

Research Article

Assessing heavy metal contamination and nutrient status in coastal soils of Bangladesh

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ABSTRACT

Heavy metals (HMs) and soil nutrient imbalances pose a significant threat to agricultural productivity in the coastal zones of Bangladesh. This study assessed the spatial variability of essential plant nutrients and heavy metals in soils and explored their interactions with soil acidity and salinity. Thirty-five topsoil samples (0–15 cm) were collected across Kalapara upazila of Patuakhali district, a salinity-affected coastal ecosystem of the Bay of Bengal. The soils were strongly acidic to moderately alkaline (pH 4.3–8.1) and highly saline (mean ECe 9.60 dS m⁻¹). Potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg) concentrations of soils were high to very high, whereas available phosphorus (P) was critically low in more than 90% of samples. Micronutrient analysis revealed very high levels of iron (Fe) and manganese (Mn), and medium levels of zinc (Zn) and medium to high levels of boron (B). Heavy metals such as cadmium (Cd), lead (Pb), and chromium (Cr) were well below the WHO's threshold limits; however, nickel (Ni) exceeded the permissible level in ~50% of samples, indicating an emerging Ni contamination. Moreover, we observed a strong positive association between HMs (Ni, Cr, Cd) and soil pH, Ca, Mg, B, Zn, Fe, and Mn, whereas EC showed a negative association with Cd. Overall, the soils of Kalapara are constrained by strong acidity, high salinity, and severe P deficiency, while Ni shows a potential contamination risk in coastal Bangladesh.

Introduction

Heavy metals (HMs) are inorganic pollutants that are prevalent across the globe (Elsagh et al., 2021). Their accretion in soils and coastal ecosystems has emerged as a significant global environmental issue. Soil contamination is common in agricultural fields especially due to repeated exposure to industrial wastewater, treatment with low quality effluent and use of large quantities of chemical fertilizers and pesticides (Rahman et al., 2012). Such soil contamination creates major environmental problems especially in developing countries (Fattahi et al., 2021).

Bangladesh, as a developing country, has a vulnerable shoreline to the risk of HM contamination from continued exposure to the Bay of Bengal, which is continuously polluted by industrial waste and used as sssssa main source of irrigation water for crops (Jannat et al., 2023). Agricultural output in the coastal areas is progressively exposed to both human activities and environmental variations (Sume et al., 2023; Haque et al., 2025a). The coastal belt, accounting for about 30% of the country's arable land, plays a dynamic role in ensuring national food sssecurity.

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However, this area falls at risk of various types of land degradation, particularly salinity intrusion (Khanam et al., 2020; Sultana et al., 2021; Bhuyan et al., 2024), nutrient depletion (Haque et al., 2023a, 2023b; 2025b), and heavy metal contamination (Jannat et al., 2023), and such upsurge in agricultural practices, industrial effluents, and intensive use of agrochemicals have led to this trend. Moreover, excessive or inadequate levels of essential soil nutrients could limit crop yields and deteriorate soil fertility, further negotiating sustainable agriculture in this previously susceptible ecosystem (Haque and Hoque, 2023; Haque et al., 2024).

Plants can absorb HMs through different mechanisms, including (i) phytostabilization, where the plant tolerates the presence of toxic elements in the soil, thereby preventing their migration; (ii) phytoextraction, which is a remedial strategy where plants bring up perilous elements from contaminated soil, (iii) rhizofiltration, where the roots adsorb HMs, and limit their migration and uptake. These HMs not only damage plant systems but also pose thoughtful health risks to humans (Tangahu et al., 2011).

Despite the life-threatening position of upholding healthy soils in coastal zones, there is limited data on the extent of HM contamination and the current status of essential soil nutrients in the agricultural lands of coastal Bangladesh. Numerous published manuscripts (e.g., Ahmed et al., 2015) have explored HM toxicity in aquaculture within this region and examined the impacts of HM contamination on soil essential nutrients and its successive effect on crop production in the southwestern coastal Bangladesh. Due to differences in crop cultivation practices, land use, topography, and climatic conditions between the south-central and south-western coast regions, there might have variation in HM concentrations along the south-central coast (present studied area). However, a complete assessment of the climate-vulnerable south-central coastal region remains immediately needed to guide land management practices, confirm food safety, and support evidence-based policy development.

The objective of this research was to assess the levels of HM contamination and examine their interactions with soil salinity and the accessibility of main macro- and micronutrients. Outcomes from this study would help identify possible environmental hazards and use strategies in the coastal area to ameliorate soil quality and mitigate HM contamination.

Materials and Methods

Site description

The soil samples were collected during 01-10 April 2024 in Kalapara upazila of Patukhali district, Bangladesh. Kalapara upazila is a south-central upazila in the country, located at the mouth of the Bay of Bengal. We selected this upazila primarily because of its vulnerability to various climate change factors, and we assumed that HM concentrations are often higher in coastal sediments and water than in inland areas. The upazila has 491.89 square kilometers of area, having primarily coastal and estuarine lands, characterized by a maze of islands, rivers, and inlets along the Bay of Bengal, with significant agricultural, residential, and water bodies. The land is low-lying and vulnerable to natural disasters, including sea level rise, coastal erosion, salinity intrusion, cyclone and floods, making it a challenging but resource-rich environment with unique land formations like tidal flats and sandy shores. Tidal water inundated the fields twice in a day during monsoon. The average elevation of the upazila is 2 m above sea level.

