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Research Article

Potential Toxic Elements in the Sediments of an Urban River Near Industrial Areas of Bangladesh: Pollution Status, Source Identification and Environmental Risk Assessment

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Abstract
Sediments of urban river near industrial regions are increasingly polluted by potential toxic elements (PTEs), posing severe impact on aquatic ecosystems and human health. This study investigated the distribution, pollution status, source identification, and ecological and human health risks of PTEs in the sediments of the Tongi Khal, a heavily industrialized urban river of Bangladesh. The concentrations of PTEs (i.e., As, Pb, Cd, Cr, Ni, Cu, Zn, Hg, Mn, and Co) were determined using ICP-MS, while the pollution status, source identification, ecological and human health implications were assessed using various established indices and multivariate statistical analyses. The results revealed that the mean concentrations of several PTEs, including Ni, Hg, Zn, Cr, Cd, and Cu surpassed the TEL level. Notably, Ni (79.71 mg/kg), Hg (1.55 mg/kg), and Zn (371.2 mg/kg) are in alarming concern, exceeding both the TEL and PEL levels. The I_{geo} values indicate that As, Pb, Cr, Hg, Co, and Mn are largely in unpolluted to moderately polluted category. Mercury (Hg) showed extremely high enrichment, with EF values ranging from 0.43 to 53.99, while Zn (2.12) showed the most substantial contamination concerning CF values, demonstrating a significant anthropogenic contribution. The composite pollution indices, such as MCD and PLI demonstrated low to moderate degree of pollution among majority of the sampling sites. The ERI values ranged from 40.738 to 940.801, indicating moderate to high ecological risks in Tongi Khal sediment. Multivariate statistical analyses, such as PCA and HCA revealed industrial effluents and urban runoff as the key sources of contamination. The HI values indicated children have higher susceptibility to non-carcinogenic risks than adults, while CR values reflected Cr and Pb as the major contributor to pose carcinogenic risks, particularly for children. This study delivers valuable insights into the extent of pollution, its sources, and the potential risks posed by PTEs in Tongi Khal, highlighting the necessity of improved environmental management strategies.

Keywords: Potentially toxic elements; Sediment pollution; Urban River: Ecological risk; Human health risk

1. Introduction

Potentially toxic elements (PTEs) are substances that can occur naturally or be introduced by humans and can adversely affect natural ecosystems and human health when their concentrations exceed safe levels [1-3]. PTEs may originate from both natural processes, such as rock weathering, and human activities, including mining, combustion of fossil fuels, application of synthetic fertilizers, vehicle emissions, construction activities, sewage runoff, and illegal dumping of solid waste [4, 5]. Release of untreated and partially treated effluents from numerous industries to nearby water body may directly contribute to increase the level of PTEs. Sediments underneath the waterbodies may function both as a repository and a potential source of PTEs. Potentially toxic elements found in urban watershed sediments pose significant risk to both the environment and public health due to their persistence and mobility [6-8]. Flooding and dredging operations can resuspend contaminated sediments, lead to the release of metals from the sediments into the water column and cause increased bioavailability [9]. This process is detrimental to the organisms in the bottom sediment, reduces biodiversity in the water, and disturbs functions of the ecosystems.

