 mg/kg in sediments, with the highest at Site 10 (12.0 mg/kg) and the lowest at Site 8 (6.12 mg/kg). Remarkably, these concentrations were below the limits set by WHO, USEPA, and FAO. While similar findings were reported in Nijhum Dweep by Rahman et al. (2022a), other studies observed significantly higher concentrations, such as 121.9 mg/kg in the Sitakunda shipbreaking area [50] and 48.8 mg/kg in Sundarbans sediment [50]. Comparative international data includes 6.48–8.86 mg/kg on the Kalpakkam coast of India [51] and 35.8 mg/kg in Coastal Pearl Bay of China [52], both notably higher than the current study (Table 3).

Table 3. Comparative Analysis of Heavy Metal Concentrations (mg/kg) in Marine/Coastal Sediments: A Global Perspective Including National and International Studies.

Sites	Cr	Cu	Ni	Mn	Zn	Pb	Fe	Country	References
				National					
Saint Martin's Island	8.91	3.76	29.6	269.5	27.17	5.88	143.8	Bangladesh	Present study
Nijhum Dweep	7.2	37	9.26	95.2	20.7	5.63	4706.2	Bangladesh	[53]
Sitakunda shipbreaking area	121.9	na	na	na	na	65.3	na	Bangladesh	[2]
Dhaleshwari River	186	1.76		3.12		8.78	42.7	Bangladesh	[54]
Sundarbans	48.8	41.8	103.95	803.14	72.1	39.1	38,432.5	Bangladesh	[49]
Hatiya and Chairman Ghat and ship-breaking yards	na	42.9	na	na	41.7	5.48	31,658	Bangladesh	[55]
Sundarbans Sela River	40.11	33.7	na	476.6	74.4	26.6	30,255	Bangladesh	[56]
Kutubdia Channel	10.7–12.2	145.6–135.4	na	570.7–606.3	149.8–146.9	21.6–23.9	2317.1–2434.7	Bangladesh	[57]
Halda river	31.9	31.9	26.7	na	71.9	20.5	na	Bangladesh	[58]
Meghna River estuary	10.6	6.22	na	na	42.4	12.5	1290	Bangladesh	[58]
Sitakunda shipbreaking area	64.6	255.4	54.2	1084.7	1226.3	68.3	93,015.1	Bangladesh	[59]
Halda river		23.8	9.44	100	24	24.5	3320		[45]
St. Martin's Island	<5.0–30.1	<3.0–30.9	<4.0–48.3	na	24.1–88.0	<10.0–37.5	na	Bangladesh	[45]
Sangu River estuary	25.1	29.2	32.8	na	89	19.6	na	Bangladesh	[12]
Shipbreaking area	7.95–19.2	15.4–22.0	BDL	na	124.3–176.4	65.5–116.9	62,990–75,210	Bangladesh	[60]
Brahmaputra River	6.6	6.2	12.8	162.2	52.7	7.6	na	Bangladesh	[7]
Sonadia Island	na	18.1	16	390.73	38.8	9.03	15,127	Bangladesh	[61]
Feni River estuary	35.3	na	33.3	37.9	na	6.47	na	Bangladesh	[62]
Sundarban	56.9–78.6	28.7–41.2	26.3–39.2	400–700	55.9–77.3	33.4–48.0	26,000–35,000	Bangladesh	[63]
Bay of Bengal coast	14.5	na	16.3	na	184.6	12.7	316.1	Bangladesh	[64]
				International					
Coastal Pearl Bay	35.8	24.2	na	na	48.5	31.3	na	China	[51]
Kalpakkam coast	6.48–8.86	3.59–5.07	na	1.83–2.77	8.34–10.7	0.32–0.60	3067.4–4545.7	India	[50]
Beibu Gulf	na	11.2	na	na	27.8	18.9	na	China	[65]
South Lagoon	99.8	27.3	71.8	na	148.5	102.2	41,727.2	Tunisia	[66]
Hong Kong coast	37.6	66.9	21.8	na	172.1	51.7	29,295.7	Hong Kong	[67]
Beibu Gulf	2.1–51	0.7–73	na	na	3.5–161	2.4–62	na	China	[68]

Table 3. *Cont.*

Sites	Cr	Cu	Ni	Mn	Zn	Pb	Fe	Country	References
Matsushima Bay		28.5	11.8	859.8	134.8	21.6	38,900	Japan	[69]
Palk Bay	290.3	54.7	27.7	686.1	252.9	14.1	52,802.3	India	[70]
Chabahar Bay	92.3	14.1	58	422	39.6	9.2	3.11	Iran	[71]
Duyen Hai Seaport		5.11	na	na	149	72.6	na	Vietnam	[72]
Zhoushan Islands	74.5	67.8	na	na	107.8	33.9	na	China	[73]
Shenzhen Bay	40.6	50.8	na	na	175.8	37.1	na	China	[74]
Mirs Bay	20–38	8–42	na	na	55–290	26–99	na	China	[75]
Izmit Bay	74.9	79.6	42.1	na	211.1	21	45,700	China	[76]
Bohai Bay	72.4	28	na	na	87.6	24.3	na	China	[77]
Fangcheng Bay	28.5	20.5	na	na	62.4	43.5	na	China	[78]
Western Taiwan Strait	86.89	22.8	31.3	na	64	18.3	na	Taiwan	[79]
Mediterranean Sea	15–93	11–49	na	na	26–72	11–22	na	Turkey	[80]
Pearl River Estuary	79.8	38.1	na	na	121.8	44.8	na	China	[81]
Ondo coastal area (Awoye)	0.92	3.21	6.69	2.77	7.27	14.5	23.6	Nigeria	[82]
Ondo coastal area (Ayetoro)	8.93	5.45	12.3	2.59	8.36	18.2	25.3	Nigeria	[82]
Ondo coastal area (Abereke)	21.1	13.4	17.2	1.84	19.3	15.9	20.4	Nigeria	[82]
Atlantic Coast	187	217	30	na	687	125	na	Congo	[83]
Montenegrin coast	97.6	154	83.3	634	234	70.3	23,400	Montenegro	[84]
Gulf of Suez	55.5	5.07	2.89	na	22.4	17.3	2384	Egypt	[85]
Bohai Sea	60.4	23.1	23.1	na	79	26.3	na	China	[86]
Yellow Sea	49.4	22.5	24.9	na	78.7	26.1	na	China	[86]
Yellow Sea	31	16.9	21.8	na	71.8	31	na	South Korea	[86]
Liaodong Bay	53	18.5	23.5	na	64.7	24.9	na	China	[77]
Bohai Bay	72.4	28	33	na	87.6	24.3	na	China	[77]
Laizhou Bay	61.4	18.6	26.7	na	57.2	20.7	na	China	[77]
Bohai Sea	14.4–88.3	3.36–30.1	na	na	24.0–99.8	11.9–28.1	na	China	[87]
Yellow Sea	0–88.8	2.98–24.6	na	na	8.84–70.1	18.6–26.5	na	China	[87]
East China Sea	38.4–95.9	17.4–43.4	na	na	86.6–180.6	24.2–74.3	na	China	[87]
South China Sea	14.4–35.3	2.21–16.7	na	na	8.47–64.4	4.81–63.9	na	China	[87]
Mimika	na	<0.02–0.54	na	na		<0.25–0.59	na	Indonesia	[88]
Kaohsiung Harbor	127	687	56	na	960	83	na	Taiwan	[89]
Gulf of Tunis	15–55	1.5–19	14–51	na	27–450	16–107	na	Tunisia	[90]
Subei shoal	19.2	11.3	47.9	na	38.2	0.13	na	China	[91]
Haizhou Bay	76.4	32	na	na	78.3	28	na	China	[92]
Yangtze River Estuary	na	26.6	na	na	63.9	21.7	na	China	[93]
Bohai Sea	na	6.7–34.6	na	na	28.7–61.2	8.7–32.3	na	China	[94]
Bohai Sea	89–219.1	38.1–61.9	na	na	na	42.8–73.6	na	China	[93]
Red Sea coast	na	9.43	17.5	198.8	44.2	11.4	8451.6	Egypt	[85]
Pearl River Estuary	39.3	88.7	20.4	na	146	47.9	na	Hong Kong	[95]
Beibu Gulf	44.4	15.1	na	na	52.4	14.6	na	China	[96]
Coromandel Coast	109.5	76.5	na	na	78.76	49.6	na	India	[11]
Gorgan Bay	17.9	16.8	16.6	na	29.5	7.4	na	Iran	[97]
Bohai Bay	48.8	16.1	na	na	50	19.4	na	China	[98]
Jiaozhou Bay	na	27.3	na	na	76	38.5	na	China	[99]
Zhelin Bay	23.1	7.95	7.5	na	75	35.7	na	China	[100]
Eastern Beibu Gulf	46.2	27	na	na	80.1	16.4	na	China	[101]

Table 3. *Cont.*

Sites	Cr	Cu	Ni	Mn	Zn	Pb	Fe	Country	References
Red Sea coast	20.2	18.7	13.7	na	16.8	3.5	1413	Saudi Arabia	[102]
Arabian Gulf	64	297	77	112	48.3	5.3	8474	Saudi Arabia	[103]
Al-Kharrar Lagoon	na	22.4	26.9	328.9	23.6	0.05	18,730	Saudi Arabia	[104]
Salman Bay	na	7.45	2.72	94	8.9	0.14	6150	Saudi Arabia	[104]
Daya Bay	108.7	24.1	26.8	na	108.9	35.3	na	Saudi Arabia	[105]
Yellow River estuary	61.6	29.4	27.3	na	71.3	24.6	na	China	[106]
Coramandal Coast	85.3	54.7	16	na	31.4	18.8	32,059.3	India	[11]
Sheyang Estuary	37.2	23.5	na	na	62.2	16.9	na	China	[107]
Xiangshan Bay	81.7	36.8	na	na	121	38.5	na	China	[108]
Persian Gulf	10.2–16.8	3.45–5.50	8.19–18.1	na	4.75–14.2	2.77–12.3	773.5–8420	Iran	[109]
Quseir Harbor	na	35.8	51	736.8	79.6	48.2	12,003	Egypt	[110]
Abutartour Harbor	na	46.7	62	653.3	91.7	63.3	15,333	Egypt	[110]
Touristic Harbor	na	21.3	32	322.3	47.7	39	15,433	Egypt	[110]
Crustal value	100	55	75	950	70	12.5	56,300	Egypt	[111]

Note: na: No data available.

3.1.2. Copper (Cu)

Copper (Cu), a metal released into the environment through various avenues, including mining, metal processing, agriculture, and chemical industries, is widely employed in both industrial and agricultural practices [112]. Although Cu, along with zinc (Zn), is essential for human health, facilitating hemoglobin synthesis and participating in enzymatic reactions, excessive concentrations can have detrimental effects [113,114].