Soil collection and preparation

Total 35 soil samples at a depth of 15 cm were collected using a stratified random sampling technique to ensure exhaustive spatial coverage of the upazila. The GPS reading of the sampling points, with village names are given in Table 1. Chemical analysis of soil samples was done at the laboratory of the Department of Soil Science, Patuakhali Science and Technology University (PSTU), and Central Laboratory of Soil Resource Development Institute (SRDI), Dhaka, Bangladesh.

Table 1. Description of 35 sampling points of Kalapara upazila of Patuakhali district, Bangladesh.

Sample no.	GPS location	Village	Sample no.	GPS location	Village
1	N 90.1969, E 22.0822	Chakamoya	19	N 90.2597, E 21.9152	Chandupara
2	N 90.3194, E 22.0844	Chalitabunia	20	N 90.2513, E 21.9022	Chandupara
3	N 90.3661, E 22.0894	Patua	21	N 90.2365, E 21.9030	Lemupara
4	N 90.3166, E 22.0500	Pachjoina	22	N 90.2177, E 21.9052	Sonapara
5	N 90.2758, E 22.0173	Londa	23	N 90.1941, E 21.9152	Tegachia
6	N 90.2616, E 22.0244	Tiakhali	24	N 90.1572, E 21.9225	Umedpur
7	N 90.2175, E 22.9993	Gamurbunia	25	N 90.1386, E 21.9001	Hajipur
8	N 90.1969, E 22.0822	Nishanbaria	26	N 90.1599, E 21.8800	Isobpur
9	N 90.2329, E 22.0064	Rojopara	27	N 90.1680, E 21.8900	Dablugonj
10	N 90.2888, E 22.0007	Modhupara	28	N 90.2339, E 21.8581	Dhulasar
11	N 90.2950, E 21.9591	Banatipara	29	N 90.2383, E 21.8444	Dhulasar
12	N 90.2524, E 21.9848	Badurtoli	30	N 90.1950, E 21.8530	Manosatoli
13	N 90.2247, E 21.9800	Nilgonj	31	N 90.1735, E 21.8599	Keranipara
14	N 90.1944, E 21.9722	Nobipur	32	N 90.1418, E 21.8544	Latachapali
15	N 90.1501, E 21.9543	Sonatola	33	N 90.1205, E 21.8622	Shibbaria
16	N 90.1720, E 21.9416	Sonatola	34	N 90.1160, E 21.8551	Latachapali
17	N 90.2441, E 21.9422	Modhukhali	35	N 90.1453, E 21.8226	Musullibad
18	N 90.2478, E 21.9320	Sotobaliatoli			

Methods for soil analysis

Soil pH was determined by Glass Electrode pH meter method with soil water ratio 1:2.5, electrical conductivity (EC) of saturation paste extract by Petersen, organic matter (OM) by Walkley-Black method, available phosphorus (P) by Olsen method, and Bray and Kurtz Method, exchangeable potassium (K), sodium (Na), calcium (Ca) & magnesium (Mg) by ammonium acetate extraction method, available zinc (Zn), iron (Fe) & manganese (Mn) by DTPA extraction extraction method. Heavy metals viz. Cd, Pb, Ni and Cr were determined by nitric acid digestion method following standard procedure (Page et al. 1982).

Data analysis

The values for minimum, maximum and standard deviations of all tested parameters for 35 soil samples were determined using Microsoft Excel software. The soil test values were divided into several classes to interpret the values following guideline outlined in FRG (2024). The number of frequencies in a specific interpretation class was determined through direct counting. Regarding heavy metals the contamination indices were calculated following a standard procedure. The contamination factor (CF) is a commonly used index to evaluate the level of heavy metal contamination in soils or sediment which was calculated as follows (Hakanson, 1980).

$$\text{Contamination factor} = \frac{C_{\text{metal}}}{C_{\text{background}}}$$

Where,

C_{metal} = measured concentration of the heavy metal in the soil (mg kg^{-1})

$C_{\text{background}}$ = background (or reference) concentration of the same metal (mg kg^{-1})

The degree of contamination (DC) is an integrated index proposed by Hakanson (1980) to assess the overall contamination status of soil considering all heavy metals together. It sums up the contamination factors of individual metals to provide a single measure of total pollution load.

$$DC = \sum_{i=1}^n CF_i$$

DC = Degree of contamination

CF_i = Contamination factor for each metal i

n = Number of analyzed metals

The pollution load index (PLI) provides a comprehensive assessment of the overall level of heavy metal contamination in a soil or sediment sample (Tomlinson et al., 1980).

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n)^{1/n}$$

Results and Discussion

Variations in soil pH, electrical conductivity, organic matter and P content

Soil pH ranged from 4.3 to 8.1, with a mean value of 5.54 (Table 2). About 60% of the soil samples were strongly acidic (pH 4.6–5.5), while 11.4% samples were very strongly acidic (pH <4.5). Among 35 samples 77.1% were acidic in nature (pH <6.5) and only 14.3% were alkaline (pH > 7.4), indicating a presence of higher extent of acidic soil in the region (Table 2). Soil pH is a very important character in controlling soil macro- and micronutrients and metal for plant uptake (Naz et al., 2022). It alters the chemical nature and solubility of these materials which governs whether the materials will be assimilated into a plant or remain bound for ever within the soil. In the study the soil pH was negatively correlated and highly significant for micronutrients like Zn ($r = -0.59^{***}$) and Fe ($r = -0.78^{***}$) (Table 3). Extremely high level of Fe might be the possible reason

for strongly acidic nature of most of the soils tested. The elevated sulfur level also had the possible reason for strong acidity in the study area (Hoque et al., 2024), although this element was not determined in the present study. This outcome is in line with established understanding that increased soil alkalinity reduces the solubility of these elements via precipitation and adsorption (Li et al., 2014). Similarly, pH was strongly associated with K ($r = 0.52^{**}$), Ca ($r = 0.53^{***}$) and Mg ($r = 0.38^*$), probably due to their utmost stability under neutral to slightly alkaline conditions. Our findings align with those of Ferrarezi et al. (2022), who stated that pH levels about 6.0–6.5 improve the availability of macronutrients like Ca and Mg.

