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Heavy Metal Contamination in Agricultural Soils of Central Bangladesh: Implications for Ecological Risk and Food Security

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ABSTRACT

This study assessed the concentrations, distribution, sources and ecological risks of heavy metals in agricultural soils near industrial zones in Gazipur, Bangladesh. Thirty soil samples were collected in mid-January 2024 and analyzed for six heavy metals (Cr, Ni, Cu, As, Cd, and Pb) using inductively coupled plasma mass spectrometry (ICP-MS). Average concentrations (mg/kg) were: Cr (7.47±1.93), Pb (6.88±2.30), Cd (1.95±0.60), Cu (11.64±2.61), As (2.55±0.85) and Ni (17.87±5.08). All metals, except Cd, were below the permissible limits set by Dutch, Canadian, and Australian soil quality guidelines. Multivariate statistical analyses suggested mixed lithogenic and anthropogenic origins of heavy metals, with industrial activities being the dominant source. Contamination factors (CF), contamination degree (CD) geo-accumulation index (Igeo), enrichment factors (EF) and pollution load index (PLI) analysis indicated safe levels for most metals, but Cd posed significant contamination and ecological concern. The potential ecological risk index (PER) showed low to moderate risk, though some sampling sites exhibited high risk due to Cd. These findings provide critical insight for policymakers to mitigate soil contamination and protect environmental and human health.

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INTRODUCTION

Soil is a vital environmental resource and serves as a primary sink for pollutants, particularly heavy metals, which pose serious ecological and human health risks (Ghiyasi et al., 2010; Kabir et al., 2021). Over recent decades, growing concerns have emerged over soil contamination from trace elements, largely driven by rapid industrialization and urban development, especially in developing countries like Bangladesh (Yassir & Alain, 2015; Tusher et al., 2017; Islam et al., 2018). In industrial areas, heavy metals can accumulate in soils through various activities, including vehicular emissions, fossil fuel combustion, industrial discharges, power generation, and wastewater irrigation (Karbassi et al., 2014; Moni et al., 2023). These toxic elements are non-biodegradable, environmentally persistent, and capable of bioaccumulation through the food chain, thereby threatening soil health, agricultural productivity, and public well-being (Wahab et al., 2020; Aghlidi et al., 2020). While soil contamination can occur naturally, anthropogenic sources remain the dominant contributors to heavy metal pollution in agricultural land (Hosseini et al., 2020). The presence of these metals alters the physical,

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chemical, and biological properties of surface soils, ultimately impairing land productivity (Barua et al., 2023).

Soil contamination by toxic metals poses significant long-term ecological and health risks. Crops grown in contaminated agricultural soils can accumulate hazardous elements, leading to both carcinogenic and non-carcinogenic health effects in humans, even at low exposure levels (Ghiyasi et al., 2010; Gbadamosi et al., 2018). Vulnerable populations, particularly children and adults, face elevated risks through direct and indirect exposure pathways. Heavy metals such as chromium (Cr), copper (Cu), cadmium (Cd), nickel (Ni) and lead (Pb), along with the metalloid arsenic (As), are of particular concern due to their well-documented toxicity (Mohammadpour et al., 2016; Kormoker et al., 2019). For example, inhalation of hexavalent chromium-laden dust can increase the lifetime risk of lung cancer, while acute and chronic arsenic exposure is linked to a range of health disorders, including cardiovascular, hepatic, neurological, reproductive, and carcinogenic effects (Islam et al., 2014a). In Bangladesh, rapid industrial growth without adequate waste management has intensified environmental pollution, especially in densely populated and industrially active districts. Therefore, assessing heavy metal concentrations in agricultural soils is essential to understand associated ecological and health risks and to guide mitigation efforts (Islam et al., 2014b; Proshad et al., 2018). To evaluate the extent and potential risks of soil contamination, various pollution indices such as the contamination factor (CF), contamination degree (CD) enrichment factor (EF), geo-accumulation index (Igeo), pollution load index (PLI), and potential ecological risk index (PER) have been developed and widely applied (Mohammadpour et al., 2016; Roy et al., 2019; Mohammadi et al., 2022). These tools help quantify the level of contamination and identify possible ecological and human health threats (Mehr et al., 2017).

Gazipur is one of Bangladesh's major industrial hubs and is presumed to be significantly contaminated with heavy metals (Islam et al., 2012). The region hosts diverse industrial activities, including aluminum production, textile and dyeing, pharmaceuticals, cosmetics, machine tools manufacturing, diesel plants, security printing, ordnance, ceramics, packaging, brick kilns, and garment industries (Tusher et al., 2017; Kabir et al., 2021). These activities contribute to widespread soil contamination across industrial zones. While numerous international studies have assessed human health risks from heavy metal contamination in urban and industrial soils, limited research has focused on industrial areas like Gazipur in Bangladesh. Therefore, this study aims to: (i) quantify the concentrations of selected toxic metals (Cr, Ni, Cu, As, Cd, and Pb) in agricultural soils, (ii) investigate the associations between metal concentrations and their potential sources, and (iii) evaluate the ecological risks using pollution indices. The findings aim to inform policymakers and environmental managers in mitigating contamination and protecting both ecosystems and public health.