In the current study, the concentration of Cu in sediments ranged from 2.74 to 4.61 mg/kg, attributed to recent anthropogenic activities. Site 1 exhibited the highest concentration of 4.61 mg/kg, while the lowest of 2.74 mg/kg was observed at Site 12. It is noteworthy that Cu concentrations across all sites remained primarily below background reference values [115,116]. For context, higher Cu concentrations have been reported in sediments of Nijhum Dweep and Sundarbans [50,53], with an exceptionally high content of 42.90 mg/kg reported in sediments from Hatiya, Chairman Ghat, and shipbreaking yards. Internationally, sediments from the coast of Hong Kong and South Lagoon in Tunisia displayed very high Cu concentrations, potentially due to industrial runoff and excessive use of disinfectants in aquaculture that drained into water bodies [66,67,117]. These data emphasize that Cu contamination is notably associated with ship construction and maintenance [118], highlighting the importance of monitoring and regulating industrial activities to minimize environmental contamination.

3.1.3. Nickel (Ni)

Ni is a non-biodegradable heavy metal ion with hazardous properties, found in wastewater and originating from both natural and anthropogenic sources [119]. Natural sources of atmospheric Ni include volcanic emissions, weathering of rocks, wind-borne dust, forest fires, and plants [120], while human-made sources encompass shipbuilding, stainless steel production, gas turbine manufacturing, battery factories, alloy production, electroplating, printing, and silver refineries [121]. Exposure to Ni can have detrimental health effects such as dry cough, cyanosis, respiratory issues, and even cancer [112]. In the present study, Ni concentrations in sediments were observed to range between 12 and 169 mg/kg (Table 3), suggesting anthropogenic influence, likely from metal processing industries. For comparison, 54.2 mg/kg of Ni was recorded in the sediment of the Sitakunda shipbreaking area [59], while 32.8 mg/kg and 16.0 mg/kg were reported in the Sangu River estuary and Sonadia Island, respectively [12,61]. Internationally, higher Ni concentrations were found in the sediment of Hong Kong and South Lagoon, Tunisia [66,67]. Conversely, a lower concentration of 11.8 mg/kg was reported in Matsushima Bay, Japan [69], and

27.7 mg/kg and 58 mg/kg were observed in the sediments of Palk Bay, India, and Chabahar Bay, Iran, respectively [70,71].

3.1.4. Manganese (Mn)

Mn, derived from crustal weathering, is sourced from terrestrial origins and undergoes a transformation into complex hydroxyl manganese compounds before precipitating into sediments. In the current study, Mn concentrations in sediments ranged from 210 to 324 mg/kg (Table 3), with the highest concentration at Site 10 (324 mg/kg) and the lowest at Site 8 (210 mg/kg). Comparative analysis with previous studies reveals varied concentrations. For instance, 390.7 mg/kg of Mn was detected in sediments from Sonadia Island [61], while an exceptionally high concentration of 1084.7 mg/kg was recorded at the Sitakunda shipbreaking area [59]. In contrast, lower Mn concentrations were reported in the sediment from South Lagoon, Tunisia [66], and in sediments from the Montenegrin coast in Montenegro, the Gulf of Suez in Egypt, and the Bohai Sea in China [84–86].

3.1.5. Zinc (Zn)

Zinc (Zn) is naturally present in the Earth's crust and tends to associate with mud and organic debris [11]. It is released into the environment from industrial activities, including metal and paper manufacturing and galvanizing processes [112]. Anti-corrosive paints containing Zn sulfate, used in shipbuilding, contribute to aquatic Zn concentrations [122]. Zn is vital for physiological functions but can cause health problems in excess [112,123]. In this study, Zn concentrations ranged from 21 to 34 mg/kg (Table 3), which is lower compared to other studies. For instance, sediment from the Sitakunda shipbreaking area contained 1226.3 mg/kg Zn [59], and Sonadia Island's sediment had 38.75 mg/kg [61]. Higher concentrations, ranging from 58 to 978 mg/kg, were reported near a shipbreaking location in Bangladesh [73–75,86].

3.1.6. Lead (Pb)

Lead (Pb) is a stable element that poses significant risks to human and animal health, particularly affecting the kidneys and nervous systems [124,125]. It is primarily introduced into marine environments through air deposition and coal combustion by-products [126]. Pb concentrations in marine sediments vary, with the highest levels found in mud due to the transportation of Pb-contaminated material [11]. In this study, Pb concentrations in sediments ranged from 4.91 to 6.31 mg/kg (Table 3), with the maximum recorded at Site 7 and the minimum at Site 5. Comparatively, [59] reported a much higher concentration of 68.3 mg/kg in the Sitakunda shipbreaking area, and [61] documented elevated levels in Sonadia Island. Notably, Coastal Pearl Bay in China had 31.3 mg/kg of Pb [52], while lower concentrations of 0.32–0.60 mg/kg were recorded on India's Kalpakkam coast [65,66]. In general, coastal areas in Bangladesh exhibited higher Pb levels than observed in this study [2,50,54,55].

3.1.7. Iron (Fe)

Iron (Fe) in marine environments originates from crustal weathering and riverine inputs and forms complex hydroxyl compounds that precipitate into sediments [127,128]. Fe oxyhydroxides are efficient scavengers for trace metals and play a critical role in controlling the concentrations of these metals in sediments [129]. There is a positive correlation between Fe and mud, indicating that mud is a primary factor in the distribution of Fe [130]. In this study, Fe concentrations in sediments ranged between 130 and 190 mg/kg, which is significantly lower compared to other studies. For instance, the Sundarbans sediments contained 38,432.5 mg/kg [50], Hatiya and shipbreaking yards had 31,658 mg/kg [55], and 93,015.1–75,210 mg/kg was recorded in shipbreaking areas [53,59]. The Kalpakkam coast recorded 3067.4–4545.7 mg/kg [51], and the South Lagoon had 41,727.2 mg/kg [66], both considerably higher than the current study.

3.2. Sediment Contamination Level Assessment

3.2.1. Geoaccumulation Index (I_{geo})

Based on the average Igeo values, the HMs contamination level in the study area was identified in the following order: Mn > Ni > Pb > Zn > Cr > Cu > Fe. Manganese had the highest Igeo value, while Fe had the lowest. The sites were not found to be contaminated with metals, according to the Igeo value (Figure 3). Moreover, a slight variation in the metals was seen in the sampling locations due to the shift in metal concentrations. The sampling area's Igeo values for Cu, Cr, Zn, Pb, Mn, Ni, and Fe all indicated that there was no contamination there. [131] discovered that the Liaohe River protected area's Igeo values were categorized as extremely contaminated. Moreover, [48] studied the Turag River and discovered that the Igeo values for Pb and Cu were still considered to be in the unpolluted group. This was mostly since metal attribution in the Turag and Liaohe rivers was significantly higher than in the present study.

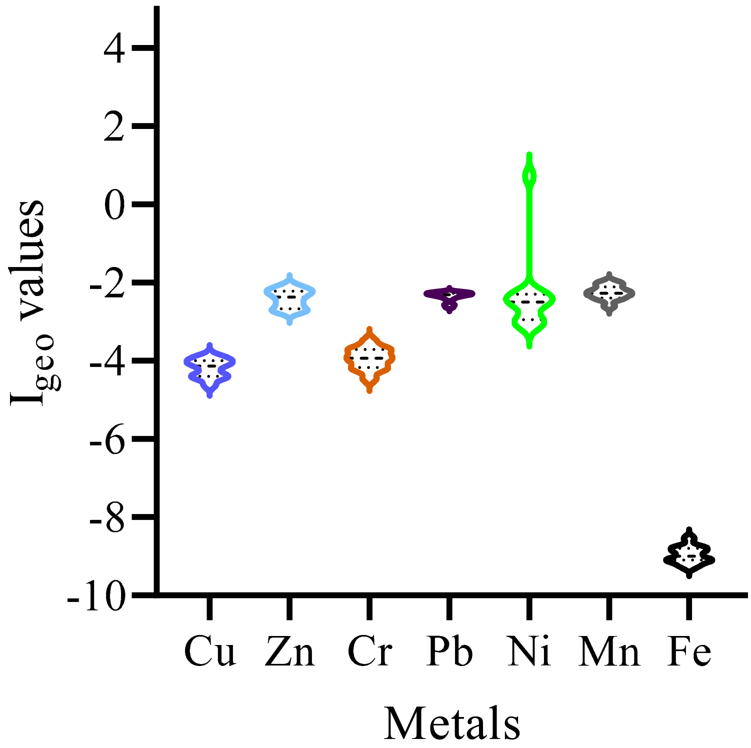

Figure 3. Igeo values for the metal in the sediment of Eastern St. Martin's Island.

3.2.2. Assessing Contamination Factor (CF) and Pollution Load Index (PLI)

The contamination factor (CF) values for the metals are shown in Figure 4 and can be organized as follows: lead ranges from 0.26 to 0.31 (mean 0.29), chromium ranges from 0.07 to 0.12 (mean 0.10), and nickel ranges from 0.18 to 2.49. The Ni CF value indicates less contamination. The Pb CF value suggests that the sediments in the study river were not contaminated. Cr had CF values below 1, indicating lower contamination levels. These types of findings were also reported by [132] in an urban river in Bangladesh. The study concluded that the primary sources of increased metal concentrations in the surface sediment were domestic wastewater discharge, municipal runoffs, industrial effluents, and atmospheric deposition. The results of a study conducted on the Meghna River by [133] aligned with the findings of the present research.

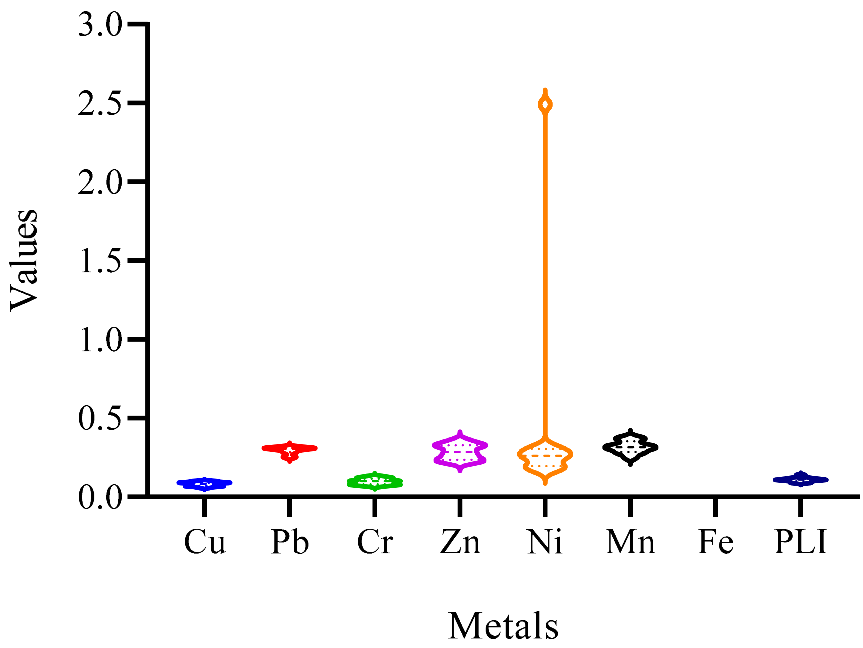

Figure 4. CF and PLI in the sediment of Eastern Saint Martin's Island.