Soil electrical conductivity (EC) varied from 1.14 to 30.2 dS m^{-1} (mean of 9.60 dS m^{-1}) (Table 2). The majority of the samples (37.1%) fell into the moderate salinity category (EC 8.1–12.0 dS m^{-1}), followed by slightly saline (22.9% in EC range 4.1–8.0 dS m^{-1}) (Table 2). Considering tolerance of crops only 20% sample was found safe for crop cultivation (EC <4.0 dS m^{-1}), 22.9% soils could be brought under crop cultivation with proper management practices along with using salt tolerant varieties, unfortunately the greater portion (57.1%) was unsuitable for crop cultivation due to high salinity (EC >8.1 dS m^{-1}). High EC induces osmotic stress, which decreases nutrient uptake by the plant and indirectly changes nutrient dynamics. Soil EC values in this study are classified as moderate and were not related to soil macronutrients. In contrast, micronutrients, particularly Fe, showed a positive association with EC ($r = 0.51^{**}$) (Table 3). This may be because soil EC is often related to the concentration of soluble salts. While macronutrients such as P and K are essential for plant growth, their concentrations do not necessarily translate linearly into higher EC values. Moreover, as EC increases—within certain limits—the availability of Fe and potentially other micronutrients (e.g. Na) also tends to rise. This could be because some micronutrients, like Fe, are more soluble in soils with higher salt concentrations. The EC is directly associated with crop performance in salt-affected soils; an increase in EC drastically reduces crop production (Kumar et al., 2018; Haque et al., 2025c).

Table 2. Interpretation of soil test values into different classes of pH, electrical conductivity and organic matter content of soil.

Soil test value interpretation classes*	Frequency of samples (no.)	% of samples	Values
Soil acidity class (pH)			
Very strongly acid (<4.5)	4	11.4	Range: 4.3-8.1
Strongly acid (4.6-5.5)	21	60.0	Mean: 5.54
Slightly acid (5.6-6.5)	2	5.7	St. Dev.: 1.22
Neutral (6.6-7.3)	3	8.6	
Slightly alkaline (7.4-8.4)	5	14.3	
Strongly alkaline (8.5-9.0)	-		
Very strongly alkaline (>9.0)	-		
Soil salinity class based on electrical conductivity			
Non saline (0-2.0 dS m ⁻¹)	3	8.6	Range: 1.14-30.2
Very slightly saline (2.1-4.0 dS m ⁻¹)	4	11.4	Mean: 9.60
Slightly saline (4.1-8.0 dS m ⁻¹)	8	22.9	St. Dev.: 6.67
Moderately saline (8.1-12.0 dS m ⁻¹)	13	37.1	
Highly saline (12.1-16.0 dS m ⁻¹)	2	5.7	
Extremely saline (>16.0 dS m ⁻¹)	5	14.3	
Organic matter content class			
Very high (>5.5 %)	-		Range: 0.88-2.76
High (3.5-5.5 %)	-		Mean: 1.75
Medium (1.8-3.4 %)	17	48.6	St. Dev.: 0.44
Low (1.0-1.7 %)	15	42.9	
Very low (<1.0 %)	3	8.6	
Olsen P			
Very low (<7.5 mg kg ⁻¹)	33	94.3	Range: 0.78-14.98
Low (7.6-15.0 mg kg ⁻¹)	2	5.7	Mean: 3.28
Medium (15.1-22.5 mg kg ⁻¹)	-		St. Dev.: 2.96
Optimum (22.6-30.0 mg kg ⁻¹)	-		Critical limit 10
High (30.1-37.5 mg kg ⁻¹)	-		
Very high (>37.5 mg kg ⁻¹)	-		

The organic matter (OM) content ranged from 0.88% to 2.76% (mean 1.75%) (Table 2). Based on the soil test value interpretation class 48.6% sample had medium level of OM (1.8–3.4% OM), followed by 42.9% low OM, and only 8.6% very low OM content. OM plays a crucial role in nutrient holding as well as binding of HMs. In this study, the OM content was found to range from low to moderate levels. Such values indicate limited soil OM, signifying poor overall soil fertility in the coastal area. The condition is mainly attributed to the region's low height and regular flooding with saline seawater, which limits the accumulation of organic residues and enhances leaching and decomposition processes (Ashrafuzzaman et al., 2022). In addition, we showed that the OM-mediated increase in the availability of micronutrients (e.g., Fe and Zn) is likely due to enhanced nutrient retention by chelation and improved cation exchange capacity. Also, OM raises the B content in the soil. According to Singh et al. (2024), OM significantly enhances the availability of trace elements such as Fe ($r = 0.77^{***}$), Zn ($r = 0.58^{***}$), and K ($r = 0.48^{**}$) while its decomposition is the key process for releasing the active form of micronutrients that plants can uptake. In comparison, soil Ca decreased with increasing OM ($r = -0.37^*$). This decrease is likely due to the acidic conditions of the soil (low pH), which also favors the leaching of basic cations, such as Ca^{2+} . OM also did not show a significant correlation with some heavy metals. The main contributing factor is OM's ability to form complexes with heavy metals through chelation and adsorption, reducing mobility and bioavailability to plants (Enya et al., 2020). This study also noted that low pH of the soil in the study area was associated with low SOC and EC as well. The main reason for this is that most of the soil in the study area has acidic soil. We have similar results as Hassani et al. (2024) and Siddique et al. (2025), who stated that, an acid pH represents the decomposition of OC and can affect the abundance of dissolved salts in the soil.