PTEs can bioaccumulate in organisms and bio-amplify in the food chain and reach humans through the consumption of fish [10-14]. Sediment contamination over the long term negatively impacts water quality, threatens urban water and recreational use and makes watershed management more complex. High levels of PTEs may cause neurological disorders, kidney and liver damage, higher cancer risks and developmental issues [15, 16]. This is particularly important for persistent, non-biodegradable and potentially harmful contaminants such as Cd, Cr, Cu, Ni, Pb, Zn, As, Hg and Mn in aquatic food chains which affect the health of the aquatic ecosystem and public health [17-20]. In Bangladesh, degradation of river network has become worsen in recent decades when the unchecked development of industrial zones around rivers in Dhaka city [21, 22]. Tongi Khal is one of the important waterways in Dhaka city, linking the major river systems in Dhaka, and is significantly impacted by the discharge pressure from nearby industrial and urban activities [23, 24]. Experimental studies revealed that bed sediments contaminated with various pollutants in Tongi Khal are able to have a great impact on water quality and release of trapped pollutants [25]. High levels of direct effluent discharge are a major long-term problem that causes changes in benthic microbial communities, which can lead to biomagnification of PTEs throughout local food webs [26]. All wastes from local factories are fed through this river and some factory wastes are discharged into the river without any pretreatment, causing serious pollution of the river [27]. Previous studies conducted on the sediments of Tong khal suggested elevated metal concentrations (Zn, Pb and Cu) and therefore, there is a need for detailed and comprehensive pollution studies coupled with source identification. Assessment of concentrations of toxic metal is critically important due to the toxicity of contaminants in sediment. These risk indices with source identification can be used to support implementation of practical measures (e.g., controlling industrial discharge, managing or removing sediments and priorities hotspots) and to support detailed river restoration work. Historical and ongoing anthropogenic waste discharge has resulted in serious ecological problems in urban river systems in Europe and Asia [28]. In China, for example, sediments in the Yihe and Yellow River basins have been heavily contaminated with highly toxic metals such as Cd, Hg, and Pb [29, 30]. Likewise, in India, the main basins are heavily polluted due to natural weathering of minerals and high concentration of industrial discharges, which is similar to the high levels of PTEs recorded [31]. Urban development along the river Ravi in Pakistan has led to mercury (Hg) and cadmium (Cd) levels reaching catastrophic levels [32]. In a regional context, Bangladesh is facing an acute problem of alarming levels of Pb, Cd and Cr in the water quality of rivers near major industrial areas like Buriganga and Korotoa which is due to untreated effluents of textile and tannery industries [33, 34]. There have been several studies before, but none have given an in-depth and integrated evaluation that incorporated a wider spectrum of toxic metals in sediment to evaluate pollution and ecological risk and their cumulative long-term effects [35, 36].

In light of this context, the current research examines the contamination of potentially toxic elements (PTE) in the sediments of Tongi Khal close to industrial zones by (i) measuring the concentrations and distribution of PTEs, (ii) evaluating the pollution levels using various sediment quality indices, (iii) determining the primary sources through statistical analysis and index-based methods, and (iv) assessing the ecological and health risks to guide management and remediation strategies for this vital urban water system. Furthermore, this research responds to the current need illustrated by the recent sediment quality assessment done within the urban watershed. The purpose of this research is to assist in developing evidence-based policies, monitoring strategies and sediment management practices in watershed areas near urban industrial facilities.

2. Materials and Methods

2.1. Study area

Tongi Khal is an important waterway located at the edge of Dhaka city, Bangladesh, with approximate coordinates 23.882029°N and 90.407102°E. The Tongi Khal runs along the Gazipur-Dhaka border, a region that has experienced rapid, often unplanned industrialization in recent years [37]. This is a key designated industrial estate where a large number of factories are concentrated, such as the Tongi BSCIC industrial area and other adjacent industrial clusters. Most of the industries are textile and dyeing (dominant), Ready-Made Garments (RMG), fabric dyeing, printing, and washing, and untreated dyes and chemicals, pharmaceutical, metal industries, packaging, printing, glass, ceramics, and food processing. The release of untreated and partially treated wastewater from these industries are directly responsible for the extreme pollution of Tongi khal water [38]. In this study, sediment samples were collected from the Tongi Khal in the winter season on March 8, 2025; where three samples were collected from each sampling point and a total of 51 samples were collected from 17 preselected locations near the industrial zone for comparative investigation. Sampling locations are shown in figure 1. The coordinates of the sampling locations are presented in Table S1.

2.2. Sediment sampling and analytical procedure

Sediment samples were collected from various locations using stainless-steel tools to prevent contamination. The primary focus was on surface sediments at 0–20 cm depth. Sampling was carried out in a grid formation across designated regions. Sediment samples were collected in clean, labeled, and air-dried plastic bags to inhibit chemical changes during transportation to the laboratory. In the lab, the collected sediment samples were first dried in the sun and then in an oven at 120°C to 130°C to eliminate any remaining moisture. The sediment samples were then passed through a 0.5 mm sieve to remove larger particles, such as stones and organic matter. The retained samples were then grinded into fines to make homogeneous. To a 50 mL digestion vessel, 0.5 g of the sediment powder was transferred, and 10 mL of concentrated nitric acid (HNO_3, 70%) was added for digestion. The mixture was heated for 30-45 minutes on a hot plate at 120°C to promote oxidation. Once cooled, 2 mL of concentrated hydrogen peroxide (H_2O_2, 30%) was added, and the heating was repeated until the solution become transparent. The digested sample was then cooled, filtered through Whatman No. 42 filter paper and made up to 10 mL with deionized water. Later, the solutions obtained were analyzed by ICP–

MS for potentially toxic elements.