The general public can receive information about sediment quality from the PLI. Also, it offers critical details on the pollution levels in the study area to policy and decision-makers [134]. Figure 2 reports the pollutant load index (PLI) estimates for sediment metals. The examined area is completely polluted if the PLI score is more than one [135]. PLI readings in the winter ranged from 1.01 to 1.42 at all test locations, indicating that the study river's silt was contaminated (PLI >1). In the summer, all locations except for 8, 9, and 10 saw PLI values below 1. PLI values are greater than unity at all sampling sites due to the influence of nearby industrial and governmental activity.

3.3. Assessing Potential Ecological Risk Index (PERI)

Using a single-factor ecological risk model [136], we assessed PERI as well as all the characteristic features that emphasized the combined eco-toxicological effects of multiple aquatic environment contaminants. The monomial potential ecological risk assessment for all metals was found to be low across all sites. The PERI values for all metals at all sites were within the permissible range. The PERI score for all metals in the study area ranged from 0.28 to 2.18, indicating no risk present (Figure 5). Based on the risk index (RI) values for the cumulative metal concentrations, the sites were ranked in descending order: S2 > S4 > S10 > S6 > S3 > S7 > S5 > S1 > S9 > S8 > S12 > S11. In terms of the sites, site S2 had the highest RI value (14.9), while site S11 had the lowest value of 3.20 (Figure 5). Most of the study area was found to pose no threat to the aquatic environment. To evaluate the quality of the sediment and identify new sources of metal content, more environmental factors should be closely monitored, as industry and urbanization are rapidly expanding in the research area.

3.4. Human Health Risk Assessment

Since the local population in the basin of the river was directly related to raising a variety of seasonal crops, the risk to human health was investigated. For their agricultural plots, most of the people used the island sediment. Risk assessment is the key concept and tool for comprehending adverse effects on human health and exposure to environmental hazards [137,138]. For three significant pathways, the following procedures were used to evaluate the risk to human health:

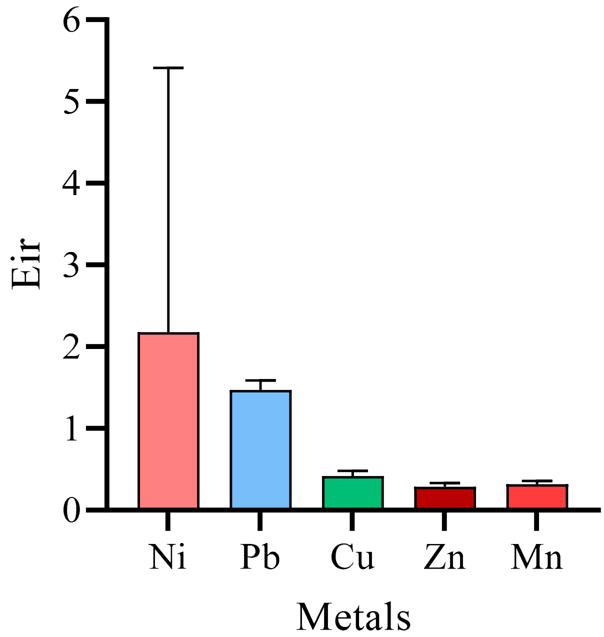

Figure 5. ERI in the sediment of Eastern Saint Martin's Island.

3.4.1. Estimating Chronic Daily Intake (CDI)

The CDIs of metals for both children and adults at the investigated sites were calculated and are presented in Table 4. The findings indicate that the exposure routes decreased in the following order: ingestion > dermal > inhalation, with CDIs being higher for children than adults. Among the examined metals, Cr exhibited the highest CDI values for both children and adults across all exposure pathways (Table 4). The dermal exposure route showed a child's concentration of 3.02×10^{-8} and an adult's concentration of 6.47×10^{-9}. Higher consumption among children (3.31×10^{-5}) compared to adults (7.09×10^{-6}) resulted in elevated levels of Pb and Cu for children through all exposure pathways. For both children and adults, Ni intake was found to be lower than that of the other metals (Table 4).

3.4.2. Assessing Target Hazard Quotient (THQ) (Non-Carcinogenic Risk)

Non-carcinogenic risk was determined using the mean CDI values. The highest HQ value for the ingestion method's Cr metal concentration for both age groups (adult: 4.07×10^{-3}, children: 1.90×10^{-2}) are highlighted in Table 4. Moreover, Cr revealed a prominent position for all types of people, whereas Cr had a higher HQ attribution via the inhalation approach (Table 4). The following sequence of overall HQ outcomes was seen for all surrounding local community pathways: Cr > Pb > Cu > Zn > Mn > Ni > Fe. HQ was measured in order to evaluate HI. The overall HI of the five components depicted that children were more sensitive than adults (Table 4). The overall findings of 1 revealed that the research region did not have a significant non-carcinogenic risk effect. Similar findings were reached in the Yangtze River, where locals were protected from rising above the unsettling level (HI < 1) [139]. Similar findings were made in Bangladesh's Gomti River by [140].

Table 4. Human health risk assessment for the metal contents found in the sediment of Eastern Saint Martin's Island.

Metals	CDI			HQ			HI	CR			TCR
	Inhalation	Dermal	Ingestion	Inhalation	Dermal	Ingestion		Inhalation	Dermal	Ingestion	
Adults											
Cr	6.47×10^{-9}	4.87×10^{-8}	1.22×10^{-5}	2.16×10^{-6}	1.62×10^{-5}	4.07×10^{-3}	4.09×10^{-3}	3.23×10^{-9}	2.43×10^{-8}	6.10×10^{-6}	6.13×10^{-6}
Pb	4.27×10^{-9}	3.22×10^{-8}	8.06×10^{-6}	1.22×10^{-6}	9.19×10^{-6}	2.30×10^{-3}	2.31×10^{-3}				
Cu	2.73×10^{-9}	2.06×10^{-8}	5.15×10^{-6}	6.82×10^{-8}	5.14×10^{-7}	1.29×10^{-4}	1.29×10^{-4}				
Zn	1.97×10^{-8}	1.48×10^{-7}	3.72×10^{-5}	9.86×10^{-7}	7.42×10^{-6}	1.86×10^{-3}	1.87×10^{-3}				
Mn	1.96×10^{-7}	1.47×10^{-6}	3.69×10^{-4}	1.40×10^{-6}	1.05×10^{-5}	2.64×10^{-3}	2.65×10^{-3}				
Ni	2.15×10^{-8}	1.62×10^{-7}	1.89×10^{-4}	1.95×10^{-6}	1.47×10^{-5}	1.72×10^{-2}	1.72×10^{-2}				
Fe	1.04×10^{-7}	7.86×10^{-7}	1.97×10^{-4}	1.49×10^{-7}	1.12×10^{-6}	2.81×10^{-4}	2.83×10^{-4}				
Children											
Cr	3.02×10^{-8}	3.19×10^{-7}	5.69×10^{-5}	1.01×10^{-5}	1.06×10^{-4}	1.90×10^{-2}	1.91×10^{-2}	1.51×10^{-8}	1.59×10^{-7}	2.84×10^{-5}	2.86×10^{-5}
Pb	1.99×10^{-8}	2.11×10^{-7}	3.76×10^{-5}	5.70×10^{-6}	6.02×10^{-5}	1.07×10^{-2}	1.08×10^{-2}				
Cu	1.27×10^{-8}	1.35×10^{-7}	2.40×10^{-5}	3.18×10^{-7}	3.37×10^{-6}	6.01×10^{-4}	6.05×10^{-4}				
Zn	1.00×10^{-7}	9.73×10^{-7}	1.74×10^{-4}	5.01×10^{-6}	4.86×10^{-5}	8.68×10^{-3}	8.74×10^{-3}				
Mn	9.13×10^{-7}	9.65×10^{-6}	1.72×10^{-3}	6.52×10^{-6}	6.89×10^{-5}	1.23×10^{-2}	1.24×10^{-2}				
Ni	1.00×10^{-7}	1.06×10^{-6}	3.72×10^{-5}	9.11×10^{-6}	9.63×10^{-5}	1.86×10^{-3}	1.97×10^{-3}				
Fe	4.87×10^{-7}	5.15×10^{-6}	9.19×10^{-4}	6.96×10^{-7}	7.36×10^{-6}	1.31×10^{-3}	1.32×10^{-3}				

3.4.3. Carcinogenic Risk (CR) Evaluation

The carcinogenic risk (CR) for Pb and Cr was estimated, but the USEPA did not provide a carcinogen slope factor for Pb. The CR results are presented in Table 1. The three exposure pathways were most frequently experienced by both adults and children through ingestion. For instance, there may be significant differences in the CRs of various metals for various age groups (Table 4). In general, it was found that children had higher CR values (2.86×10^{-5}) than adults (6.13×10^{-6}) (Table 4). Also, through the ingestion route, children were exposed to increased CR in terms of Cr with a bigger effect than any other factor. As we can see, the total TCR of Cr value was discovered to be more than 1×10^{-5}, depicting that the research area was not free from the negative effects of CR on both adults and children (Table 4). Contrarily, El-Alfy [137] found that youngsters, as compared to adults, were exposed to carcinogenic risk while consuming metals from the Burullus Lake sediment.

3.5. Identification of Sources of Heavy Metals in Sediment

The sediments of the study island contained materials that were generally normally distributed according to the findings of Shapiro-Wilk and Kolmogorov-Smirnov tests. Using CM, PCA, and cluster analysis, further statistical analyses were performed to give some prospects that delivered some associated possibilities.

The correlation matrix showed how the metals interacted with one another. Cr vs. Mn (r = 0.960) showed a very strong positive relationship at the significance level of 0.01 (Table 5). Cr vs. Fe (r = 0.498), Cr vs. Cu (r = 0.463), Cu vs. Ni (r = 0.446), and Cu vs. Mn (r = 0.438) exhibited moderate linear relation at the alpha level 0.01. Pb vs. Fe (r = 0.009), Cu vs. Zn (r = 0.053), Mn vs. Cr vs. Zn (r = 0.146), Zn (r = 0.223), and Zn vs. Pb (r = 0.28) showed a very weak relation. Cu vs. Pb (r = −0.474) showed a moderate negative, weak association (Table 5).

Table 5. Correlation and principal component analysis among the metal contents.

	Cr	**Cu**	**Ni**	**Mn**	**Zn**	**Pb**	**Fe**	**PC1**	**PC2**	**PC3**
Cr	1							0.589	0.158	−0.010
Cu	0.463	1						0.394	−0.428	0.362
Ni	−0.002	0.446	1					0.085	−0.558	−0.061
Mn	0.960	0.438	−0.011	1				0.592	0.154	0.036
Zn	0.146	0.053	−0.358	0.223	1			0.072	0.376	0.703
Pb	−0.084	−0.474	−0.204	−0.179	0.28	1		−0.214	0.450	0.117
Fe	0.498	−0.187	−0.170	0.467	−0.12	0.009	1	0.299	0.336	−0.596
Eigenvalue								2.57	1.85	1.21
% of Variance								36.77%	26.47%	17.32%
Cumulative %								36.77%	63.24%	80.56%

PCA was used to qualitatively assess the clustering tendency of some characteristics. The PCA results for each factor with an eigenvalue larger than one and a cumulative variance of 80.56% are displayed in Figure 6. The three grouping components were investigated by the PCA. PC1 contributed 36.77% of the overall variation and had corresponding loadings of 0.589 and 0.592 due to the large loadings of Cr and Mn (Table 5). According to the results, PC1 was demonstrated to originate from both anthropogenic and geogenic sources, including manufacturing firms and refineries [141]. PC2 has a total variance of 26.47% when Pb is loaded (0.450). The high loading of Zn (0.703) in PC3 showed a total variance (17.32%), which was related to industrial issues.