MATERIALS AND METHODS

Soil samples were collected from Gazipur District, located in central Bangladesh (Fig. 1), covering an area of 1,741.53 km^2 between 23°53′-24°21′N and 90°09′-92°39′E (BBS, 2011). According to the 2022 Census, the district had a population of 5.26 million across 1.58 million households, with 64.2% residing in urban areas. The district experiences a tropical savanna climate with an average annual temperature of 29.5°C, approximately 2400 mm of mean rainfall per year (Tusher et al., 2017). Sampling sites were selected based on preliminary field visits and presumed levels of soil contamination. Site-1 (23°53′41.8″N, 90°24′40.8″E) was adjacent to Radiant Pharmaceuticals Ltd. in Tongi. Site-2 (23°54′18.9″N, 90°23′54.2″E) was located in the densely industrialized Charag Ali area. Site-3 (23°57′07.4″N, 90°23′17.4″E) was near Zhongxin Textile Factory, affected by both industrial waste and agricultural runoff. Site-4 (23°58′10.8″N, 90°22′49.5″E) was surrounded by Columbia Garments, with garment

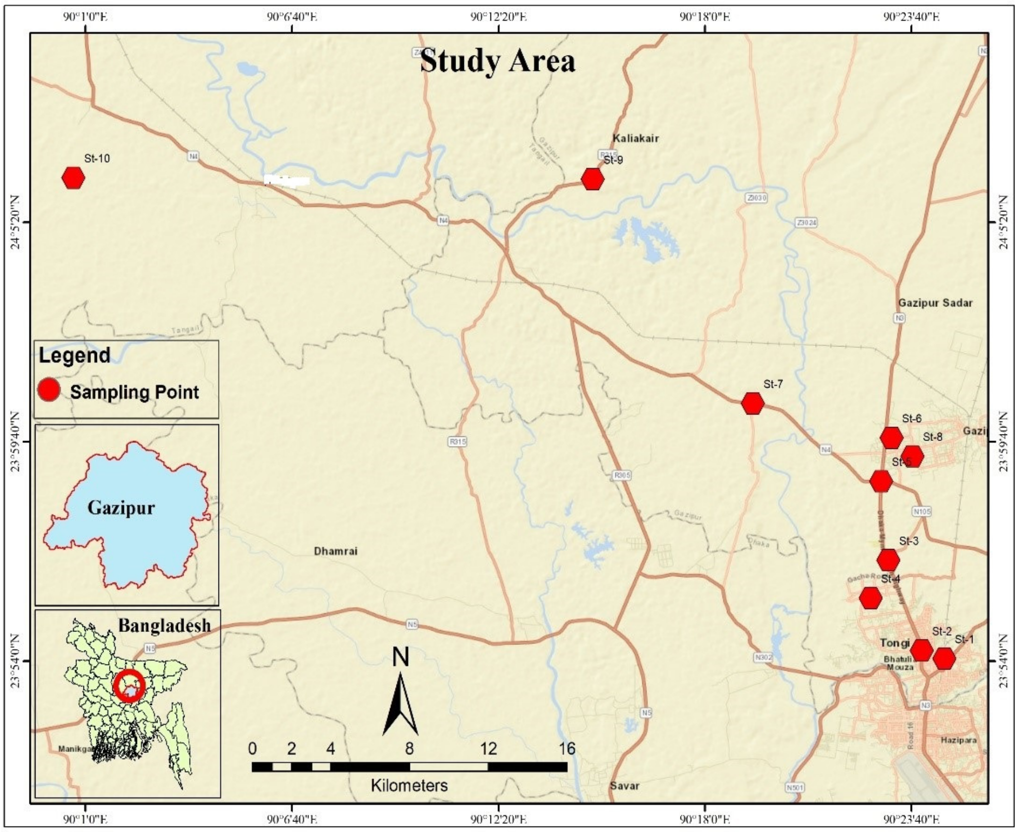

Fig. 1. Map of the study area showing all the sampling sites in the Gazipur district

waste as the primary pollution source. Site-5 (23°97′57.9″N, 90°37′24.1″E), near Alema Textiles Ltd., was identified as the most polluted due to direct waste discharge onto land. Site-6 (23°99′69.1″N, 90°38′53.2″E), located in Telipara, was relatively distant from industrial zones and considered less polluted. Site-7 (24°00′10.1″N, 90°19′26.4″E) was influenced by cement, textile, and pesticide industries, as well as municipal and domestic wastewater. Site-8 (24°08′43.8″N, 90°27′35.5″E) was adjacent to Boshunia Garments, where seepage from dyeing processes and nearby vegetable gardens contributed to soil pollution. Site-9 (24°11′58.1″N, 90°27′48.2″E) was near Unilliance Textiles Ltd., and Site-10 (24°14′09.3″N, 90°28′05.7″E) was heavily impacted by waste from Blue Planet Knit and a fertilizer company, with both municipal and agricultural runoff being significant pollution sources.