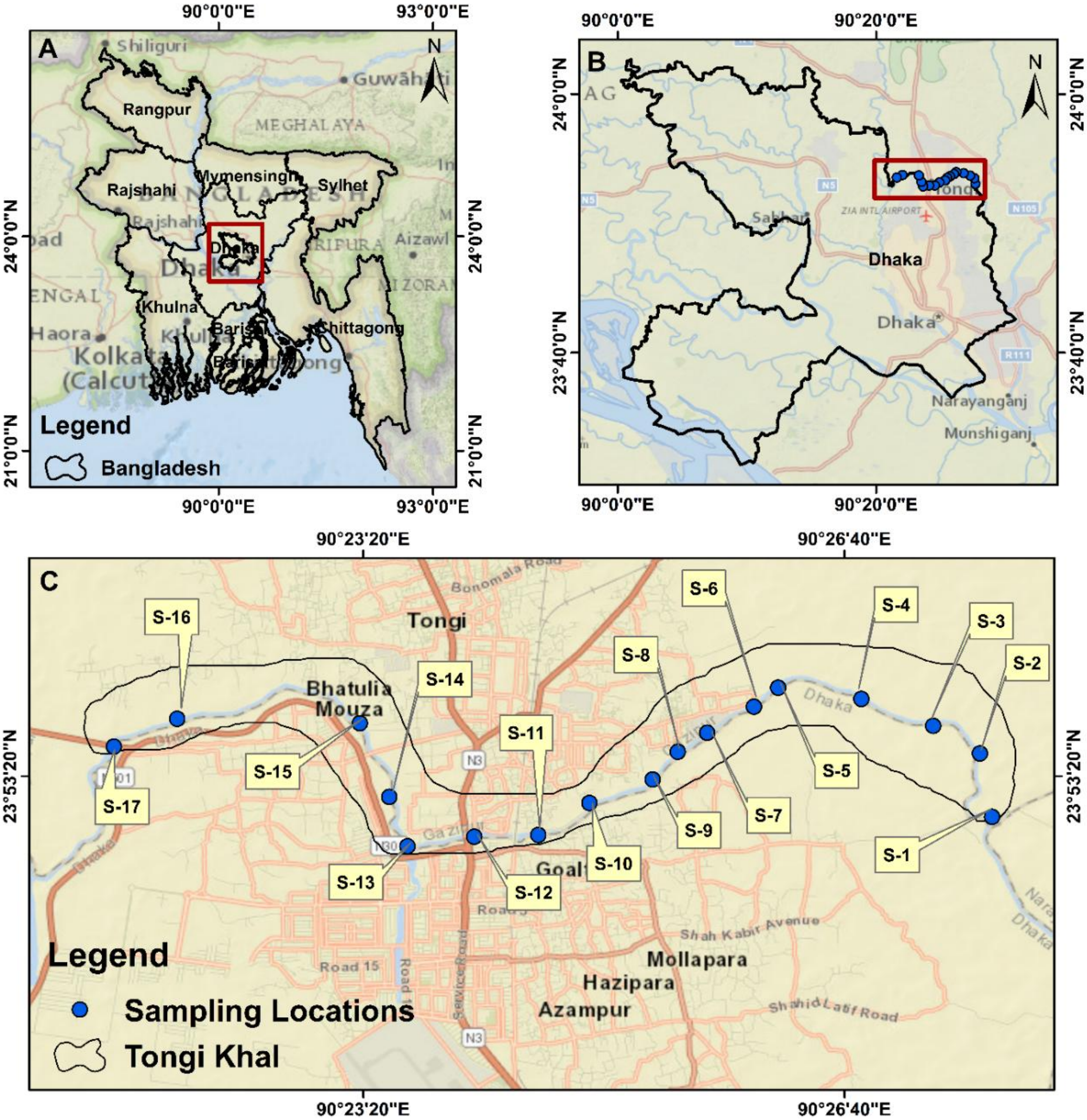


Figure 1. Location of the study area and sediment sampling stations along Tongi Khal, Bangladesh. Panel (A) shows the geographical position of Bangladesh; Panel (B) presents the location of Tongi Khal within the Dhaka-Gazipur region; and Panel (C) illustrates the spatial distribution of the seventeen sediment sampling stations (S1–S17).