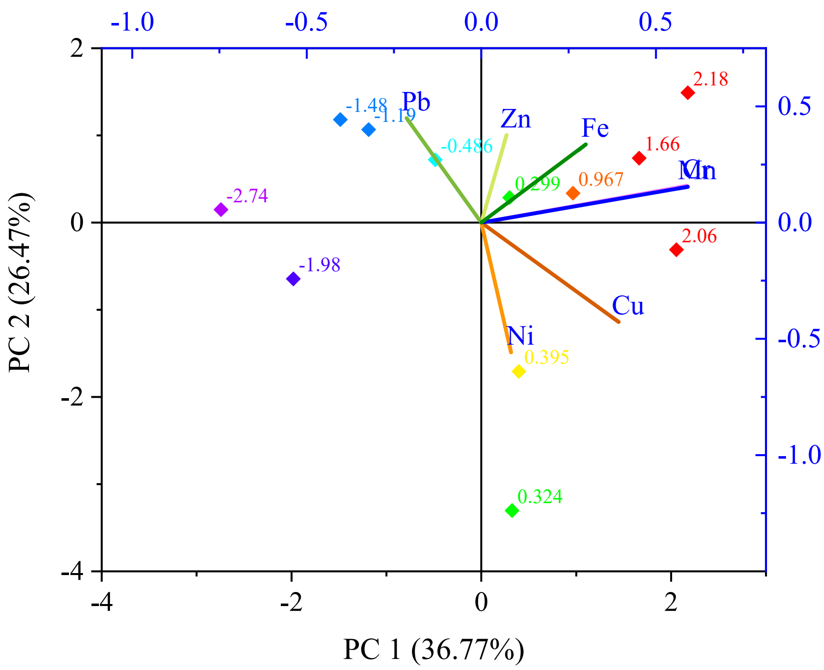

Figure 6. PCA is among the metals in the sediment of Eastern St. Martin's Island.

To identify specific contamination sites, one cluster displayed a distinct set of locations, while another cluster showcased a different set of sites [142,143]. Euclidean distance and Ward's linkage were used to determine the clusters. The relationship between the analyzed metals and potential sources was examined using cluster analysis at (Dlink/Dmax) × 100 < 1 [144]. Cluster 1 consisted of Cr, Cu, Pb, Zn, and Ni, while Mn and Fe were in Cluster 2 (Figure 7). The dendrogram generated by the cluster analysis for sampling sites depicted a significant cluster at (Dlink/Dmax) × 100 < 30 and three notable clusters: Cluster 1, Cluster 2, and Cluster 3. Cluster 1 included sites S1, S9, S11, and S8; Cluster 2 comprised sites S3, S6, S7, and S12; and Cluster 3 contained sites S5 and S10 (Figure 7).

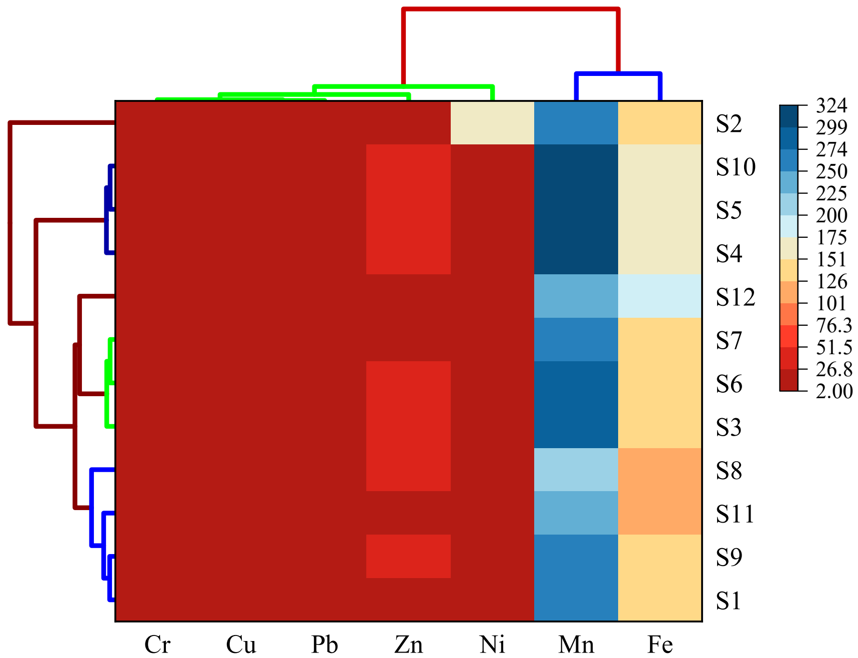

Figure 7. Hierarchy of dendrogram among the metals in the sediment of Eastern St. Martin's Island.

3.6. Policy Implications

The research findings elucidate the need for comprehensive environmental management policies to mitigate heavy metal pollution in marine and coastal ecosystems [145,146]. Based on the findings, it is clear that governments should implement policies that regulate tourism in ecologically sensitive areas by establishing carrying capacities and encouraging eco-friendly tourism [147–150]. Such sustainable tourism policies will protect natural habitats from the pressures of over-tourism and ensure that the tourism sector thrives without compromising environmental integrity. Furthermore, the maritime sector is identified as a significant contributor to heavy metal pollution [151]. Policies that enforce maintenance protocols for ships and engine boats, focusing on the use of cleaner fuels and technologies, proper ballast water management, and waste handling, are essential [152]. This will not only reduce pollution but also drive innovation and sustainability in the maritime sector. Additionally, the findings call for a regulatory framework for industries operating in coastal areas. Mandatory environmental impact assessments (EIAs) and adherence to environmental best practices should be required for approval and operation [153]. The policy should also necessitate that industries have effective pollution control measures in place, especially regarding heavy metal emissions, and enforce strict penalties for non-compliance. One industry that deserves particular attention is shipbuilding and shipbreaking. Policies should ensure that these industries are not only complying with national regulations but also adhering to international environmental standards [154]. Encouraging cleaner production processes, proper waste management, and regular monitoring of environmental impact should be integral parts of the policy. Lastly, the research indicates that agricultural activities can be a source of heavy metal pollution. As such, policies that promote the use of less toxic pesticides and fertilizers, implement soil conservation practices, and provide education and resources for sustainable agriculture are imperative. This will not only reduce pollution but will also enhance food security and the livelihoods of farming communities. Overall, the policy implications drawn from this research are instrumental in shaping an integrated approach to environmental management. These recommendations, when implemented effectively, have the potential to mitigate heavy metal pollution, protect marine and coastal ecosystems, and foster sustainable development in the concerned regions.

4. Conclusions

This study presents a meticulous evaluation of heavy metal concentrations in the sediments of St. Martin's Island, establishing a foundation for ecologically-informed decision-making. The results conclusively show that heavy metal concentrations, including manganese and iron, are within acceptable limits, indicative of a non-polluted environment conducive to aquatic life and human well-being. Comparatively, the concentrations of heavy metals in the study area are significantly lower than in other regional, national, and international contexts. However, a salient observation was the potential heightened susceptibility of children to heavy metal hazards, despite the absence of carcinogenic risks. While the study provides valuable insights, it is important to acknowledge certain limitations. First, the study's scope is confined to a singular geographic region and does not consider temporal variations, which could be vital for understanding seasonal fluctuations in heavy metal concentrations. Moreover, the study did not delve into the chemical speciation of metals, which is essential for a comprehensive understanding of metal bioavailability and toxicity. Based on the results and limitations, several avenues for future research emerge. There is a need to extend the study through longitudinal monitoring to understand temporal trends and assess the effects of climate change and anthropogenic activities on heavy metal accumulation. Furthermore, incorporating chemical fractionation and speciation studies would offer a more detailed assessment of the ecological risks and exposure pathways of heavy metals in marine environments. It is also imperative to explore and develop innovative and sustainable remediation strategies to manage and mitigate heavy metal contamination. Additionally, collaborative research at a broader geographic scale can enhance understanding and facilitate the development of comprehensive policies for the conservation of marine ecosystems. Overall, the study underlines the importance of continuous monitoring and adaptive management for the preservation of St. Martin's Island's ecosystem health. Commitment to research and the implementation of science-based strategies will be crucial in ensuring the ecological sustainability of this marine environment for future generations.

Author Contributions: Conceptualization, M.S.B.; Data curation, M.S.B., G.M. and M.T.I.; Formal analysis, M.S.B. and M.A.B. (Muhammad Abu Bakar); Investigation, M.S.B.; Methodology, M.S.B., M.A.B. (Muhammad Abu Bakar) and M.T.I.; Visualization, M.S.B., M.A.B. (Mohd Aadil Bhat) and M.M.A.; Writing—original draft, M.S.B.; Writing—review & editing, S.M.B.H., G.M., M.T.I., M.K., M.A.B.S., M.M.A., S.M., I.A.M. and M.A.B. (Mohd Aadil Bhat); Supervision, S.M.B.H. and M.K. funding acquisition, M.A.B. (Mohd Aadil Bhat). All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data of this work is available with the corresponding authors and can be availed on special request.