Olsen P concentrations varied between 0.78 and 14.98 mg kg^{-1} , with mean 3.28 mg kg^{-1} , indicating a general deficiency of P in the soil (Table 2). The majority (94.3%) of the soil samples had a very low Olsen P level ($<7.5 \text{ mg kg}^{-1}$), whereas rest of the 5.7% samples had low Olsen P level (Table 2). Similarly, the Bray P varied from 0.16 to 14.04 mg kg^{-1} with mean of 4.75 mg kg^{-1} . Although the mean Bray P was higher than Olsen P, no

distinct pattern was observed among Olsen and Bray P (Table 4).

Heavy metal (Cd, Pb, Ni and Cr) concentration in the coastal soils

The concentration of Cd ranged from 0 to 0.08 mg kg^{-1} , with a mean of 0.02 mg kg^{-1} (Table 4). According to WHO guidelines, the Cd contamination factor of all the samples had far lower than the threshold limit of 0.8 mg kg^{-1} , indicating very low contamination of the soils under study (Fig. 1a). The concentrations of Pb ranged from 12.34 to 20.85 mg kg^{-1} with mean of 16.26 mg kg^{-1} , while WHO safe limit was 85 mg kg^{-1} . Therefore, considering Pb contamination for all the soil samples also had below the safe limit; however, based on the contamination factor the Pb contamination was higher than Cd (Fig. 1b). The concentrations of Ni ranged from 26.47 to 38.81 mg kg^{-1} with mean of 34.07 mg kg^{-1} , respectively. The mean Ni concentration (34.07 mg kg^{-1}) was close to the threshold limit of 35 mg kg^{-1} . Alarming, about 50% samples had Ni concentration higher than the threshold limit (Fig. 1c), indicating possible contamination of Ni in the south coastal region of Bangladesh. The Cr concentration ranged from 23.05 to 34.28 with mean of 28.36 mg kg^{-1} soil, while the critical limit of Cr was 100 mg kg^{-1} . Therefore, the Cr contamination factor of all the samples had below the threshold limit (Fig. 1d). Similarly, the degree of contamination (Fig. 2) and total pollution load index (Fig. 3) also indicated that the heavy metal level in soil was below threshold level.

The pH level influenced the movement of HMs in the soil. This study found that pH is significantly interrelated with Cd availability ($r = 0.54^{***}$), and is negatively correlated with Pb mobility ($r = -0.50^{**}$) in the projected area (Table 3). This is largely because lower (more acidic) pH values increase the mobility and bioavailability of Cd. Nevertheless, the outputs of this research reverse those of Kicińska et al. (2022), who reported that acidic pH increases the availability of both Cd and Pb. The behavior and ecological risk of HMs was also affected by EC. High EC is commonly associated with increased metal binding in sediments, influencing the degree of contamination and enhancing the potential of remobilization under fluctuating environmental conditions (Hasan et al., 2022). Higher EC values were associated with lower Cd concentrations ($r = -0.41^*$) in the research area, but there was no such dependence for other HMs.

Table 3. Pearson correlation coefficients between different chemical parameters of soils.

	pH	EC	OC	Olsen P	Bray P	K	Na	Ca	Mg	B	Zn	Fe	Mn	Cd	Pb	Ni	Cr
pH	1.00																
EC	-0.38*	1.00															
OC	-0.61***	0.20	1.00														
Olsen P	0.19	-0.07	-0.12	1.00													
Bray P	0.16	0.02	-0.05	0.36*	1.00												
K	0.52**	-0.24	0.48**	0.06	0.07	1.00											
Na	0.33*	-0.27	-0.32	0.28	0.03	0.51**	1.00										
Ca	0.53***	-0.15	-0.37*	0.41*	0.32	0.48**	0.56***	1.00									
Mg	0.38*	-0.27	-0.29	0.27	0.14	0.50**	0.74***	0.66***	1.00								
B	0.45**	-0.28	-0.41*	0.27	-0.02	0.69***	0.81***	0.60***	0.74***	1.00							
Zn	-0.59***	0.31	0.58***	0.23	-0.02	-0.18	0.07	0.04	0.14	0.03	1.00						
Fe	-0.78***	0.51**	0.77***	-0.20	-0.05	-0.43**	-0.51**	-0.50**	-0.42*	-0.58***	0.56***	1.00					
Mn	0.03	-0.25	0.02	0.78***	0.33*	-0.05	0.34*	0.48**	0.37*	0.29	0.34*	-0.15	1.00				
Cd	0.54***	-0.41*	-0.05	0.56***	0.39*	0.18	0.29	0.45**	0.40*	0.30	-0.11	-0.31	0.55**	1.00			
Pb	-0.50**	0.18	0.16	-0.02	-0.22	-0.03	-0.29	-0.25	-0.10	-0.13	0.42*	0.42*	0.01	-0.46**	1.00		
Ni	0.05	-0.13	-0.25	0.25	-0.07	0.04	-0.002	0.21	0.07	0.15	0.13	-0.13	0.42*	-0.02	0.59***	1.00	
Cr	0.26	0.03	-0.23	0.39*	0.25	0.30	0.23	0.65***	0.35*	0.45**	0.21	-0.21	0.49**	0.17	0.27	0.67***	1.00

*- Significant at 5% level, **- Significant at 1% level, ***- Significant at 0.1% level.