Soil samples were collected from industrial areas of Gazipur District, Bangladesh, during the dry season in mid-January 2024-a period suitable for assessing metal contamination due to minimal rainfall (Duong and Lee, 2011). A total of 30 surface soil samples (0-15 cm depth) were collected from 10 sites, with each composite sample formed by mixing three sub-samples. The samples were air-dried at room temperature for two weeks, then ground with a porcelain mortar and pestle, sieved through a 2 mm nylon mesh, and stored in airtight Ziploc bags at freezing temperatures until chemical analysis. For digestion, ultra-pure $HClO_4$ and HNO_3 were used in a 1:2.5 ratio. Approximately 0.5 g of powdered soil was placed in a 100 mL Pyrex beaker and mixed with 15 mL of the acid mixture. The mixture was heated on a hot plate at 130°C for about 5 hours until the volume was reduced to 2-3 mL. An additional 5 mL of the di-acid mixture were added and boiled repeatedly until a clear or light-colored solution was obtained. After cooling, the digest was diluted with deionized water, filtered through Whatman No. 41 filter paper, and analyzed for heavy metals using an inductively coupled plasma mass

Table 1. Description of the pollution level and ecological risk assessment

Index and Formula	Standards	References
Geo-accumulation index ($\mathbf{I_{geo}}$): $\mathbf{I_{geo} = \log_2 (C_n/1.5 \times B_n)}$	Class 0 ($I_{geo} \leq 0$): uncontaminated, Class 1 (I_{geo}=0-1): uncontaminated to moderately contaminated, Class 2 (I_{geo}=1-2): moderately contaminated, Class 3 (I_{geo}=2-3): moderately to strongly contaminated, Class 4 (I_{geo}=3-4): strongly contaminated, Class 5 (I_{geo}=4-5): strongly to extremely contaminated, and Class 6 ($I_{geo} \geq 5$): extremely contaminated.	Muller (1969) Pan et al. (1017)
Enrichment factor ($\boldsymbol{EF}$): $\boldsymbol{EF = \frac{(^{C_M}/_{C_{Al}})Sample}{(^{C_M}/_{C_{Al}})Background}}$	EF <1 (no enrichment), EF <3 (minor enrichment), EF =3-5 (moderate enrichment), EF =5-10 (moderately severe enrichment), EF =10-25 (severe enrichment), EF =25-50 (very severe enrichment) and EF >50 (extremely severe enrichment)	Chen et al. (1991) Aghlidi et al. (2020)
Contamination factor ($\mathbf{CF}$) & Contamination degree ($\boldsymbol{CD}$): $\mathbf{CF = (C_m)(B_m)}$ $\boldsymbol{CD = \sum_{i=1}^{n} CF}$	CF <1: low, 1≤ CF <3: moderate, 3≤ CF <6: considerable, and CF ≥6: very high. CD <6: low, 6≤ CD <12: moderate, 12≤ CD <24: considerable, and CD ≥24: very high.	Hakanson (1980) Tomlinson (1980) Mehr et al. (2017)
Pollution load index ($\mathbf{PLI}$): $\mathbf{PLI = \sqrt[n]{(CF_1 \times CF_2 \times CF_3 \times \ldots . CF_n)}}$	PLI>1 specifies pollution exists, conversely, if PLI<1 designates there are nonexistence metal pollution.	Roy et al. (2019) Kabir et al. (2020)
Potential ecological risk ($\mathbf{PER}$): $\mathbf{C_f^i = \frac{C_m^i}{C_n^i}}$ $\mathbf{E_r^i = C_f^i \times T_f^i}$ $\mathbf{PER = \sum_{i=1}^{n} E_r^i}$	E_r^i< 40 or PER < 150: low, 40 ≤ E_r^i< 80 or 150 ≤ PER < 300: moderate, 80 ≤ E_r^i< 160 or 300 ≤ PER <600: considerable and 160 ≤ E_r^i< 320 or 600 ≤ PER: very high ecological risk for the soils.	Chen & Zhou. (1992) Hosseini et al. (2020)

spectrometer (ICP-MS, Agilent 7500i, USA). Contamination factor (CF), geo-accumulation index (Igeo), enrichment factor (EF), contamination degree (CD), pollution load index (PLI) and potential ecological risk index (PER) were calculated to assess soil contamination levels and related ecological risks in the study area. Key characteristics of these indices are summarized in Table 1. Statistical analyses were conducted using SPSS 20.0 (SPSS Inc., USA). Principal component analysis (PCA) was applied to identify potential sources of toxic metals, while Pearson correlation was used to assess inter-element relationships. Additional computations were performed in Microsoft Excel 2013.