Acknowledgments: The authors would like to extend their gratitude to the Bangladesh Oceanographic Research Institute for technical support. Additionally, appreciation is given to the Bangladesh Council of Scientific and Industrial Research (BCSIR), Chittagong, for providing analysis facilities. Furthermore, the authors would like to thank three anonymous reviewers for their valuable feedback and insights that greatly contributed to the improvement of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bat, L.; Öztekin, A.; Arici, E.; Şahin, F.; Bhuyan, S. Trace Element Risk Assessment for the Consumption of Sarda sarda (Bloch, 1793) from the mid-South Black Sea Coastline. *Water Air Soil Pollut.* **2022**, *233*, 44. [CrossRef]
2. Ali, M.M.; Ali, M.L.; Bhuyan, M.; Islam, M.; Rahman, M.; Alam, M.; Mustary, S. Spatiotemporal variation and toxicity of trace metals in commercially important fish of the tidal Pasur River in Bangladesh. *Environ. Sci. Pollut. Res.* **2022**, *29*, 40131–40145. [CrossRef] [PubMed]
3. Bhuyan, M.; Bakar, M.A.; Rashed-Un-Nabi, M.; Senapathi, V.; Chung, S.Y.; Islam, M. Monitoring and assessment of heavy metal contamination in surface water and sediment of the Old Brahmaputra River, Bangladesh. *Appl. Water Sci.* **2019**, *9*, 125. [CrossRef]
4. Bhuyan, M.S.; Bakar, M.A.; Akhtar, A.; Hossain, M.B.; Ali, M.M.; Islam, M.S. Heavy metal contamination in surface water and sediment of the Meghna River, Bangladesh. *Environ. Nanotechnol. Monit. Manag.* **2017**, *8*, 273–279. [CrossRef]
5. Bhuyan, M.S.; Bakar, M.A. Seasonal variation of heavy metals in water and sediments in the Halda River, Chittagong, Bangladesh. *Environ. Sci. Pollut. Res.* **2017**, *24*, 27587–27600. [CrossRef]
6. Dvorak, P.; Roy, K.; Andreji, J.; Liskova, Z.D.; Mraz, J. Vulnerability assessment of wild fish population to heavy metals in military training area: Synthesis of a framework with example from Czech Republic. *Ecol. Indic.* **2020**, *110*, 105920. [CrossRef]
7. Zhelev, Z.M.; Arnaudova, D.N.; Popgeorgiev, G.S.; Tsonev, S.V. In situ assessment of health status and heavy metal bioaccumulation of adult Pelophylax ridibundus (Anura: Ranidae) individuals inhabiting polluted area in southern Bulgaria. *Ecol. Indic.* **2020**, *115*, 106413. [CrossRef]
8. Bacchi, E.; Cammilleri, G.; Tortorici, M.; Galluzzo, F.G.; Pantano, L.; Calabrese, V.; Vella, A.; Macaluso, A.; Dico, G.M.L.; Ferrantelli, V.; et al. First Report on the Presence of Toxic Metals and Metalloids in East Asian Bullfrog (*Hoplobatrachus rugulosus*) Legs. *Foods* **2022**, *11*, 3009. [CrossRef]
9. Aydın, H.; Tepe, Y.; Ustaoğlu, F. A holistic approach to the eco-geochemical risk assessment of trace elements in the estuarine sediments of the Southeastern Black Sea. *Mar. Pollut. Bull.* **2023**, *189*, 114732. [CrossRef]
10. Du, S.; Zhu, R.; Cai, Y.; Xu, N.; Yap, P.-S.; Zhang, Y.; He, Y.; Zhang, Y. Environmental fate and impacts of microplastics in aquatic ecosystems: A review. *RSC Adv.* **2021**, *11*, 15762–15784. [CrossRef]
11. Anbuselvan, N.; Sridharan, M. Heavy metal assessment in surface sediments off Coromandel Coast of India: Implication on marine pollution. *Mar. Pollut. Bull.* **2018**, *131*, 712–726. [CrossRef]
12. Hossain, M.B.; Shanta, T.B.; Ahmed, A.S.; Hossain, K.; Semme, S.A. Baseline study of heavy metal contamination in the Sangu River estuary, Chattogram, Bangladesh. *Mar. Pollut. Bull.* **2019**, *140*, 255–261. [CrossRef]
13. Bhuyan, M.S.; Bakar, M.A. Assessment of water quality in Halda River (the Major carp breeding ground) of Bangladesh. *Pollution* **2017**, *3*, 429–441.
14. Bhuyan, M.S.; Islam, M.S. Status and impacts of industrial pollution on the karnafully river in Bangladesh: A review. *Int. J. Mar. Sci.* **2017**, *7*, 16. [CrossRef]

15. Sarker, K.K.; Bristy, M.S.; Alam, N.; Baki, M.A.; Shojib, F.H.; Quraishi, S.B.; Khan, F. Ecological risk and source apportionment of heavy metals in surface water and sediments on Saint Martin's Island in the Bay of Bengal. *Environ. Sci. Pollut. Res.* **2020**, *27*, 31827–31840. [CrossRef]
16. Tokatlı, C.; Varol, M.; Ustaoğlu, F. Ecological and health risk assessment and quantitative source apportionment of dissolved metals in ponds used for drinking and irrigation purposes. *Environ. Sci. Pollut. Res.* **2023**, *30*, 52818–52829. [CrossRef]
17. Dogru, T.; Bulut, U.; Kocak, E.; Isik, C.; Suess, C.; Sirakaya-Turk, E. The nexus between tourism, economic growth, renewable energy consumption, and carbon dioxide emissions: Contemporary evidence from OECD countries. *Environ. Sci. Pollut. Res.* **2020**, *27*, 40930–40948. [CrossRef]
18. Jafarabadi, A.R.; Bakhtiyari, A.R.; Toosi, A.S.; Jadot, C. Spatial distribution, ecological and health risk assessment of heavy metals in marine surface sediments and coastal seawaters of fringing coral reefs of the Persian Gulf, Iran. *Chemosphere* **2017**, *185*, 1090–1111. [CrossRef]
19. Clark, N.; Rickards, L. An Anthropocene species of trouble? Negative synergies between earth system change and geological destratification. *Anthr. Rev.* **2022**, *9*, 425–442. [CrossRef]
20. Ghose, T.; Hossain, M. Socioeconomic factors affecting profitability of seaweed culture in Saint Martin Island of Bangladesh. *Progress. Agric.* **2020**, *31*, 227–234. [CrossRef]
21. Alam, O.; Deng, T.; Uddin, M.; Alamgir, M. Application of Environmental Ethics for Sustainable Development and Conservation of Saint Martin's Island in Bangladesh. *J. Environ. Sci. Nat. Resour.* **2015**, *8*, 19–27. [CrossRef]
22. Wildlife Conservation Society. A New Marine Protected Area to Protect Biodiversity and Coral Habitat Around Saint Martin's Island in Bangladesh. Available online: https://newsroom.wcs.org/News-Releases/articleType/ArticleView/articleId/17095/A-New-Marine-Protected-Area-to-Protect-Biodiversity-and-Coral-Habitat-Around-Saint-Martins-Island-in-Bangladesh.aspx350593 (accessed on 2 April 2023).
23. The Business Standard. High-Powered Team Suggested for Supervision of Marine Protected Areas. 2021. Available online: https://www.tbsnews.net/bangladesh/high-powered-team-suggested-supervision-marine-protected-areas-350593 (accessed on 2 February 2023).
24. Banglapedia. St Martin's Island. 2021. Available online: https://en.banglapedia.org/index.php/St_Martin\T1\textquoterights_Island (accessed on 1 February 2023).
25. Müller, G. Die Schwermetallbelstung der sedimente des Neckars und seiner Nebenflusse: Eine Bestandsaufnahme. *Chemiker-Zeitung* **1981**, *105*, 157–164.
26. Håkanson, L. An ecological risk index for aquatic pollution control. A sedimentological approach. *Water Res.* **1980**, *14*, 975–1001. [CrossRef]
27. Bi, B.; Liu, X.; Guo, X.; Lu, S. Occurrence and risk assessment of heavy metals in water, sediment, and fish from Dongting Lake, China. *Environ. Sci. Pollut. Res.* **2018**, *25*, 34076–34090. [CrossRef] [PubMed]
28. Kusin, F.M.; Azani, N.N.M.; Hasan SN, M.S.; Sulong, N.A. Distribution of heavy metals and metalloid in surface sediments of heavily mined area for bauxite ore in Pengerang, Malaysia and associated risk assessment. *Catena* **2018**, *165*, 454–464. [CrossRef]
29. Zhao, X.-M.; Yao, L.-A.; Ma, Q.-L.; Zhou, G.; Wang, L.; Fang, Q.-L.; Xu, Z.-C. Distribution and ecological risk assessment of cadmium in water and sediment in Longjiang River, China: Implication on water quality management after pollution accident. *Chemosphere* **2018**, *194*, 107–116. [CrossRef]
30. Ahmed, A.S.S.; Hossain, M.B.; Babu, S.M.O.F.; Rahman, M.; Sun, J.; Sarker, M.S.I. Spatial distribution, source apportionment, and associated risks of trace metals (As, Pb, Cr, Cd, and Hg) from a subtropical river, Gomti, Bangladesh. *Int. J. Sediment Res.* **2021**, *37*, 83–96. [CrossRef]
31. United States Environmental Protection Agency (USEPA). Exposure Factors Handbook 2011 Edition (Final). Available online: http://cfpub.epa.gov/ (accessed on 31 December 2022).
32. United States Environmental Protection Agency (USEPA). *Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites OSWER 9355.4-24*; USEPA: Washington, DC, USA, 2002.
33. United States Environmental Protection Agency (USEPA). *Risk Assessment Guidance for Superfund: Human Health Evaluation Manual, (Part A)*; Office of Emergency and Remedial Response: Washington, DC, USA, 1989; Volume I.
34. United States Environmental Protection Agency (USEPA). *Risk-Based Concentration Table*; USEPA: Washington, DC, USA, 2000.
35. Saha, N.; Mollah, M.; Alam, M.; Rahman, M.S. Seasonal investigation of heavy metals in marine fishes captured from the Bay of Bengal and the implications for human health risk assessment. *Food Control* **2016**, *70*, 110–118. [CrossRef]
36. IARC. *Cancer, Agents Classified by the IARC Monographs*; IARC Monographs on the Evaluation of Carcinogenic Risks to Humans; IARC: Geneva, Switzerland, 2011.
37. Ahmed, A.S.S.; Rahman, M.; Sultana, S.; Babu, S.M.O.F.; Sarker, M.S.I. Bioaccumulation and heavy metal concentration in tissues of some commercial fishes from the Meghna River Estuary in Bangladesh and human health implications. *Mar. Pollut. Bull.* **2019**, *145*, 436–447. [CrossRef]
38. Ahmed, A.S.S.; Sultana, S.; Habib, A.; Ullah, H.; Musa, N.; Hossain, M.B.; Rahman, M.; Sarker, S.I. Bioaccumulation of heavy metals in some commercially important fishes from a tropical river estuary suggests higher potential health risk in children than adults. *PLoS ONE* **2019**, *14*, e0219336. [CrossRef]
39. Yin, S.; Feng, C.; Li, Y.; Yin, L.; Shen, Z. Heavy metal pollution in the surface water of the Yangtze Estuary: A 5-year follow-up study. *Chemosphere* **2015**, *138*, 718–725. [CrossRef]