Table 4. Phosphorus, sodium and heavy metal (Cd, Pb, Ni and Cr) concentrations in soils of Kalapara upazila.

Sample no.	Bray P (mg kg ⁻¹)	Na (mg kg ⁻¹)	Cd (mg kg ⁻¹)	Pb (mg kg ⁻¹)	Ni (mg kg ⁻¹)	Cr (mg kg ⁻¹)
1	10.29	28.4	0.00	17.18	33.64	32.99
2	9.65	14	0.05	15.65	36.16	31.94
3	6.86	7.5	0.02	15.65	33.64	30.07
4	11.79	15.5	0.01	15.29	33.17	29.32
5	10.67	4	0.04	14.94	34.13	29.55
6	1.93	10	0.02	17.89	35.98	31.88
7	1.82	8	0.00	19.19	38.81	30.89
8	1.77	19	0.03	15.53	34.94	33.87
9	1.45	13.5	0.03	14.94	35.12	27.63
10	1.45	18	0.01	15.64	34.81	27.51
11	14.04	31	0.08	16.12	37.68	34.28
12	11.85	11	0.01	14.94	32.55	27.28
13	11.69	9.5	0.01	15.76	35.79	32.7
14	0.21	5.5	0.00	17.06	33.15	26.18
15	3.22	18.5	0.00	16.00	30.9	26.01
16	0.70	13	0.01	14.94	30.08	26.24
17	0.91	36	0.00	17.18	38.15	30.89
18	0.96	9	0.00	17.30	32.19	26.93
19	0.27	13.5	0.01	17.65	33.25	28.91
20	2.41	29	0.01	15.64	33.53	26.7
21	2.36	20	0.03	12.34	29.59	24.61
22	2.25	9	0.00	19.66	36.42	28.21
23	0.16	8.5	0.00	18.48	34.99	27.45
24	1.29	14.5	0.01	20.85	38.46	30.36
25	6.22	2.5	0.02	14.58	31.95	24.32
26	10.29	3	0.02	19.43	38.1	28.15
27	1.39	10.5	0.01	17.77	35.33	25.83
28	1.07	6.5	0.05	13.99	34.00	25.71
29	0.43	6.5	0.01	17.06	35.09	25.65
30	2.95	47.5	0.05	14.35	33.48	27.92
31	5.25	30	0.04	14.58	33.87	29.84
32	5.25	5.5	0.02	16.35	32.94	26.47
33	8.20	27.5	0.02	13.64	29.48	23.05
34	4.99	31.5	0.04	15.41	34.70	30.07
35	10.29	11	0.04	16.23	26.47	23.11
Mean	4.75	15.65	0.02	16.26	34.07	28.36
Minimum	0.16	2.5	0.00	12.34	26.47	23.05
Maximum	14.04	47.5	0.08	20.85	38.81	34.28
St. Dev.	4.33	10.73	0.02	1.84	2.71	2.93
WHO's MPL	-	-	3	85	35	100