RESULTS AND DISCUSSION

The concentrations of Cr, Pb, Cd, Cu, As, and Ni in agricultural soils ranged from 4.29-9.82, 3.41-9.71, 1.04-2.82, 8.36-16.72, 1.22-4.16, and 12.19-28.76 mg/kg, respectively (Table 2). The mean concentrations followed the descending order: Ni > Cu > Cr > Pb > As > Cd, indicating spatial heterogeneity across the study area. Urban activities including waste dumping, municipal and industrial discharges, heavy traffic, and urbanization in Gazipur are likely major contributors to the varied metal concentrations (Kabir et al., 2020; Ali et al., 2016). Comparison with Average Shale Values (ASV) by CNEMC (1990) revealed that mean Cd concentration exceeded ASV. While Cr, Pb, Cu, Ni, and As were below the permissible threshold effect levels (PTE-MPC) set by CEPA (1995), Cd levels exceeded the limits across all sampling sites. The variation coefficients (VC) for Cr, Pb, Cd, Cu, As, and Ni were 25.90, 33.36, 30.66, 22.39, 33.28 and 28.44%, respectively (Table 2), suggesting anthropogenic sources predominantly influence Pb, Cd, and As distribution. Moreover, Cr and As concentrations surpassed the Soil Invertebrate Toxicity Reference Values (SI-TRV) set by USEPA (1999), while Pb, Cd, Cu, and Ni remained below (Table 2). These findings indicate potential ecological hazards from Cr and As in the agricultural soils of the study area.

The mean concentration of chromium (Cr) in agricultural soils was 7.47 ± 1.93 mg/kg, ranging from 4.29 mg/kg at Site-5 to 9.82 mg/kg at Site-1 (Table 2). Elevated Cr levels may result from untreated discharges of waste and waste water from industries including printing

Table 2. Descriptive statistics of heavy metal concentration (mg/kg) in agricultural soil of Gazipur, Bangladesh

Elements	Mean	SD (±)	Min.	Max.	VC (%)	Skewness	Kurtosis	BV-China	PTE-MPC	SI-TRV
Cr	7.47	1.93	4.29	9.82	25.90	-0.33	-1.33	90.0	200.0	0.200
Pb	6.88	2.30	3.41	9.71	33.36	-0.39	-1.37	20.0	300.0	100.0
Cd	1.95	0.60	1.04	2.82	30.66	-0.07	-1.17	0.30	0.300	10.00
Cu	11.64	2.61	8.36	16.72	22.39	0.71	-0.03	45.0	100.0	32.00
As	2.55	0.85	1.22	4.16	33.28	0.31	0.26	13.0	20.00	0.250
Ni	17.87	5.08	12.19	28.76	28.24	1.04	1.15	68.0	50.00	100.0

Note: -PTE-MPC= maximum permissible concentrations of potential toxic elements for agricultural soils of China (CEPA 1995); BV-China= background value of soil environment in China (CNEMC 1990); SI-TRV= soil invertebrate toxicity reference values (USEPA 1999).

Table 3. Comparison of metal concentration (mg/kg) in soils of this study with other studies and guideline values

District (country)	Cr	Ni	Cu	As	Cd	Pb	References
Gazipur (Bangladesh)	7.47	17.87	11.64	2.55	1.95	6.88	Present Study
Kushtia (Bangladesh)	5.78	21.0	31.8	8.05	1.20	19.2	Kormoker et al. (2019)
Tangail (Bangladesh)	11.56	23.92	37.27	6.11	2.01	17.46	Proshad et al. (2018)
Dhaka (Bangladesh)	384.0	192.0	311.0	64.00	7.10	199.0	Islam et al. (2014a)
Bogra (Bangladesh)	41.00	45.00	42.00	10.00	4.20	44.00	Islam et al. (2014b)
Guandong (China)	12.30	8.83	324.0	NA	0.09	96.00	Luo et al. (2011)
Maharastra (India)	164.0	171.0	155.0	2.80	30.00	42.00	Bhagure and Mirgane (2011)
Murcia (Spain)	18.00	14.00	11.00	NA	0.22	49.00	Acosta et al. (2011)
Kayseri (Turkey)	29.00	45.00	37.00	NA	2.50	75.00	Tokalıoğlu and Kartal (2006)
DSQS	100.0	35.00	36.00	29.00	0.80	85.00	VROM (2000)
CEQG	64.00	50.00	63.00	12.00	1.40	70.00	CCME (2003)
DEPA	50.00	60.00	60.00	20.00	3.00	300.0	DEP (2003)

Note: DSQS= Dutch Soil Quality Standard, CEQG= Canadian Environmental Quality guidelines, DEPA= Department of Environmental Protection Australia, NA=Not Available.