40. Kalipci, E.; Cüce, H.; Ustaoğlu, F.; Dereli, M.A.; Türkmen, M. Toxicological health risk analysis of hazardous trace elements accumulation in the edible fish species of the Black Sea in Türkiye using multivariate statistical and spatial assessment. *Environ. Toxicol. Pharmacol.* **2023**, *97*, 104028. [CrossRef]
41. Varol, M.; Şen, B. Assessment of surface water quality using multivariate statistical techniques: A case study of Behrimaz Stream, Turkey. *Environ. Monit. Assess.* **2009**, *159*, 543–553. [CrossRef]
42. Otto, M. Multivariate Methods. In *Analytical Chemistry*; Kellner, R., Mermet, J., Otto, M., Widmer, H., Eds.; Wiley-VCH: Weinheim, Germany, 1998.
43. Ward, J.H., Jr. Hierarchical grouping to optimize an objective function. *J. Am. Stat. Assoc.* **1963**, *58*, 236–244. [CrossRef]
44. Shrestha, S.; Kazama, F. Assessment of surface water quality using multivariate statistical techniques: A case study of the Fuji river basin, Japan. *Environ. Model. Softw.* **2007**, *22*, 464–475. [CrossRef]
45. Islam, M.A.; Das, B.; Quraishi, S.B.; Khan, R.; Naher, K.; Hossain, S.M.; Karmaker, S.; Latif, S.A.; Hossen, M.B. Heavy metal contamination and ecological risk assessment in water and sediments of the Halda river, Bangladesh: A natural fish breeding ground. *Mar. Pollut. Bull.* **2020**, *160*, 111649. [CrossRef]
46. Genchi, G.; Lauria, G.; Catalano, A.; Carocci, A.; Sinicropi, M.S. The Double Face of Metals: The Intriguing Case of Chromium. *Appl. Sci.* **2021**, *11*, 638. [CrossRef]
47. Maurya, P.; Kumari, R. Toxic metals distribution, seasonal variations and environmental risk assessment in surficial sediment and mangrove plants (A. marina), Gulf of Kachchh (India). *J. Hazard. Mater.* **2021**, *413*, 125345. [CrossRef]
48. Mohiuddin, K.M.; Ogawa, Y.; Zakir, H.M.; Otomo, K.; Shikazono, N. Heavy metals contamination in water and sediments of an urban river in a developing country. *Int. J. Environ. Sci. Technol.* **2011**, *8*, 723–736. [CrossRef]
49. Martin, S.; Griswold, W. Human health effects of heavy metals. *Environ. Sci. Technol. Briefs Citiz.* **2009**, *15*, 1–6.
50. Islam, M.; Akther, S.M.; Hossain, F.; Parveen, Z. Spatial distribution and ecological risk assessment of potentially toxic metals in the Sundarbans mangrove soils of Bangladesh. *Sci. Rep.* **2022**, *12*, 10422. [CrossRef]
51. Adani, P.; Sawale, A.A.; Nandhagopal, G. Bioaccumulation of heavy metals in the food components from water and sediments in the coastal waters of Kalpakkam, Southeast coast of India. *Environ. Nanotechnol. Monit. Manag.* **2022**, *17*, 100627. [CrossRef]
52. Yang, C.; Yu, G.; Liu, Y.; Shan, B.; Wang, L.; Sun, D.; Huang, Y. Heavy Metal Distribution in Surface Sediments of the Coastal Pearl Bay, South China Sea. *Processes* **2022**, *10*, 822. [CrossRef]
53. Rahman, M.; Saima, J.; Rima, S.A.; Hossain, I.S.; Das, D.K.; Abu Bakar, M.; Siddique, M.A.M. Ecological risks of heavy metals on surficial sediment of Nijhum Dweep (Island), an important biodiversity area of Bangladesh. *Mar. Pollut. Bull.* **2022**, *179*, 113688. [CrossRef] [PubMed]
54. Rahman, M.S.; Ahmed, Z.; Seefat, S.M.; Alam, R.; Islam, A.R.M.T.; Choudhury, T.R.; Begum, B.A.; Idris, A.M. Assessment of heavy metal contamination in sediment at the newly established tannery industrial Estate in Bangladesh: A case study. *Environ. Chem. Ecotoxicol.* **2022**, *4*, 1–12. [CrossRef]
55. Rakib, R.J.; Hossain, M.B.; Jolly, Y.N.; Akther, S.; Islam, S. EDXRF Detection of Trace Elements in Salt Marsh Sediment of Bangladesh and Probabilistic Ecological Risk Assessment. *Soil Sediment Contam. Int. J.* **2022**, *31*, 220–239. [CrossRef]
56. Choudhury, T.R.; Acter, T.; Uddin, N.; Kamal, M.; Chowdhury, A.S.; Rahman, M.S. Heavy metals contamination of river water and sediments in the mangrove forest ecosystems in Bangladesh: A consequence of oil spill incident. *Environ. Nanotechnol. Monit. Manag.* **2021**, *16*, 100484. [CrossRef]
57. Hossain, M.S.; Ahmed, M.K.; Liyana, E.; Hossain, M.S.; Jolly, Y.N.; Kabir, M.J.; Akter, S.; Rahman, M.S. A case study on metal contamination in water and sediment near a coal thermal power plant on the eastern coast of Bangladesh. *Environments* **2021**, *8*, 108. [CrossRef]
58. Hossain, M.B.; Semme, S.A.; Ahmed, A.S.S.; Rahman, M.; Hossain, K.; Porag, G.S.; Parvin, A.; Shanta, T.B.; Senapathi, V.; Sekar, S. Contamination levels and ecological risk of heavy metals in sediments from the tidal river Halda, Bangladesh. *Arab. J. Geosci.* **2021**, *14*, 158. [CrossRef]
59. Hasan, A.B.; Reza, A.H.M.; Kabir, S.; Siddique, M.; Bakar, A.; Ahsan, M.; Akbor, M. Accumulation and distribution of heavy metals in soil and food crops around the ship breaking area in southern Bangladesh and associated health risk assessment. *SN Appl. Sci.* **2020**, *2*, 155. [CrossRef]
60. Rahman, M.S.; Hossain, M.B.; Babu, S.O.F.; Ahmed, A.S.; Jolly, Y.; Choudhury, T.; Begum, B.; Kabir, J.; Akter, S. Source of metal contamination in sediment, their ecological risk, and phytoremediation ability of the studied mangrove plants in ship breaking area, Bangladesh. *Mar. Pollut. Bull.* **2019**, *141*, 137–146. [CrossRef]
61. Kabir, M.Z.; Deeba, F.; Majumder, R.K.; Khalil, M.I.; Islam, M.S. Heavy mineral distribution and geochemical studies of coastal sediments at Sonadia island, Bangladesh. *Nucl. Sci. Appl.* **2018**, *27*, 2.
62. Islam, M.S.; Hossain, M.B.; Matin, A.; Sarker, M.S.I. Assessment of heavy metal pollution, distribution and source apportionment in the sediment from Feni River estuary, Bangladesh. *Chemosphere* **2018**, *202*, 25–32. [CrossRef]
63. Ranjan, P.; Ramanathan, A.; Kumar, A.; Singhal, R.; Datta, D.; Venkatesh, M. Trace metal distribution, assessment and enrichment in the surface sediments of Sundarban mangrove ecosystem in India and Bangladesh. *Mar. Pollut. Bull.* **2018**, *127*, 541–547. [CrossRef]
64. Rashid, T.; Hoque, S.; Akter, S. Pollution in the Bay of Bengal: Impact on Marine Ecosystem. *Open J. Mar. Sci.* **2015**, *5*, 55–63. [CrossRef]

65. Hainan, C.H.E.N.; Zhang, C.; Guoqiang, L.I.U.; Qibin, L.A.O. Evaluation on Sediment Pollution and Potential Ecological Risks in Guangxi Beibu Gulf. *Environ. Chem.* **2022**, *41*, 2872–2879.
66. Abidi, M.; Yahyaoui, A.; Ben Amor, R.; Chouba, L.; Gueddari, M. Evaluation of heavy metal pollution risk in surface sediment of the South Lagoon of Tunis by a sequential extraction procedure. *Sci. Mar.* **2022**, *86*, e028. [CrossRef]
67. Huang, F.; Chen, C. GIS-based approach and multivariate statistical analysis for identifying sources of heavy metals in marine sediments from the coast of Hong Kong. *Environ. Monit. Assess.* **2023**, *195*, 518. [CrossRef]
68. Lin, H.; Lan, W.; Feng, Q.; Zhu, X.; Li, T.; Zhang, R.; Song, H.; Zhu, Y.; Zhao, B. Pollution and ecological risk assessment, and source identification of heavy metals in sediment from the Beibu Gulf, South China Sea. *Mar. Pollut. Bull.* **2021**, *168*, 112403. [CrossRef]
69. Ota, Y.; Suzuki, A.; Yamaoka, K.; Nagao, M.; Tanaka, Y.; Irizuki, T.; Fujiwara, O.; Yoshioka, K.; Kawagata, S.; Kawano, S.; et al. Geochemical distribution of heavy metal elements and potential ecological risk assessment of Matsushima Bay sediments during 2012–2016. *Sci. Total Environ.* **2021**, *751*, 141825. [CrossRef]
70. Perumal, K.; Antony, J.; Muthuramalingam, S. Heavy metal pollutants and their spatial distribution in surface sediments from Thondi coast, Palk Bay, South India. *Environ. Sci. Eur.* **2021**, *33*, 63. [CrossRef]
71. Agah, H. Ecological risk assessment of heavy metals in sediment, fish, and human hair from Chabahar Bay, Makoran, Iran. *Mar. Pollut. Bull.* **2021**, *169*, 112345. [CrossRef] [PubMed]
72. Tham, T.T.; Lap, B.Q.; Mai, N.T.; Trung, N.T.; Thao, P.P.; Huong, N.T.L. Ecological Risk Assessment of Heavy Metals in Sediments of Duyen Hai Seaport Area in Tra Vinh Province, Vietnam. *Water Air Soil Pollut.* **2021**, *232*, 49. [CrossRef]
73. Zhai, B.; Zhang, X.; Wang, L.; Zhang, Z.; Zou, L.; Sun, Z.; Jiang, Y. Concentration distribution and assessment of heavy metals in surface sediments in the Zhoushan Islands coastal sea, East China Sea. *Mar. Pollut. Bull.* **2021**, *164*, 112096. [CrossRef] [PubMed]
74. Zhang, Q.; Ren, F.; Xiong, X.; Gao, H.; Wang, Y.; Sun, W.; Leng, P.; Li, Z.; Bai, Y. Spatial distribution and contamination assessment of heavy metal pollution of sediments in coastal reclamation areas: A case study in Shenzhen Bay, China. *Environ. Sci. Eur.* **2021**, *33*, 90. [CrossRef]
75. Wu, M.-L.; Cheng, H.; Zhao, H.; Sun, F.-L.; Wang, Y.-T.; Yin, J.-P.; Fei, J.; Sun, C.-C.; Wang, Y.-S. Distribution patterns and source identification for heavy metals in Mirs Bay of Hong Kong in China. *Ecotoxicology* **2020**, *29*, 762–770. [CrossRef]
76. Tan, I.; Aslan, E. Metal pollution status and ecological risk assessment in marine sediments of the inner Izmit Bay. *Reg. Stud. Mar. Sci.* **2020**, *33*, 100850. [CrossRef]
77. Zhu, A.; Liu, J.; Qiao, S.; Zhang, H. Distribution and assessment of heavy metals in surface sediments from the Bohai Sea of China. *Mar. Pollut. Bull.* **2020**, *153*, 110901. [CrossRef]
78. Yu, X.; Zhang, Z.; Feng, A.; Gu, D.; Zhang, R.; Xia, P.; Yan, W.; Zhou, X. Recent history of metal contamination in the Fangcheng Bay (Beibu Gulf, South China) utilizing spatially distributed sediment cores: Responding to local urbanization and industrialization. *Mar. Pollut. Bull.* **2020**, *158*, 111418. [CrossRef]
79. Zhai, B.; Liu, Z.; Wang, X.; Bai, F.; Wang, L.; Chen, Z.; Zhang, X. Assessment of heavy metal contamination in surface sediments in the western Taiwan Strait. *Mar. Pollut. Bull.* **2020**, *159*, 111492. [CrossRef]
80. Abbasi, A.; Mirekhtiary, F. Heavy metals and natural radioactivity concentration in sediments of the Mediterranean Sea coast. *Mar. Pollut. Bull.* **2020**, *154*, 111041. [CrossRef]
81. Ye, Z.; Chen, J.; Gao, L.; Liang, Z.; Li, S.; Li, R.; Jin, G.; Shimizu, Y.; Onodera, S.-I.; Saito, M.; et al. 210Pb dating to investigate the historical variations and identification of different sources of heavy metal pollution in sediments of the Pearl River Estuary, Southern China. *Mar. Pollut. Bull.* **2020**, *150*, 110670. [CrossRef]
82. Ogundele, L.T.; Ayeku, P.O. Source apportionment and associated potential ecological risk assessment of heavy metals in coastal marine sediments samples in Ondo, Southwest, Nigeria. *Stoch. Environ. Res. Risk Assess.* **2020**, *34*, 2013–2022. [CrossRef]
83. Suami, R.B.; Sivalingam, P.; Al Salah, D.M.; Grandjean, D.; Mulaji, C.K.; Mpiana, P.T.; Breider, F.; Otamonga, J.-P.; Poté, J. Heavy metals and persistent organic pollutants contamination in river, estuary, and marine sediments from Atlantic Coast of Democratic Republic of the Congo. *Environ. Sci. Pollut. Res.* **2020**, *27*, 20000–20013. [CrossRef]
84. Joksimović, D.; Perošević, A.; Castelli, A.; Pestorić, B.; Šuković, D.; Đurović, D. Assessment of heavy metal pollution in surface sediments of the Montenegrin coast: A 10-year review. *J. Soils Sediments* **2020**, *20*, 2598–2607. [CrossRef]
85. Nour, H.E.; El-Sorogy, A.S. Heavy metals contamination in seawater, sediments and seashells of the Gulf of Suez, Egypt. *Environ. Earth Sci.* **2020**, *79*, 274. [CrossRef]
86. Tian, K.; Wu, Q.; Liu, P.; Hu, W.; Huang, B.; Shi, B.; Zhou, Y.; Kwon, B.-O.; Choi, K.; Ryu, J.; et al. Ecological risk assessment of heavy metals in sediments and water from the coastal areas of the Bohai Sea and the Yellow Sea. *Environ. Int.* **2020**, *136*, 105512. [CrossRef]
87. Zhao, M.; Wang, E.; Xia, P.; Feng, A.; Chi, Y.; Sun, Y. Distribution and pollution assessment of heavy metals in the intertidal zone environments of typical sea areas in China. *Mar. Pollut. Bull.* **2019**, *138*, 397–406. [CrossRef]
88. Tanjung, R.H.R.; Hamuna, B.; Yonas, M.N. Assessing Heavy Metal Contamination in Marine Sediments Around the Coastal Waters of Mimika Regency, Papua Province, Indonesia. *J. Ecol. Eng.* **2019**, *20*, 35–42. [CrossRef]
89. Chang, C.-Y.; Chen, S.-Y.; Klipkhayai, P.; Chiemchaisri, C. Bioleaching of heavy metals from harbor sediment using sulfur-oxidizing microflora acclimated from native sediment and exogenous soil. *Environ. Sci. Pollut. Res.* **2019**, *26*, 6818–6828. [CrossRef]