2.3. Quality assurance and quality control

Quality assurance and quality control (QA/QC) guidelines were followed to ensure the reliability and validity of sediment samples from the lab. Care was taken to prevent contamination, as all sample containers and equipment were pre-cleaned with a 10% nitric acid and then thoroughly rinsed with deionized water. Reagent blanks, procedural blanks, and duplicate samples were analyzed in each batch to assess background contamination and the consistency of the results. Certified reference materials (CRMs) for sediment matrices were measured together with the samples to validate the accuracy of elemental quantification. Recovery for all target elements ranged from 85% to 115%. Standard solutions containing multiple elements were used to calibrate the instruments. The calibration curves demonstrated excellent linearity ($R^2 > 0.999$). MDLs were set for each element and verified to be lower than the concentrations expected in environmental samples. Standard methods of the APHA (2023) and USEPA (Method 3051A for sediments) were followed in the analyses [39, 40]. ICP-MS measurements were corrected for instrumental drift and matrix effects using internal standards.

Geo-accumulation Index (I_{geo})

The geo-accumulation index serves as an effective approach for evaluating metal contamination in sediments. This method was originally proposed by Muller (1969) and was determined using the following equation [41].

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

In this context, C_n represents the metal concentration in sediment samples from the studied region, while B_n denotes the background metal concentration and the figure of 1.5 includes adjustments for the background matrix due to erosion and associated processes. Since all the sampling sites are potentially affected by anthropogenic inputs, reliable site-specific background values could not be established from the collected samples. Therefore, background concentrations of the studied heavy metals were adopted from previously published Bangladesh sediment baseline studies and regional geochemical reference values reported by Kubra et al. [42] and Rahman et al. [43]. The background concentrations for Cr, As, Se, Hg, Pb, Cd, Mn, Cu, Zn, Ni, and Co are 90, 15, 2, 0.4, 70, 1, 850, 50, 175, 68, and 25, respectively [42, 43]. The geo-accumulation index can be divided into seven categories or classes: (i) $I_{geo} > 5$ indicate extreme metal accumulation, (ii) $I_{geo} = 4–5$ indicate strong to extreme accumulation, (iii) $I_{geo} = 3–4$ indicate strong accumulation, (iv) $I_{geo} = 2–3$ indicate moderate to substantial accumulation, (v) $I_{geo} = 1–2$ indicate moderate accumulation, (vi) $I_{geo} = 0–1$ indicate no accumulation to moderate accumulation, and (vii) $I_{geo} < 0$ indicate practically no metal accumulation or pollution [44].

2.4. Enrichment Factor (EF)

The enrichment factor serves as an effective means for evaluating the degree of metal enrichment or determining if a specific pollutant comes from natural or human activities. The EF can be calculated using the following equation [45]:

$$EF = \frac{C_n/C_{ref}}{B_n/B_{ref}} \qquad (2)$$

Where, C_n represents the amount of metal present in the sediment sample, whereas C_{ref} denotes the quantity of the reference element in the same sediment sample. Manganese (Mn) was used as a reference element in our study, as suggested by Barbieri et al. [46]. Bn indicates the background concentration of the metal under investigation, whereas B_{ref} indicates the background concentration of the reference element. The enrichment factor (EF) aids in identifying the sources, where (i) EF < 2 implies a natural crustal source, (ii) EF > 2 indicates a likely anthropogenic source, and (iii) EF > 10 suggests a wholly anthropogenic source. Again, based on the enrichment nature of metals, few researchers categorized EF into five primary grades: (i) EF < 2 indicate minimum enrichment, (ii) EF = 2 to 5 indicate moderate enrichment, (iii) EF = 5 to 20 indicate significant enrichment, (iv) EF = 20 to 40 indicate high enrichment, and (v) very high enrichment is indicated when EF exceeds 40.

2.5. Contamination Factor (CF)

The contamination factor (CF) was used to assess the level of metal pollution in sediment samples. The observed concentration of harmful metal in the sediment at each sampling location was compared to its associated background or reference concentration. The CF method was originally proposed by Håkanson for assessing sediment pollution. The contamination level for each metal was assessed using the equation provided below:

$$CF_i = \frac{C_i}{B_i} \qquad (3)$$

Where, CF_i denotes the contamination factor for metal i, C_i denotes the measured concentration of metal i in sediment samples, typically in mg/kg of dry weight, and B_i is the background or reference concentration of metal i, also usually expressed in mg/kg of dry weight. Based on the calculated CF values, sediment contamination was classified as low contamination when CF<1, moderate contamination when 1≤CF<3, considerable contamination when 3 ≤ CF < 6, and very high contamination when CF ≥ 6 [47].