and dyeing, electroplating and metal finishing, stainless steel production which commonly use chromium salts in the study area. Despite these inputs, the mean Cr concentration remained below guideline limits set by the Dutch Soil Quality Standards (VROM, 2000), Canadian Environmental Quality Guidelines (CCME, 2003), and Australian Soil Quality Guidelines (DEP, 2003) (Table 3). Comparative analysis showed that Cr levels in this study were lower than those reported in soils from Tangail, Dhaka, Bogura, Guangdong, Maharashtra, Murcia, and Kayseri (Table 3). Lead (Pb) concentrations averaged 6.88 ± 2.30 mg/kg, with Site-10 showing the highest level (9.71 mg/kg) and Site-5 the lowest (3.41 mg/kg). The Pb concentrations were well below the Average Shale Value (20 mg/kg) and regulatory thresholds (DSQS, CEQG, DEPA), indicating limited contamination (Table 3). Sources of Pb may include industrial emissions, construction materials (paints, coatings), and improper waste disposal (Mohammadi et al., 2022; Aghlid et al., 2020). Cadmium (Cd) levels averaged 1.95 ± 0.60 mg/kg, exceeding both DSQS and CEQG limits. Site-10 recorded the highest Cd (2.82 mg/kg), while Site-6 had the lowest (1.04 mg/kg) (Table 3). Around 80% of samples surpassed the Dutch target value, suggesting significant ecological risk. Cd contamination in the study area is likely attributed to both natural and anthropogenic sources. Natural weathering of rocks contributes to background levels of Cd, while human activities significantly elevate its concentration. Key anthropogenic sources include the application of phosphate fertilizers, sewage irrigation, fossil fuel combustion, and waste incineration. Moreover, various industrial operations such as metal production, smelting and the manufacturing of batteries, plastics and coatings play a substantial role in releasing

Cd into the environment. Nevertheless, Cd levels were lower than those reported in studies from Tangail, Dhaka, Bogura, Maharashtra, and Kayseri (Table 3). Copper (Cu) concentrations ranged from 8.36 mg/kg (Site-3) to 16.72 mg/kg (Site-10), with a mean of 12.38 ± 2.61 mg/kg. All observed levels were below the Dutch, Canadian, and Australian soil quality standards (Table 3), indicating minimal Cu contamination. Moreover, the unregulated discharge of untreated or partially treated industrial effluents, particularly from textile dyeing and electroplating industries operating in and around the study area are the key sources of Cu pollution. However, the elevated levels of Cu may result from the occasional use of Cu-rich wastewater for irrigation in the study area, particularly during the dry season, which poses potential phytotoxic risks (Bhagure & Mirgane, 2011). Arsenic (As) concentrations averaged 2.55 ± 0.85 mg/kg, with a maximum of 4.16 mg/kg at Site-1 and a minimum of 1.22 mg/kg at Site-7 (Table 2 & Fig. 2).