90. Ben Amor, R.; Yahyaoui, A.; Abidi, M.; Chouba, L.; Gueddari, M. Bioavailability and Assessment of Metal Contamination in Surface Sediments of Rades-Hamam Lif Coast, around Meliane River (Gulf of Tunis, Tunisia, Mediterranean Sea). *J. Chem.* **2019**, *2019*, 4284987. [CrossRef]
91. Zhang, M.; He, P.; Qiao, G.; Huang, J.; Yuan, X.; Li, Q. Heavy metal contamination assessment of surface sediments of the Subei Shoal, China: Spatial distribution, source apportionment and ecological risk. *Chemosphere* **2019**, *223*, 211–222. [CrossRef] [PubMed]
92. Liu, B.; Wang, J.; Xu, M.; Zhao, L.; Wang, Z. Spatial distribution, source apportionment and ecological risk assessment of heavy metals in the sediments of Haizhou Bay national ocean park, China. *Mar. Pollut. Bull.* **2019**, *149*, 110651. [CrossRef]
93. Li, L.; Jiang, M.; Liu, Y.; Shen, X. Heavy metals inter-annual variability and distribution in the Yangtze River estuary sediment, China. *Mar. Pollut. Bull.* **2019**, *141*, 514–520. [CrossRef] [PubMed]
94. Xu, Y.; Jiang, T.; Yang, Q.; Zhao, J.; Qu, K.M. Distribution characteristics and pollution assessment of heavy metals in the surface sediments of the central region of the Bohai Sea during the summer. *Prog. Fish. Sci.* **2019**, *40*, 52–61.
95. Gu, Y.-G.; Gao, Y.-P. An unconstrained ordination- and GIS-based approach for identifying anthropogenic sources of heavy metal pollution in marine sediments. *Mar. Pollut. Bull.* **2019**, *146*, 100–105. [CrossRef]
96. Lao, Q.; Su, Q.; Liu, G.; Shen, Y.; Chen, F.; Lei, X.; Qing, S.; Wei, C.; Zhang, C.; Gao, J. Spatial distribution of and historical changes in heavy metals in the surface seawater and sediments of the Beibu Gulf, China. *Mar. Pollut. Bull.* **2019**, *146*, 427–434. [CrossRef]
97. Gholizadeh, M.; Patimar, R. Ecological risk assessment of heavy metals in surface sediments from the Gorgan Bay, Caspian Sea. *Mar. Pollut. Bull.* **2018**, *137*, 662–667. [CrossRef]
98. Ding, X.; Ye, S.; Yuan, H.; Krauss, K.W. Spatial distribution and ecological risk assessment of heavy metals in coastal surface sediments in the Hebei Province offshore area, Bohai Sea, China. *Mar. Pollut. Bull.* **2018**, *131*, 655–661. [CrossRef]
99. Liang, X.; Song, J.; Duan, L.; Yuan, H.; Li, X.; Li, N.; Qu, B.; Wang, Q.; Xing, J. Source identification and risk assessment based on fractionation of heavy metals in surface sediments of Jiaozhou Bay. *China Mar. Pollut. Bull.* **2018**, *128*, 548–556. [CrossRef]
100. Gu, Y.-G. Heavy metal fractionation and ecological risk implications in the intertidal surface sediments of Zhelin Bay, South China. *Mar. Pollut. Bull.* **2018**, *129*, 905–912. [CrossRef]
101. Chen, F.; Lin, J.; Qian, B.; Wu, Z.; Huang, P.; Chen, K.; Li, T.; Cai, M. Geochemical Assessment and Spatial Analysis of Heavy Metals in the Surface Sediments in the Eastern Beibu Gulf: A Reflection on the Industrial Development of the South China Coast. *Int. J. Environ. Res. Public Health* **2018**, *15*, 496. [CrossRef]
102. Kahal, A.Y.; El-Sorogy, A.S.; Alfaifi, H.J.; Almadani, S.; Ghrefat, H.A. Spatial distribution and ecological risk assessment of the coastal surface sediments from the Red Sea, northwest Saudi Arabia. *Mar. Pollut. Bull.* **2018**, *137*, 198–208. [CrossRef]
103. El-Sorogy, A.; Al-Kahtany, K.; Youssef, M.; Al-Kahtany, F.; Al-Malky, M. Distribution and metal contamination in the coastal sediments of Dammam Al-Jubail area, Arabian Gulf, Saudi Arabia. *Mar. Pollut. Bull.* **2018**, *128*, 8–16. [CrossRef]
104. Hariri, M.S.B.; Abu-Zied, R.H. Factors influencing heavy metal concentrations in the bottom sediments of the Al-Kharrar Lagoon and Salman Bay, eastern Red Sea coast, Saudi Arabia. *Arab. J. Geosci.* **2018**, *11*, 495. [CrossRef]
105. Tang, H.; Ke, Z.; Yan, M.; Wang, W.; Nie, H.; Li, B.; Zhang, J.; Xu, X.; Wang, J. Concentrations, Distribution, and Ecological Risk Assessment of Heavy Metals in Daya Bay, China. *Water* **2018**, *10*, 780. [CrossRef]
106. Rao, Q.; Sun, Z.; Tian, L.; Li, J.; Sun, W.; Sun, W. Assessment of arsenic and heavy metal pollution and ecological risk in inshore sediments of the Yellow River estuary, China. *Stoch. Environ. Res. Risk Assess.* **2018**, *32*, 2889–2902. [CrossRef]
107. Zhao, Y.; Xu, M.; Liu, Q.; Wang, Z.; Zhao, L.; Chen, Y. Study of heavy metal pollution, ecological risk and source apportionment in the surface water and sediments of the Jiangsu coastal region, China: A case study of the Sheyang Estuary. *Mar. Pollut. Bull.* **2018**, *137*, 601–609. [CrossRef]
108. Zhao, B.; Wang, X.; Jin, H.; Feng, H.; Shen, G.; Cao, Y.; Yu, C.; Lu, Z.; Zhang, Q. Spatiotemporal variation and potential risks of seven heavy metals in seawater, sediment, and seafood in Xiangshan Bay, China (2011–2016). *Chemosphere* **2018**, *212*, 1163–1171. [CrossRef]
109. Bibak, M.; Sattari, M.; Agharokh, A.; Tahmasebi, S.; Namin, J.I. Assessing some heavy metals pollutions in sediments of the northern Persian Gulf (Bushehr province). *Environ. Health Eng. Manag.* **2018**, *5*, 175–179. [CrossRef]
110. El-Taher, A.; Zakaly, H.M.; Elsaman, R. Environmental implications and spatial distribution of natural radionuclides and heavy metals in sediments from four harbours in the Egyptian Red Sea coast. *Appl. Radiat. Isot.* **2018**, *131*, 13–22. [CrossRef] [PubMed]
111. Birch, G.; Taylor, S.; Matthai, C. Small-scale spatial and temporal variance in the concentration of heavy metals in aquatic sediments: A review and some new concepts. *Environ. Pollut.* **2001**, *113*, 357–372. [CrossRef] [PubMed]
112. Yunus, K.; Zuraidah, M.; John, A. A review on the accumulation of heavy metals in coastal sediment of Peninsular Malaysia. *Ecofeminism Clim. Chang.* **2020**, *1*, 21–35. [CrossRef]
113. Singh, R.; Gautam, N.; Mishra, A.; Gupta, R. Heavy metals and living systems: An overview. *Indian J. Pharmacol.* **2011**, *43*, 246–253. [CrossRef]
114. Al-Fartusie, F.S.; Mohssan, S.N. Essential trace elements and their vital roles in the human body. *Indian J. Adv. Chem. Sci.* **2017**, *5*, 127–136.
115. USEPA. *Screening Level Ecological Risk Assessment Protocol for Hazardous Waste Combustion Facilities*; Appendix E Toxicity Ref Values; USEPA: Washington, DC, USA, 1999; Volume 3.
116. Turekian, K.K.; Wedepohl, K.H. Distribution of the elements in some major units of the earth's crust. *Geol. Soc. Am. Bull.* **1961**, *72*, 175–192. [CrossRef]