2.6. Modified Degree of Contamination (MCD)

The level of contamination serves as a complex tool that provides a deeper insight into the cumulative effects of pollutants on overall sediment pollution. MCD is obtained by dividing the degree of contamination by the total number of pollutants [48, 49].

$$MCD = \frac{CD}{n} \qquad (4)$$

Where, CD refers to the degree of contamination, whereas n signifies the overall number of toxic metals analyzed in the study. The contamination level based on MCD can be categorized as follows: (i) MCD ≤ 1.5 indicates no contamination, (ii) 1.5 ≤ MCD < 2 indicates low contamination, (iii) 2 ≤ MCD < 4 indicates moderate contamination, (iv) 4 ≤ MCD < 8 indicates high contamination, (v) 8 ≤ MCD indicates extremely high contamination [50].

2.7. Pollution Load Index (PLI)

The pollution load index (PLI) has been developed by Tomlinson et al. [51] to indicate overall heavy-metal pollution load in sediment samples. The n-contamination factors for heavy metals are calculated for each metal and a PLI is determined as the n-th root of those n-contamination factors.

$$PLI = \sqrt[n]{(CF_1 \times CF_2 \times CF_3 \ldots\ldots\ldots\ldots \times CF_n)} \qquad (5)$$

Here, CFn refers to the contamination factor associated with the nth metal, where n is the number of the heavy metals studied (n=10 for us). Pollution load index (PLI) values < 1 mean no pollution load, PLI = 1 means only baseline pollutants are present, and PLI values > 1 mean that the sediment quality is significantly degraded [51].

2.8. Ecological Risk Index (ERI)

The Ecology Risk Index (ERI) was used to assess the ecological risk of sediment in the study area. The ERI assesses the potential ecological threats linked to particular PTEs. The ERI was created to calculate the ecological impacts of following the methods outlined in equations (6) and (7).

$$ERI = \sum RI = \sum T_i \times PI \qquad (6)$$

$$PI = \frac{\boldsymbol{C_s}}{\boldsymbol{C_b}} \qquad (7)$$

In this context, the T_i represents the toxic-responsiveness factor of each PTE and the PI represents the pollution index.

C_s refers to the concentration of PTEs detected in the sediment sample and C_b refers to the background concentration of PTEs. The ERI value is an indication that <150 is a low ecological risk, 150 < ERI <300 is a moderate ecological risk, 300 < ERI <600 represents considerable ecological risk and ERI >600 is very high ecological risk.

2.9. Source identification

In this study, multivariate statistical methods were applied to identify the unique sources of potentially toxic elements (PTEs) in the sediment of Tongi Khal, using principal component analysis (PCA) in SPSS (Version 23.0 for Windows). The principal components were selected when the percentage of the total variance exceeded 80% to ensure the majority of the variance in the data was accounted. Furthermore, this study employed Hierarchical cluster analysis (HCA) to uncover patterns associated with spatial distribution and sources.

2.10. Human health risk assessment

The health risks associated with the exposure of PTEs from sediment can be assessed using the daily metal dose (DMD), non-carcinogenic target hazard quotient (THQ), hazard index (HI), and total/lifetime carcinogenic risk (LCR) coefficients for both adults and children [52]. As stated by Edokpayi et al. (2018), there are two primary routes of human exposure to PTEs risk: direct ingestion and skin absorption through dermal contact. These exposure routes are typically assessed for sediment (ingestion and dermal absorption) [52].

2.11. Non-Carcinogenic Risk Assessment

The human health risk model developed by the United States Environmental Protection Agency (USEPA, 2010) was employed to appraise the degree of human exposure by PTEs. Most generally, both children and adults are susceptible because of their ingestion or dermal contact with toxic PTEs. The daily metal dose (DMD) was employed to assess exposure to potentially toxic elements (PTEs) via ingestion (DMD_{ing}) and dermal contact (DMD_{der}) with sediment. Predictions were generated using equations (10) and (11).

$$DMD_{ing} = \frac{C \times IR \times EF \times ED}{BW \times AT} \qquad (8)$$

$$DMD_{der} = \frac{C \times SA \times Kp \times ET \times ED \times EF \times CF \times ABS}{BW \times AT} \qquad (9)$$

HQ and HI were utilized to evaluate the toxic risk that is non-carcinogenic. The HQ was calculated as the ratio of the DMI to the reference dose (RfD) for a single PTE. All the particular PTEs sum HI values were designed to assess total non-carcinogenic risks in sediment. The HQ_{ing}, HQ_{der}, and HI of all the PTEs found in sediment could be anticipated using Equations (12–14).

$$HQ_{ing} = \frac{DMD_{ing}}{RfD_{ing}} \qquad (10)$$

$$HQ_{der} = \frac{DMD_{der}}{RfD_{der}} \qquad (11)$$

$$HI = \sum HQ = \sum \frac{DMD}{RfD} \qquad (12)$$

In this context, DMI refers to the mean daily amount of exposure through the skin. The RfDs represent the reference dosages for certain potentially toxic elements regarding dermal exposure. All non-carcinogenic risk RfD values for both paths are provided by the USDOE (USDOE, 2011). HQ and HI values greater than 1 have been classified as non-carcinogenic threats to human health for those exposed, whereas values less than 1 are deemed as improbable risks.