Critical limit of Bray P - 7.0 mg kg⁻¹

MPL = Maximum Permissible Limit

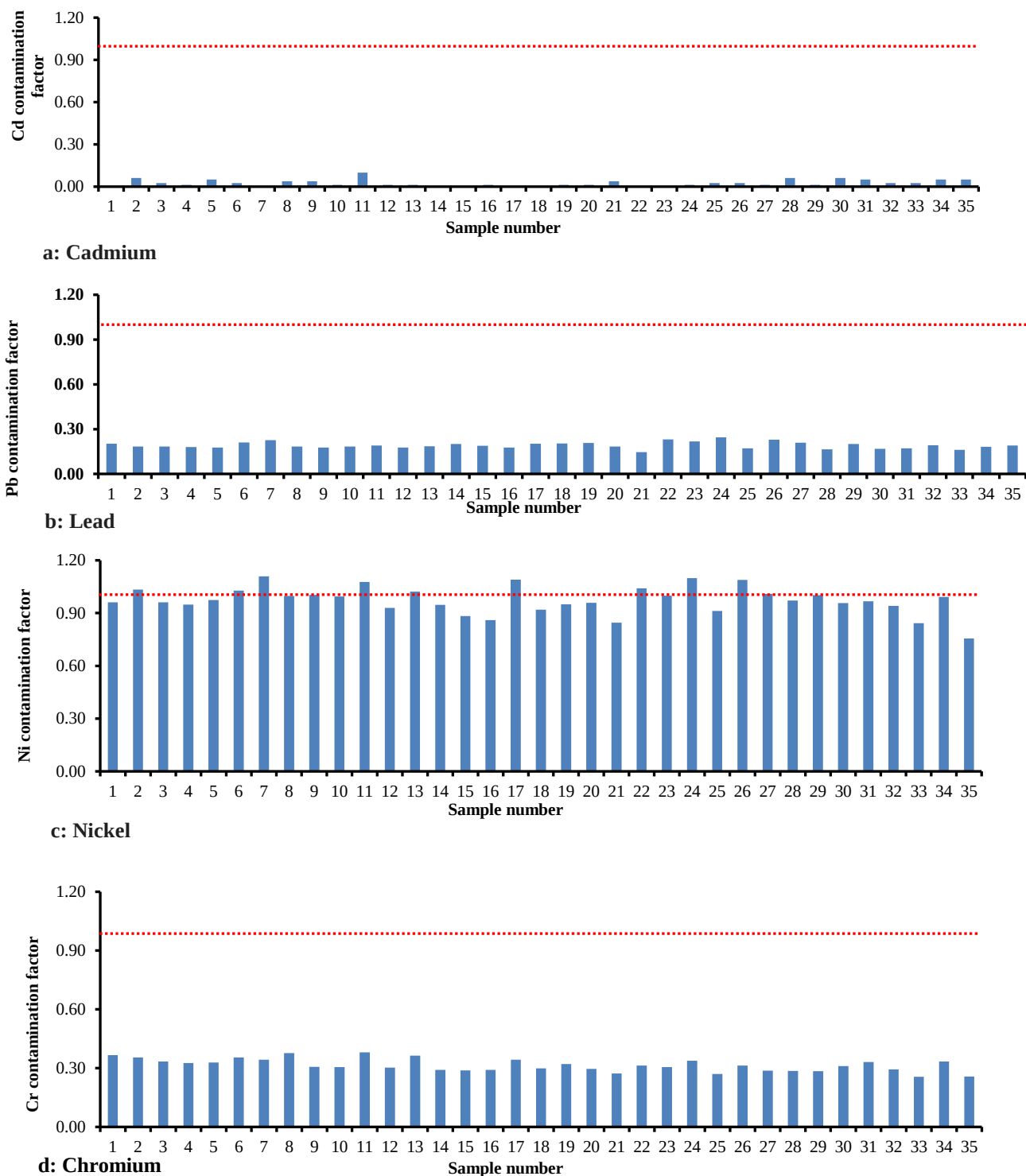


Fig. 1. Figure showing the contamination factors of heavy metals in soil: a) cadmium, b) lead, c) nickel and d) chromium. Interpretation of contamination factor (CF): $CF < 1$ - Low contamination; $1 \leq CF < 3$ - Moderate contamination; $3 \leq CF < 6$ - Considerable contamination; $CF \geq 6$ - Very high contamination (Hakanson 1980). Red dot line indicates safe limit.

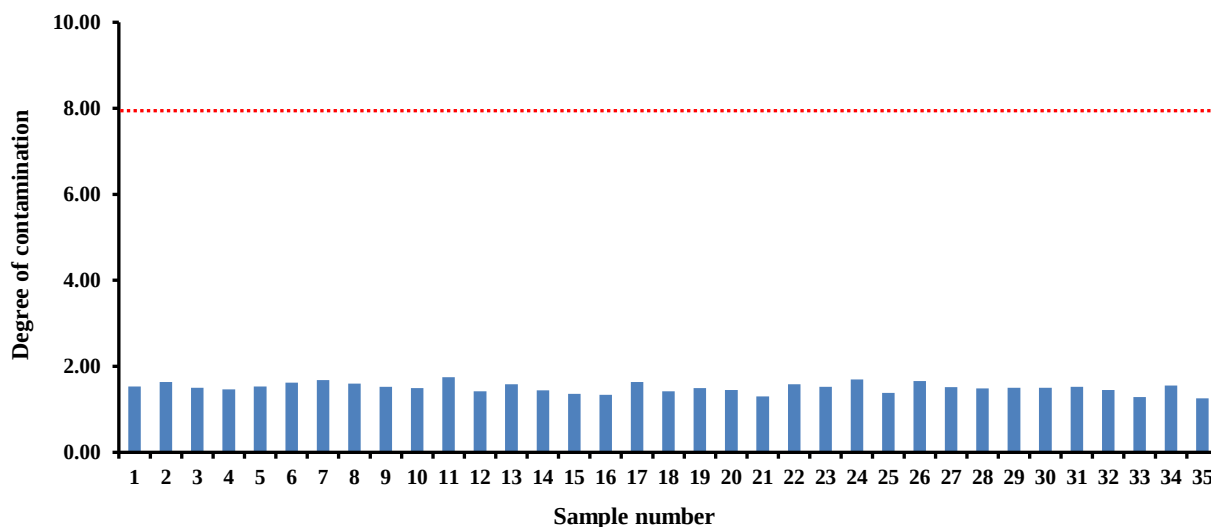


Fig. 2. Figure showing the degree of contamination of heavy metals (Cd, Pb, Ni and Cr) in soil. Interpretation of degree of contamination (DC): $DC < 8$ - Low contamination; $8 \leq DC < 16$ - Moderate contamination; $16 \leq DC < 32$ - Considerable contamination; $DC \geq 32$ - Very high contamination (Hakanson, 1980). Red dot line indicates safe limit.