117. Barg, U.C. *Guidelines for the Promotion of Environmental Management of Coastal Aquaculture Development*; Food & Agriculture Organization: Rome, Italy, 1992; Volume 328.
118. Fan, Y.; Chen, X.; Chen, Z.; Zhou, X.; Lu, X.; Liu, J. Pollution characteristics and source analysis of heavy metals in surface sediments of Luoyuan Bay, Fujian. *Environ. Res.* **2022**, *203*, 111911. [CrossRef]
119. Kanwar, V.S.; Sharma, A.; Srivastav, A.L.; Rani, L. Phytoremediation of toxic metals present in soil and water environment: A critical review. *Environ. Sci. Pollut. Res.* **2020**, *27*, 44835–44860. [CrossRef]
120. Cempel, M.; Nikel, G.J.P.J.S. Nickel: A review of its sources and environmental toxicology. *Pol. J. Environ. Stud.* **2006**, *15*, 375–382.
121. Neves, A.; Godina, R.; Azevedo, S.G.; Matias, J.C.O. A comprehensive review of industrial symbiosis. *J. Clean. Prod.* **2020**, *247*, 119113. [CrossRef]
122. Abioye, O.P.; Loto, C.A.; Fayomi, O.S.I. Evaluation of Anti-biofouling Progresses in Marine Application. *J. Bio- Tribo-Corros.* **2019**, *5*, 22. [CrossRef]
123. Kambe, T.; Tsujimura, N.; Hashimoto, A.; Itsumura, N.; Nakagawa, M.; Miyazaki, S.; Kizu, K.; Goto, T.; Komatsu, Y.; Matsunaga, A.; et al. The Physiological, Biochemical, and Molecular Roles of Zinc Transporters in Zinc Homeostasis and Metabolism. *Physiol. Rev.* **2015**, *95*, 749–784. [CrossRef]
124. Giannakoula, A.; Therios, I.; Chatzissavvidis, C. Effect of lead and copper on photosynthetic apparatus in citrus (Citrus aurantium L.) plants. The role of antioxidants in oxidative damage as a response to heavy metal stress. *Plants* **2021**, *10*, 155. [CrossRef]
125. Fasae, K.D.; Abolaji, A.O. Interactions and toxicity of non-essential heavy metals (Cd, Pb and Hg): Lessons from Drosophila melanogaster. *Curr. Opin. Insect Sci.* **2022**, *51*, 100900. [CrossRef]
126. Whiteside, M.; Herndon, J.M. Role of aerosolized coal fly ash in the global plankton imbalance: Case of Florida's toxic algae crisis. *Asian J. Biol.* **2019**, *8*, 1–24. [CrossRef]
127. Gopal, V.; Krishnamurthy, R.R.; Vignesh, R.; SabariNathan, C.; Anshu, R.; Kalaivanan, R.; Mohana, P.; Magesh, N.S. Heavy metal pollution in the surface sediments off the Vedaranyam coast, Southern India. *Res. Sq.* 2022, *preprint*.
128. Jonathan, M.P.; Ram-Mohan, V.; Srinivasalu, S. Geochemical variations of major and trace elements in recent sediments, off the Gulf of Mannar, the southeast coast of India. *Environ. Geol.* **2004**, *45*, 466–480. [CrossRef]
129. Liaghati, T.; Preda, M.; Cox, M. Heavy metal distribution and controlling factors within coastal plain sediments, Bells Creek catchment, southeast Queensland, Australia. *Environ. Int.* **2004**, *29*, 935–948. [CrossRef]
130. Boughriet, A.; Proix, N.; Billon, G.; Recourt, P.; Ouddane, B. Environmental Impacts of Heavy Metal Discharges from a Smelter in Deûle-canal Sediments (Northern France): Concentration Levels and Chemical Fractionation. *Water Air Soil Pollut.* **2007**, *180*, 83–95. [CrossRef]
131. Ke, X.; Gui, S.; Huang, H.; Zhang, H.; Wang, C.; Guo, W. Ecological risk assessment and source identification for heavy metals in surface sediment from the Liaohe River protected area, China. *Chemosphere* **2017**, *175*, 473–481. [CrossRef]
132. Islam, M.S.; Ahmed, M.K.; Habibullah-Al-Mamun, M.; Hoque, M.F. Preliminary assessment of heavy metal contamination in surface sediments from a river in Bangladesh. *Environ. Earth Sci.* **2015**, *73*, 1837–1848. [CrossRef]
133. Hassan, M.; Tanvir Rahman, M.A.T.M.; Saha, B.; Kamal, A.K.I. Status of Heavy Metals in Water and Sediment of the Meghna River, Bangladesh. *Am. J. Environ. Sci.* **2015**, *11*, 427–439. [CrossRef]
134. Suresh, G.; Sutharsan, P.; Ramasamy, V.; Venkatachalapathy, R. Assessment of spatial distribution and potential ecological risk of the heavy metals in relation to granulometric contents of Veeranam lake sediments, India. *Ecotoxicol. Environ. Saf.* **2012**, *84*, 117–124. [CrossRef] [PubMed]
135. Tomlinson, D.L.; Wilson, J.G.; Harris, C.R.; Jeffrey, D.W. Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgoländer Meeresunters.* **1980**, *33*, 566–575. [CrossRef]
136. Karydas, C.G.; Tzoraki, O.; Panagos, P. A New Spatiotemporal Risk Index for Heavy Metals: Application in Cyprus. *Water* **2015**, *7*, 4323–4342. [CrossRef]
137. El-Alfy, M.A.; Darwish, D.; El-Amier, Y.A. Land use Land cover of the Burullus Lake shoreline (Egypt) and health risk assessment of metal-contaminated sediments. *Hum. Ecol. Risk Assess. Int. J.* **2021**, *27*, 898–920. [CrossRef]
138. Chonokhuu, S.; Batbold, C.; Chuluunpurev, B.; Battsengel, E.; Dorjsuren, B.; Byambaa, B. Contamination and Health Risk Assessment of Heavy Metals in the Soil of Major Cities in Mongolia. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2552. [CrossRef]
139. Hu, B.; Jia, X.; Hu, J.; Xu, D.; Xia, F.; Li, Y. Assessment of Heavy Metal Pollution and Health Risks in the Soil-Plant-Human System in the Yangtze River Delta, China. *Int. J. Environ. Res. Public Health* **2017**, *14*, 1042. [CrossRef]
140. Ahmed, A.S.S.; Hossain, M.B.; Semme, S.A.; Babu, S.M.O.F.; Hossain, K.; Moniruzzaman, M. Accumulation of trace elements in selected fish and shellfish species from the largest natural carp fish breeding basin in Asia: A probabilistic human health risk implication. *Environ. Sci. Pollut. Res.* **2020**, *27*, 37852–37865. [CrossRef]
141. Shikazono, N.; Tatewaki, K.; Mohiuddin, K.M.; Nakano, T.; Zakir, H.M. Sources, spatial variation, and speciation of heavy metals in sediments of the Tamagawa River in Central Japan. *Environ. Geochem. Health* **2012**, *34*, 13–26. [CrossRef]
142. Yang, Z.; Wang, Y.; Shen, Z.; Niu, J.; Tang, Z. Distribution and speciation of heavy metals in sediments from the mainstream, tributaries, and lakes of the Yangtze River catchment of Wuhan, China. *J. Hazard. Mater.* **2009**, *166*, 1186–1194. [CrossRef]
143. Sundaray, S.K.; Nayak, B.B.; Lin, S.; Bhatta, D. Geochemical speciation and risk assessment of heavy metals in the river estuarine sediments—A case study: Mahanadi basin, India. *J. Hazard. Mater.* **2011**, *186*, 1837–1846. [CrossRef]
144. Chung, C.-Y.; Chen, J.-J.; Lee, C.-G.; Chiu, C.-Y.; Lai, W.-L.; Liao, S.-W. Integrated estuary management for diffused sediment pollution in Dapeng Bay and neighboring rivers (Taiwan). *Environ. Monit. Assess.* **2011**, *173*, 499–517. [CrossRef]

145. Bera, A.; Meraj, G.; Kanga, S.; Farooq, M.; Singh, S.K.; Sahu, N.; Kumar, P. Vulnerability and Risk Assessment to Climate Change in Sagar Island, India. *Water* **2022**, *14*, 823. [CrossRef]
146. Singh, S.; Singh, S.K.; Prajapat, D.K.; Pandey, V.; Kanga, S.; Kumar, P.; Meraj, G. Assessing the Impact of the 2004 Indian Ocean Tsunami on South Andaman's Coastal Shoreline: A Geospatial Analysis of Erosion and Accretion Patterns. *J. Mar. Sci. Eng.* **2023**, *11*, 1134. [CrossRef]
147. Meraj, G.; Kanga, S.; Kranjčić, N.; Đurin, B.; Singh, S.K. Role of Natural Capital Economics for Sustainable Management of Earth Resources. *Earth* **2021**, *2*, 622–634. [CrossRef]
148. Debnath, J.; Meraj, G.; Das Pan, N.; Chand, K.; Debbarma, S.; Sahariah, D.; Gualtieri, C.; Kanga, S.; Singh, S.K.; Farooq, M.; et al. Integrated remote sensing and field-based approach to assess the temporal evolution and future projection of meanders: A case study on River Manu in North-Eastern India. *PLoS ONE* **2022**, *17*, e0271190. [CrossRef]
149. Bera, A.; Taloor, A.K.; Meraj, G.; Kanga, S.; Singh, S.K.; Đurin, B.; Anand, S. Climate vulnerability and economic determinants: Linkages and risk reduction in Sagar Island, India; A geospatial approach. *Quat. Sci. Adv.* **2021**, *4*, 100038. [CrossRef]
150. Meraj, G.; Singh, S.K.; Kanga, S.; Islam, N. Modeling on comparison of ecosystem services concepts, tools, methods and their ecological-economic implications: A review. *Model. Earth Syst. Environ.* **2021**, *8*, 15–34. [CrossRef]
151. Naser, H.A. Assessment and management of heavy metal pollution in the marine environment of the Arabian Gulf: A review. *Mar. Pollut. Bull.* **2013**, *72*, 6–13. [CrossRef]
152. Lakshmi, E.; Priya, M.; Achari, V.S. An overview on the treatment of ballast water in ships. *Ocean Coast. Manag.* **2021**, *199*, 105296. [CrossRef]
153. Clausen, A.; Vu, H.H.; Pedrono, M. An evaluation of the environmental impact assessment system in Vietnam: The gap between theory and practice. *Environ. Impact Assess. Rev.* **2011**, *31*, 136–143. [CrossRef]
154. Chowdhury, P.A.; Ali, M.M.; Shahjahan, A.T. Impacts of Ship Breaking Industries on Environment and Socio-Economic Condition of Bangladesh-A Case Study of Sitakunda Shitolpur Ship Breaking Yard, Chittagong. Doctoral Dissertation, Chittagong University of Engineering & Technology, Chattogram, Bangladesh, 2015.