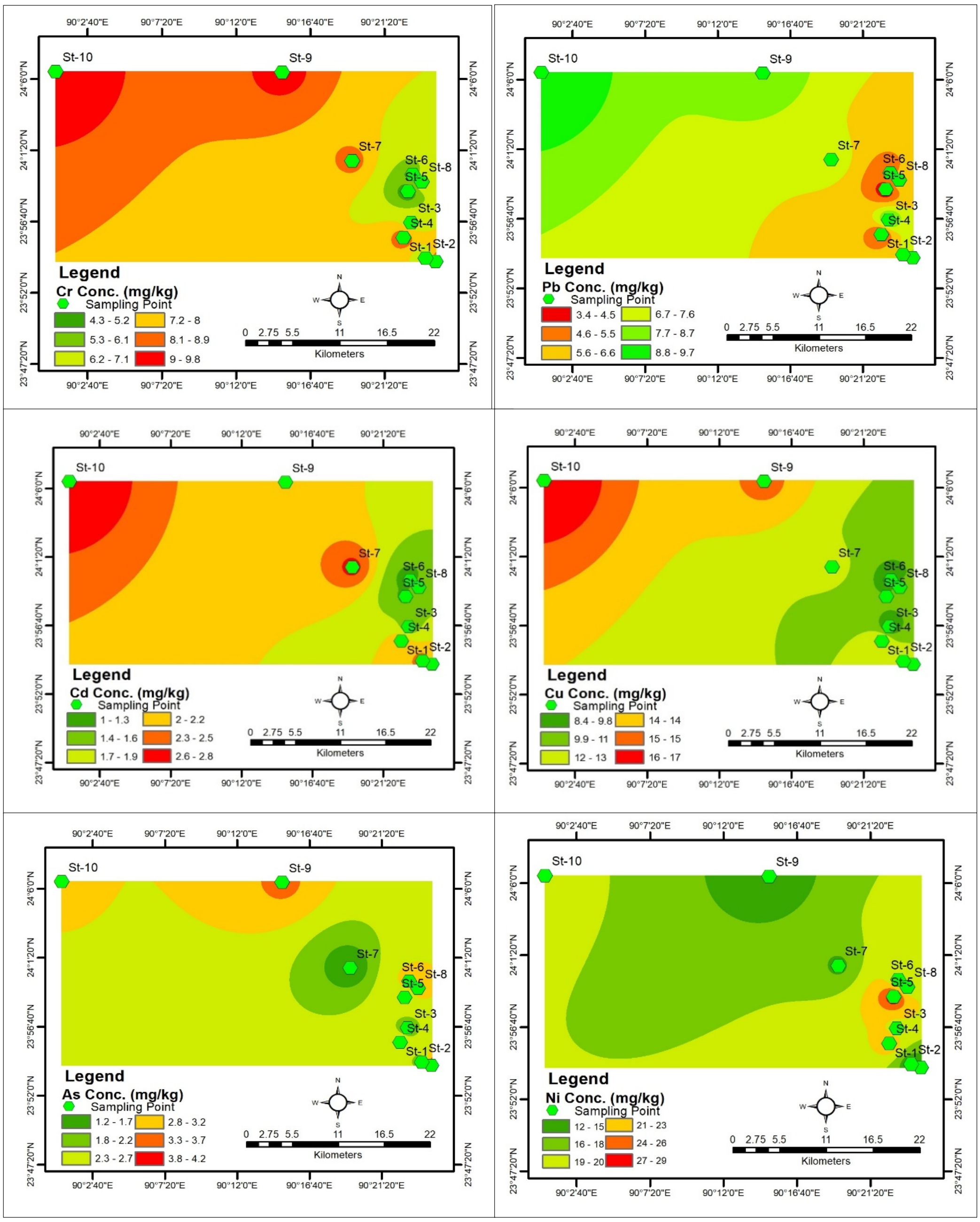

Fig. 2. Spatial distribution of heavy metal concentrations in soils of Gazipur, Bangladesh

Table 4. Pearson correlation matrix for heavy metals concentration in soil samples

Metals	Cr	Pb	Cd	Cu	As	Ni
Cr	1					
Pb	0.593*	1				
Cd	0.576*	0.406	1			
Cu	0.605*	0.297	0.839**	1		
As	0.479	0.228	-0.248	.056	1	
Ni	-0.457	-0.595	-0.459	-0.272	-0.163	1

** Correlation is significant at the 0.01 level (two-tailed); * Correlation is significant at the 0.05 level (two-tailed).

Potential sources include the use of As-contaminated irrigation water, fertilizers, pesticides, and emissions from brick kilns and incineration (Aghlidi et al., 2020; Gbadamos et al., 2018). All measured As levels were below international soil quality guidelines and lower than values reported in related studies across Bangladesh and other countries (Table 3). Nickel (Ni) showed the highest average concentration among the analyzed metals, with a mean of 17.87 ± 5.08 mg/kg. Concentrations ranged from 12.19 mg/kg at Site-9 to 28.76 mg/kg at Site-5 (Fig. 2). While all samples exceeded the PTE-MPC value (CEPA, 1995), Ni levels remained within the Dutch, Canadian, and Australian guideline limits (Table 3). The elevated Ni levels may be attributed to localized anthropogenic inputs (e.g., untreated industrial wastewater, improper slurry disposal, or atmospheric deposition near industrial facilities) or accidental spills (e.g., plating solutions or industrial leaks) of Ni-containing materials.

Pearson's correlation matrix for analyzed soils parameters interrelated with each other and the results are presented in Table 4. The study showed positive correlations between Cr with Pb, Cr with Cd, and Cr with Cu. The Cd showed a significant positive correlation with Cu. Considering the relationship between the combinations showed a positive relationship which indicates the parameters were interrelated with each other and may be originated from the same source to study area. Other relationships among the constituents of soil were not significant. The negative correlation between Ni and other metals likely reflects a combination of differing natural geochemical controls and distinct anthropogenic inputs. This pattern suggests Ni may originate from natural background levels rather than the broader industrial contamination affecting the other metals.

Principal Component Analysis (PCA) was employed to identify potential sources of heavy metals in the soil. Two principal components (PCs) explained most of the variance in the dataset. PC1 accounted for 70.24% of the total variance (eigenvalue: 30.03), showing positive loadings for Cr (0.040), Cd (0.003), and moderately for Cu (0.001), indicating an anthropogenic origin (Fig. 3). Likely contributors include fertilizers, pesticides, fungicides, wastewater, sewage sludge, smelting, battery disposal, electronic and plastic waste, paint pigments, wood preservatives, and livestock manure (Roy et al., 2019; Hossein et al., 2020). PC2 explained 17.41% of the variance (eigenvalue: 7.44), with positive loadings for As, Pb, and Ni, suggesting a lithogenic or geochemically controlled source (Fig. 3). However, the clustering suggests that PC1 metals are primarily influenced by anthropogenic sources, commonly found in industrial zones and introduced through wastewater, air deposition, and waste dumping, whereas PC2 metals are mainly controlled by geogenic factors, originating from natural rock and soil weathering. Overall, both natural and anthropogenic factors influence metal accumulation, with Cd-largely attributed to phosphate fertilizers-posing the greatest ecological risk.