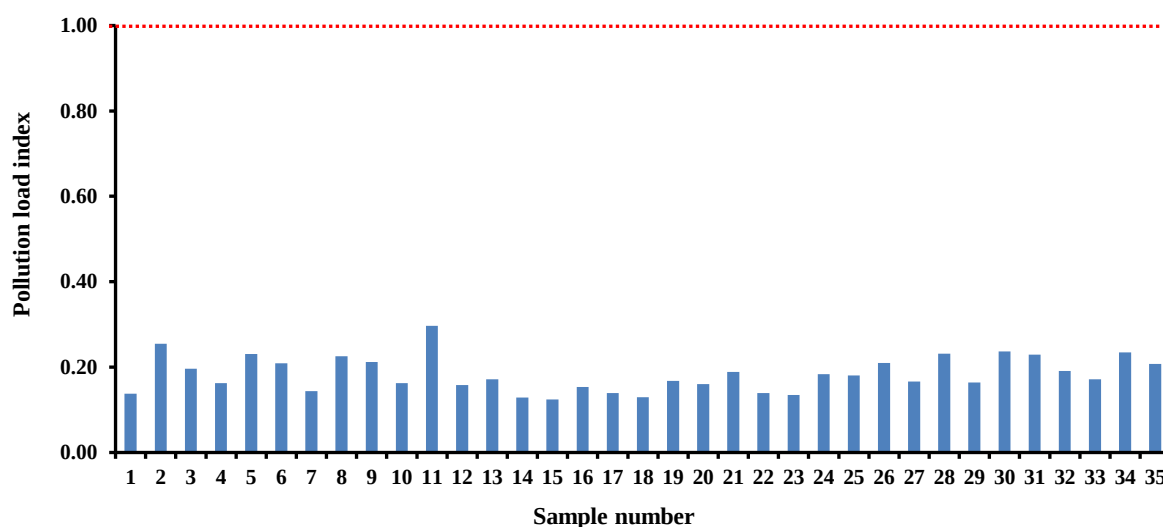


Fig. 3. Figure showing the pollution load index (PLI) of heavy metals (Cd, Pb, Ni and Cr) in soil. Interpretation of PLI: $PLI = 1$ - Base line; $PLI < 1$ - low level; $PLI > 1$ - Deterioration (Tomlinson et al., 1980). Red dot line indicates safe limit.

This study observed that the various HMs concentrations, particularly Pb, Cd, and Cr in the soil, were much below the acceptable limits for crop cultivation. Moreover, the HMs is positively linked with one another. For instance, this research observed that the concentration of Pb increases alongside Ni, and Cr also rises with increasing Ni levels (Table 3).

This suggests that these metals may share a common source or exhibit possibly originating from industrial or other anthropogenic causes (Islam et al., 2020).

Basic cation (K, Na, Ca and Mg) concentrations of the coastal soils

The concentration of available K ranged from 0.23 to 0.93 meq 100g⁻¹ soil (mean 0.48 meq 100g⁻¹

soil) (Table 5). More than 50% of the samples had available K levels greater than $0.45 \text{ meq } 100\text{g}^{-1}$, indicating a very high concentration. Notably none of the samples had K content low or very low level, indicating less possibility of crop response to added K (Table 5). Calcium and Mg concentrations ranged from 1.90 to 13.48, and 3.54 to $20.63 \text{ meq } 100\text{g}^{-1}$, with mean values of 6.08 and 8.60, respectively (Table 5). About 31% of the samples (the largest portion) showed a very high Ca concentration ($>7.5 \text{ meq } 100\text{g}^{-1}$) and only 11.4% samples had low Ca content (Table 5). Interestingly, 100% samples exhibited very high level of Mg, indicating no expected crop response to added Mg in the region (Table 5). Moreover, the mean Na concentration was $15.65 \text{ meq } 100\text{g}^{-1}$, ranging from 2.5 to 47.5, indicating very high level of Na in the study soils (Table 4).

Across all nutrients, K has positive correlations to Na, Ca, and Mg (Table 3). observed that irrigation water with high concentrations of Ca, Mg, and Na facilitates

K absorption. Moreover, in this study, we also observed that macronutrients like Na, Ca, K, and Mg tend to be positively correlated with B because they all participate together in plant cell walls (Table 3). Long and Peng (2023) indicated that an appropriate amount of B can help with the absorption of Ca, Mg, Na, and K in plants. In current research, we observed that P, K, Ca, and Mg availability was positively correlated with Cd availability (Table 3). This is mainly attributed to the low soil pH in the study area, which is insufficient to reduce the solubility and mobility of Cd in the soil. Moreover, our research found that micronutrients such as B and Mn enhanced the availability of Cr.

Table 5. Interpretation of soil test values into different classes of K, Ca and Mg content of soils.

Soil test value interpretation classes*	Frequency of samples (no.)	% of samples	Values
K content of soil ($\text{meq } 100\text{g}^{-1}$)			
Very low (<0.09)	-		Range: 0.23-0.93
Low (0.091-0.18)	-		Mean: 0.48
Medium (0.181-0.27)	4	11.4	St. Dev.: 0.17
Optimum (0.271-0.36)	4	11.4	Critical limit: 0.12
High (0.361-0.45)	8	22.9	
Very high (>0.45)	19	54.3	
Ca content of soil ($\text{meq } 100\text{g}^{-1}$)			
Very low (<1.5)	-		Range: 1.90-13.48
Low (1.51-3.0)	4	11.4	Mean: 6.08
Medium (3.1-4.5)	10	28.6	St. Dev.: 3.0
Optimum (4.51-6.0)	5	14.3	Critical limit: 2.0
High (6.1-7.5)	5	14.3	
Very high (>7.5)	11	31.4	
Mg content of soil ($\text{meq } 100\text{g}^{-1}$)			
Very low (<0.40)	-		Range: 3.54-20.63
Low (0.40-0.80)	-		Mean: 8.60
Medium (0.81-1.20)	-		St. Dev.: 3.23
Optimum (1.21-1.60)	-		Critical limit: 0.55
High (1.61-2.00)	-		
Very high (>2.00)	35	100	

*FRG (2024)

Table 6. Interpretation of soil test values into different classes of micronutrient (B, Zn, Fe and Mn) content of soils.