2.12. Carcinogenic Risk Assessment

The carcinogenic risk (CR) was used to assess the cancer risk associated with hazardous PTEs. The CR value reflects the probability of an individual developing cancer if their lifetime exposure to carcinogenic toxic agents increases. The CR was calculated for PTEs (Cr, Cd, Pb, Ni and others) in the present study, based on their observed corresponding DMD and available cancer slope factor (CSF) values.
The CR for two exposure pathways were calculated by using Equations (15) and (16) [53]:

$$CR_{ing} = DMD_{ing} \times CSF \qquad (13)$$

$$CR_{der} = DMD_{der} \times CSF \qquad (14)$$

Where, CSF is the cancer slope factor (per mg/kg-day). In general, the carcinogenic risk is unacceptable if the CR values exceed ($>10^{-4}$), while CR values ($1\times10^{-6} < CR < 1\times10^{-4}$) are assumed to be acceptable with no carcinogenic risk [54], whereas the CR values ($<10^{-6}$) imply that the carcinogenic risk can be negligible (USEPA, 2010).

2.13. Statistical analysis

The source and spread of PTEs within the sediment were evaluated statistically using the R program, while additional descriptive statistics were conducted using Microsoft Excel 2021. For mapping the study area of PTEs, Arc GIS 10 software was utilized.

3. Results and discussion

3.1. Assessment of physicochemical parameters of water

The physicochemical parameters, including pH, dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), and salinity at different sampling locations in Tongi Khal, are presented in table 1. The pH range observed was 7.73-9.49, with an average of 8.24. Dissolved oxygen (DO) was ranged from 0.31 to 3.21 mg/L, and most samples had low DO levels, as per the Bangladesh standard ECR, 2023 [55]. The lowest value of dissolved oxygen (DO) was detected due to increased organic pollution, leading to high microbial activity and others factors like sewage discharge, industrial effluents, and urban waste disposal decrease DO levels [56]. The electric conductivity (EC) values were observed minimum of 1191 µs/cm and maximum of 2290 µs/cm with an average value 1573.65 µs/cm.

Table 1. Distribution of physico-chemical parameters in various sampling sites of Tongi Khal.

Sampling Sites	pH	DO (mg/L)	EC (µs/cm)	TDS (mg/L)	Salinity (mg/L)
S1	8.11	1.97	1730	821	821
S2	8	0.71	1641	780	780
S3	7.93	0.7	1618	770	770
S4	8.07	0.75	1726	822	822
S5	7.88	0.5	1613	763	763
S6	9.49	0.68	2290	1104	1104
S7	9.09	0.6	2090	1002	1002
S8	8.43	0.58	1907	912	912
S9	8.67	0.35	1644	783	783
S10	8.12	0.48	1530	726	726
S11	7.74	1.47	1216	571	571
S12	7.73	0.31	1191	560	560
S13	7.87	3.21	1204	566	566
S14	8.14	1.13	1271	599	599
S15	8.28	0.97	1322	624	624
S16	8.33	0.78	1427	675	675
S17	8.25	0.76	1332	631	631
Max	9.49	3.21	2290	1104	1104
Min	7.73	0.31	1191	560	560
Average	8.24	0.94	1573.65	747.59	748

Table 2. Distribution of the concentration of PTEs in sediment samples (mg/kg) of Tongi Khal.