The mean geo-accumulation index (Igeo) values for the six analyzed metals followed the decreasing order: Cd (2.046) > Pb (-2.210) > Ni (-2.562) > Cu (-2.568) > As (-3.012) > Cr (-4.224) (Table 5). According to Müller's (1981) classification, Cd fell into class 2 (moderately polluted), while the remaining metals Pb, Ni, Cu, As, and Cr were categorized as class 0

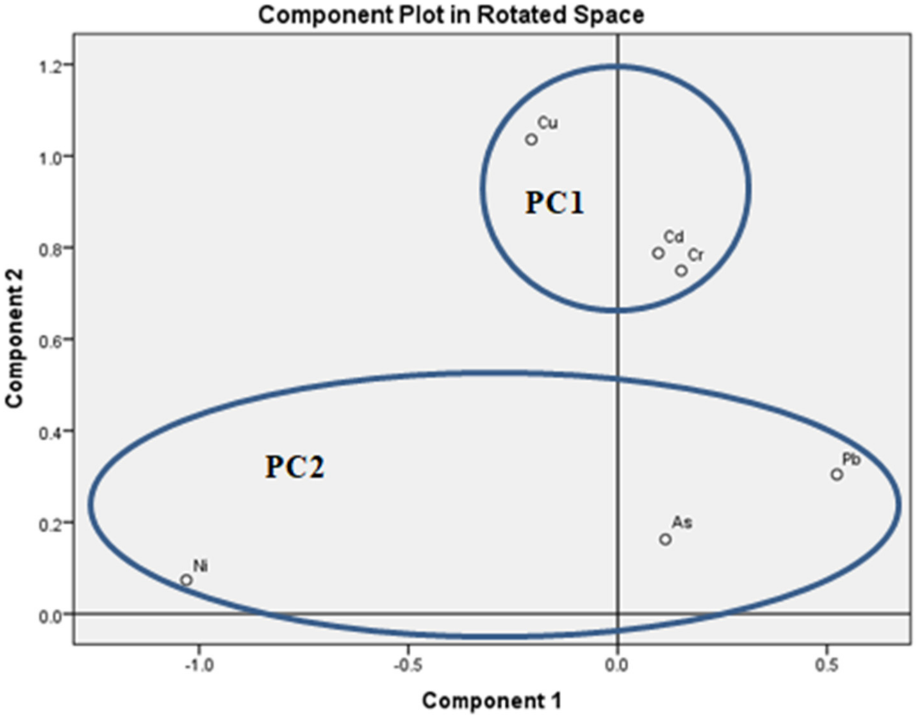

Fig. 3. PCA loading plot of studied heavy metals

Table 5. Igeo of heavy metals in soil collected from different sites of Gazipur, Bangladesh

Sampling Site	Cr	Pb	Cd	Cu	As	Ni
Site-1	-3.781	-1.783	2.008	-2.676	-2.229	-2.874
Site-2	-4.641	-2.275	2.451	-2.431	-3.546	-3.011
Site-3	-4.388	-1.690	1.668	-3.013	-3.329	-2.382
Site-4	-3.952	-2.981	2.270	-2.351	-2.993	-2.167
Site-5	-4.976	-3.137	1.474	-2.790	-3.141	-1.826
Site-6	-4.558	-2.680	1.209	-2.912	-2.764	-2.520
Site-7	-4.029	-2.021	2.542	-2.519	-3.999	-2.821
Site-8	-4.223	-2.106	1.943	-2.733	-2.710	-2.476
Site-9	-3.874	-1.796	2.250	-2.237	-2.572	-3.065
Site-10	-3.817	-1.627	2.648	-2.013	-2.842	-2.475
Mean	-4.224	-2.210	2.046	-2.568	-3.012	-2.562
Minimum	-4.976	-3.137	1.209	-3.013	-3.999	-3.065
Maximum	-3.781	-1.627	2.648	-2.013	-2.229	-1.826

(unpolluted). The highest Igeo was observed for Cd (2.648) at Site-10, whereas the lowest value was recorded for Cr (−4.976) at Site-5. These results indicate that among the assessed elements, agricultural soils in the study area are primarily impacted by Cd contamination. The elevated Igeo values for Cd are likely attributed to anthropogenic inputs such as fossil fuel combustion, application of phosphate fertilizers, sewage sludge amendments, and industrial discharges.

The mean contamination factor (CF) values for the analyzed heavy metals in agricultural soils followed the descending order: Cd (6.490, very high) > Pb (0.344, low) > Ni (0.263, low) > Cu (0.259, low) > As (0.196, low) > Cr (0.083, low) (Table 6). These results suggest that, although most metals exhibited low contamination levels, cadmium posed a considerable concern. The

Table 6. CF, CD and PLI of heavy metals in soil of different sites of Gazipur, Bangladesh

Sampling Site	Contamination Factors (CF)						CD	PLI
	Cr	Pb	Cd	Cu	As	Ni		
Site-1	0.109	0.436	6.033	0.235	0.320	0.205	7.338	0.405
Site-2	0.060	0.310	8.200	0.278	0.128	0.186	9.163	0.317
Site-3	0.072	0.465	4.767	0.186	0.149	0.288	5.926	0.328
Site-4	0.097	0.190	7.233	0.294	0.188	0.334	8.337	0.368
Site-5	0.048	0.171	4.167	0.217	0.170	0.423	5.195	0.284
Site-6	0.064	0.234	3.467	0.199	0.221	0.261	4.446	0.289
Site-7	0.092	0.370	8.733	0.262	0.094	0.212	9.763	0.340
Site-8	0.080	0.349	5.767	0.226	0.229	0.270	6.920	0.362
Site-9	0.102	0.432	7.133	0.318	0.252	0.179	8.417	0.407
Site-10	0.106	0.486	9.400	0.372	0.209	0.270	10.843	0.466
Mean	0.083	0.344	6.490	0.259	0.196	0.263	7.635	0.357
Minimum	0.048	0.171	3.467	0.186	0.094	0.179	4.446	0.284
Maximum	0.109	0.486	9.400	0.372	0.320	0.423	10.843	0.466