Soil test value interpretation classes*	Frequency of samples (no.)	% of samples	Value
B content of soil (mg kg⁻¹)			
Very low (<0.203)	2	5.7	Range: 0.10-1.70
Low (0.204-0.406)	6	17.1	Mean: 0.73
Medium (0.407-0.609)	7	20.0	St. Dev.: 0.46
Optimum (0.610-0.812)	7	20.0	Critical limit: 0.27
High (0.813-1.015)	3	8.6	
Very high (>1.015)	10	28.6	
Zn content of soil (mg kg⁻¹)			
Very low (<0.54)	2	5.7	Range: 0.46-2.75
Low (0.55-1.08)	11	31.4	Mean: 1.43
Medium (1.09-1.62)	10	28.6	St. Dev.: 0.66
Optimum (1.63-2.16)	6	17.1	Critical limit: 0.72
High (2.17-2.70)	5	14.3	
Very high (>2.70)	1	2.9	
Fe content of soil (mg kg⁻¹)			
Very low (<3.0)	-	-	Range: 24.5-275.9
Low (3.1-6.0)	-	-	Mean: 135.4
Medium (6.1-9.0)	-	-	St. Dev.: 79.8
Optimum (9.1-12.0)	-	-	Critical limit: 4.0
High (12.1-15.0)	-	-	
Very high (>15)	35	100	
Mn content of soil (mg kg⁻¹)			
Very low (<0.75)	-	-	Range: 6.62-151.16
Low (0.76-1.50)	-	-	Mean: 30.8
Medium (1.51-2.25)	-	-	St. Dev.: 26.9
Optimum (2.26-3.0)	-	-	Critical limit: 1.0
High (3.1-3.75)	-	-	
Very high (>3.75)	35	100	

*FRG (2024)

Micronutrient (B, Zn, Fe and Mn) concentration in the coastal soils

The concentration of B ranged from 0.10 to 1.70 mg kg⁻¹, with a mean of 0.73 mg kg⁻¹, where critical limit of B was 0.27 mg kg⁻¹ soil (Table 6). A significant portion of the samples (28.6%) had very high concentrations (>1.015 mg kg⁻¹), while 5.7% had very low concentrations (<0.203 mg kg⁻¹) and 17.1% sample had low B concentration (0.204–0.406 mg kg⁻¹) (Table 6). Moreover, the mean concentrations of Zn, Fe, and Mn were 1.43 mg kg⁻¹ (ranging from 0.46 to 2.25 mg kg⁻¹), 135.4 mg kg⁻¹ (ranging from 24.5 to 275.9 mg kg⁻¹), and 30.80 mg kg⁻¹ (ranging from 6.62 to 151.2 mg kg⁻¹), respectively. A significant portion of the samples (31.4%) had low (0.55–1.08 mg kg⁻¹) Zn levels, while only a small fraction (2.9%) showed very high Zn concentrations, indicating a moderate deficiency of zinc in the study region (Table 6). In contrast, 100% of the samples contained very high levels of both Fe (>15 mg kg⁻¹) and Mn (>3.75 mg kg⁻¹), which indicates possibility of higher fixing capacity with lower availability of P in the soils (Table 6).

According to the research, the concentration of micronutrients such as B is extremely high; the Zn concentration is medium. Moreover, Fe and Mn concentrations were extremely elevated. In the south-central coastal part of the region, high levels of Fe, Mg, and B in soils are attributed to sea water intrusion, periodic flooding, and sedimentary geology (Hasan et al., 2022; Haque et al., 2000, Khanam et al., 2000). Salinity intrusion causes an influx of ions from seawater and an increase in ionic strength, which may boost the mobilization and redistribution of trace elements and also enhance the accumulation of B because of its strong association with marine sources and saline water. Periodic flooding alternates anaerobic and aerobic conditions in the soil; under reducing conditions (waterlogged), Fe and Mn oxides are reductively dissolved, releasing soluble Fe²⁺ and Mn²⁺ into the soil solution, which can migrate upward and re-precipitate during

drying periods. The region of this activity is unique from the rest of Bangladesh, where this process enhances mineral solubility and subsequently micronutrient accumulation.

Conclusions

This study highlights the complex interactions among soil salinity, acidity, nutrient dynamics, and heavy metal contamination in the south-central coastal soils of Bangladesh. The soils were predominantly acidic, highly saline, and severely deficient in P, despite having very high levels of K, Ca, Mg, Fe, and Mn. Although Cd, Pb, and Cr remained below the critical limits, the widespread exceeding of Ni in nearly half of the samples indicates a growing contamination concern. The correlation revealed strong positive associations of several heavy metals (Ni, Cr, Cd) with basic cations and micronutrients, suggesting that soil chemical conditions, particularly pH, Ca–Mg saturation, and micronutrient abundance play significant roles in controlling HM mobility and accumulation. Managing soil acidity and salinity, restoring P fertility, and monitoring Ni accumulation should therefore be prioritized to sustain crop production and reduce long-term contamination risks in coastal Bangladesh.

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Conflict of interest

Regarding the publication of this paper, the authors have no conflict of interest.

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