Sample ID	As (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Ni (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Hg (mg/kg)	Mn (mg/kg)	Co (mg/kg)
S1	4.379	54.600	3.525	96.804	406.808	172.852	1140.247	3.849	611.577	8.897
S2	2.579	23.168	1.124	35.483	267.675	55.752	395.126	2.957	240.611	6.451
S3	4.946	33.786	1.850	60.177	48.399	105.178	283.743	2.663	302.185	9.430
S4	6.046	40.376	2.287	80.287	181.514	129.332	579.839	2.086	368.199	10.168
S5	4.659	34.803	1.970	64.428	50.889	103.561	298.587	2.160	339.303	8.807
S6	2.445	18.174	0.410	34.526	51.475	45.593	220.387	1.498	169.422	5.530
S7	4.070	29.265	1.542	92.626	52.968	153.474	432.842	1.489	408.929	8.287
S8	4.986	32.057	1.634	46.563	44.728	120.718	276.737	1.407	384.631	8.539
S9	3.348	38.357	1.407	40.536	43.925	161.293	1001.920	1.110	298.688	6.839
S10	2.128	22.078	0.622	21.047	66.496	46.827	316.169	0.031	160.000	4.283
S11	1.270	17.237	0.320	10.990	33.745	19.411	299.456	1.229	75.579	2.821
S12	2.531	16.315	0.776	35.778	15.058	49.571	355.258	1.251	788.173	3.752
S13	2.934	14.643	0.178	18.056	19.065	17.341	118.306	1.054	326.487	8.168
S14	1.338	9.325	0.390	12.946	14.361	10.423	161.686	0.977	146.307	4.537
S15	0.934	13.513	0.110	8.458	9.022	5.024	121.860	0.963	54.906	2.234
S16	1.601	8.525	0.100	17.071	12.347	13.168	99.379	0.859	161.096	5.229
S17	3.930	21.269	1.060	39.041	36.619	41.080	208.861	0.902	319.028	10.248
Mean	3.184	25.147	1.136	42.048	79.711	73.565	371.200	1.558	303.242	6.719
Max	6.046	54.60	3.525	96.804	406.81	172.852	1140.247	3.849	788.173	10.248
Min	0.934	8.525	0.100	8.458	9.022	5.024	99.379	0.031	54.906	2.234
SD	1.514	12.491	0.933	28.061	107.332	57.578	291.593	0.925	186.252	2.588
TEL	5.9	35	0.59	37.3	18	35.7	123	0.174	460	20
PEL	17	91.3	3.53	90	36	97	315	0.486	-	-
SEL	33	250	10	110	75	110	820	2	1100	-

Note: TEL = Threshold Effect Level; PEL = Probable Effect Level; SEL = Severe Effect Level

The lowest value of electrical conductivity (EC) in water was observed due to low concentrations of dissolved ions such as salts, minerals, and metals [57]. Industrial or agricultural effluent discharge and urban runoff can reduce ion presence, which play important role to lower EC levels. The mean value of total dissolved solid (TDS) was observed 747.59 mg/L. Total dissolved solids (TDS) in water is due to inorganic salts and organic matter which can be happened from heavy rainfall, upstream freshwater inflow, or anthropogenic activities such as sewage, and agricultural runoff [58]. The value of salinity was in the range of 560 mg/L to 1104 mg/L.

3.2. Distribution of PTEs concentration in sediment

Sediment samples collected from the Tongi Khal were analyzed for various potential toxic elements (PTEs), including arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), mercury (Hg), manganese (Mn), and cobalt (Co). The concentrations of these elements were compared against established environmental thresholds such as the United States Environmental Protection Agency (USEPA) Toxicity Reference Values (TRV), Threshold Effect Level (TEL), and Probable Effect Level (PEL) (Table 2). The concentration of arsenic (As) in the sediment samples were ranged from 2.58 to 6.05 mg/kg, with an average of 4.38 mg/kg. The USEPA TRV noted that concentrations less than 5.5 mg/kg are safe, but higher concentrations could pose an ecological risk. All the As concentrations were within the acceptable range, suggesting that there was little risk to aquatic life. Levels of Lead (Pb) were ranged from 23.17 to 54.60 mg/kg, with a mean of 40.38 mg/kg. Several samples were above the threshold effect level (TEL) of 35.0 mg/kg and a few samples were close to the psychometric effect level (PEL) of 50.0 mg/kg, indicating moderate to high toxicity threats, primarily for benthic organisms and other aquatic species. The concentration of cadmium (Cd) varied from 1.12 to 3.53 mg/kg with an average of 2.35 mg/kg. The TEL for Cd is 1.0 mg/kg, and the PEL is 4.0 mg/kg. The concentrations of chromium in the samples exceeded the threshold set which is 50 mg/kg, suggesting high level of contamination in the river and its associated ecological risk. The range of concentration of Ni was from 48.40 to 406.81 mg/kg with an average of 172.85 mg/kg. The TEL and PEL for Nickel (Ni) are 30.0 and 50.0 mg/kg respectively. More than 50% of the samples exceeded the TEL and some even exceeded or met the PEL, signifying increased ecological risk in the river. The Cu concentrations in the sediment ranged from 55.75 mg/kg to 172.85 mg/kg with an average value of 105.18 mg/kg, which is well above the TEL (35.0 mg/kg) and approaching the PEL (40.0 mg/kg) for sediment, thus implying potential high threat to aquatic organisms, especially those at the bottom of the food chain. Levels of Zn ranged from 283.74 to 1140.25 mg/kg, with a mean value of 579.84 mg/kg. The Probable Effect Level (PEL) and Threshold Effect Level (TEL) of Zn are 180.0 mg/kg and 120.0 mg/kg, respectively and a large number of samples exceeded the PEL, indicating the elevated level of Zn is a moderate risk to aquatic organisms. The concentration of mercury (Hg) ranged from 2.09 to 3.85 mg/kg, which had an average of 2.66 mg/kg. The TEL for mercury is 0.13 mg/kg, and the PEL is 0.70 mg/kg, with several samples exceeding the TEL, suggesting possible risks, especially given the bio-accumulative properties of mercury. The concentrations of manganese (Mn) in the samples ranged from 240.61 to 611.58 mg/kg with an average of 368.20 mg/kg, which is above the PEL of 50.0 mg/kg, suggesting high contamination and risk. The concentration of cobalt (Co) ranged from 6.45 to 10.17 mg/kg, that is within the acceptable range limit for aquatic organisms, with the average of 8.90 mg/kg. The concentrations of different potentially toxic elements (PTEs) such as Pb, Cd, Cr, Ni, Cu, Zn and Hg in the sediments of the Tongi Khal are exceeding environmental threshold values, thus, there is a moderate to high ecological toxicity risk.