Table 7. Potential ecological risk (PER) of heavy metals in soil of Gazipur, Bangladesh

Sampling Site	Potential ecological risk factors (E^i_r)						PER
	Cr	Pb	Cd	Cu	As	Ni	
Site-1	0.22	2.18	181.00	1.17	3.20	1.23	189.00
Site-2	0.12	1.55	246.00	1.39	1.28	1.12	251.46
Site-3	0.14	2.33	143.00	0.93	1.49	1.73	149.62
Site-4	0.19	0.95	217.00	1.47	1.88	2.00	223.50
Site-5	0.10	0.85	125.00	1.08	1.70	2.54	131.27
Site-6	0.13	1.17	104.00	1.00	2.21	1.57	110.07
Site-7	0.18	1.85	262.00	1.31	0.94	1.27	267.55
Site-8	0.16	1.74	173.00	1.13	2.29	1.62	179.94
Site-9	0.20	2.16	214.00	1.59	2.52	1.08	221.55
Site-10	0.21	2.43	282.00	1.86	2.09	1.62	290.21
Mean	0.17	1.72	194.70	1.29	1.96	1.58	201.42
Minimum	0.10	0.85	104.00	0.93	0.94	1.08	110.07
Maximum	0.22	2.43	282.00	1.86	3.20	2.54	290.21

highest CF value was recorded for Cd (9.400) at Site-10, likely due to industrial effluents, while the lowest CF value was observed for Cr (0.048) at Site-5. The contamination degree (CD) values for all sites ranged between 4.446 (Site-6) and 10.843 (Site-10), as presented in Table 6. These values indicate moderate to significant cumulative contamination across the study area, potentially threatening the ecological balance. The observed contamination is likely influenced by both natural (geogenic) and anthropogenic sources, such as industrial activities, fertilizer application, and waste mismanagement. Pollution load index (PLI) values ranged from 0.284 at Site-5 to 0.466 at Site-10, with a mean of 0.357 (Table 6). Although these values indicate a generally low level of pollution, the increasing industrialization in the region may lead to further soil degradation and a potential rise in PLI in the future.

The potential ecological risk indexes (PER) values for heavy metals in agricultural soils are presented in Table 7. Among the studied metals, cadmium (Cd) exhibited the highest ecological risk, with an individual risk factor (E^i_r) reaching 282.00 at Site-10. This elevated risk is likely attributed to industrial discharges and other anthropogenic activities in the area. In contrast, arsenic (As) showed a mean E^i_r of 1.96, with notable spatial variation across sampling sites. The average E^i_r values for the metals followed the descending order: Cd (194.70) > As (1.96) > Pb (1.72) > Ni (1.58) > Cu (1.29) > Cr (0.17). These results indicate that cadmium (Cd) is the dominant contributor to ecological risk among the analyzed metals. Moreover, Cd is particularly problematic due to its high bioaccumulation potential and persistence in the environment (Moni et al., 2023). Once absorbed by plants or ingested by humans, it accumulates in vital organs, especially the kidneys and liver, leading to long-term toxicity (Islam et al., 2014b). Chronic exposure to Cd is associated with serious health issues, including kidney dysfunction, bone demineralization, and increased risk of cancer (Barua et al., 2023). Thus, its mobility in soil and uptake by crops further enhances the risk of entry into the food chain, making it a critical contaminant of concern. The overall PER values ranged from 110.07 to 290.21 across the study area, indicating a considerable level of ecological risk. This pattern reflects the cumulative impact of both geogenic inputs and intensified anthropogenic pressures, particularly industrial activities prevalent in the region.

CONCLUSION

This study assessed the extent of heavy metal contamination in agricultural soils across ten industrially influenced sites in Gazipur, Bangladesh. Analysis of 30 soil samples revealed that concentrations of Cr, Pb, Cd, Cu, As, and Ni varied spatially, with several sites exceeding international soil quality standards such as those set by the Dutch and Canadian guidelines. The average concentrations of these metals followed the decreasing order: Ni > Cu > Cr > Pb > As > Cd. Among them, cadmium (Cd) posed the greatest concern, as indicated by high values of contamination factor (CF), geo-accumulation index (Igeo), and potential ecological risk index (PER). The spatial distribution of metal concentrations ranged from low to very high, highlighting localized pollution likely linked to unregulated industrial discharges. These findings emphasize the urgent need for environmental management strategies to mitigate further degradation of Gazipur's agricultural soil quality and protect surrounding ecosystems and human health. A key limitation of this study is the reliance on single-season sampling, which may not fully capture the temporal dynamics of metal contamination; therefore, future studies are recommended to incorporate multi-seasonal sampling to better understand seasonal variability and its influence on metal concentrations.

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CONFLICT OF INTERESTS

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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