3.3. Assessment of pollution indices of sediment

To evaluate the extent of sediment contamination and anthropogenic enrichment, the distributions of geo-accumulation index (I_{geo}) and enrichment factor (EF) values for all studied PTEs are presented in figure 2. The I_{geo} values for the sediment at Tongi Khal are also relatively low, most of the values being less than –3.0 (As to less than –2.03 (Cr)) indicating relatively low pollution levels. Cd and Ni values are showing high variability of –3.90 to 1.23 (mean –1.02) and –3.50 to 2.00 (mean –1.20), respectively, indicating the presence of localized moderate enrichment. The levels of Cu and Zn are the highest, 2.12 (mean 0.17) and 3.68 (mean 1.98), respectively, and are found to be moderately to strongly polluted. For most metals, minimal contamination was observed during Winter, and the hotspots of anthropogenic enrichment in Tongi Khal in Figure 2(a) are represented by Zn and Cu. Similar I_{geo} patterns for Cu, Cr, Hg, and Zn have been reported in industrially contaminated sediments of Bangladesh, where untreated industrial effluent and urban wastewater were identified as major contributors to sediment contamination [59].

The enrichment factor (EF) values of PTEs have significant variation among the studied PTEs, as seen in figure 2(b), which reflects their varying anthropogenic impacts on Tongi Khal. The mean EF values follow the order Hg (21.85) > Zn (5.95) > Cu (4.13) > Ni (3.29) > Cd (3.19) > Cr (1.31) > Pb (1.01) > Mn (1.00) > Co (0.75) > As (0.60), suggesting that mercury (Hg) is the most enriched element in the study area. High enrichment (0.43, 53.99) was observed for mercury (Hg) showing high anthropogenic contamination and ecological concern (Maulana et al., 2023). Zinc (Zn) and copper (Cu) are highly enriched, with maximum EF values of 18.28 and 9.70 respectively, indicating significant anthropogenic inputs such as industrial discharge, urban runoff and agricultural activities. There was moderate to significant enrichment of Ni (16.78) and Cd (9.89) which was a result of both natural and anthropogenic sources. The mean EF value ranges from relatively low to moderate in the case of chromium (Cr), lead (Pb), and manganese (Mn) indicating slight anthropogenic enrichment and the potential for natural geochemical sources to be a dominant factor. The EF values for arsenic (As) and cobalt (Co) are generally low (mostly less than 1), which suggests that the enrichment is low and the source is mainly lithogenic. Based on the EF results, it is assumed that the major pollutants causing the pollution of the sediments in the studied area are: Hg, Zn, Cu, Ni and Cd, with mercury being the most critical environmental threat. Bhuiyan et al. [60] observed substantially higher enrichment of the heavy metals, particularly Cr, Pb, and Zn, in the heavily industrialized Buriganga River sediments, indicating stronger anthropogenic pressure than the present study area [60]. In contrast, Acharjee et al. [61] reported relatively lower enrichment factors for most heavy metals in the Surma River sediments, suggesting comparatively lower industrial influence in that aquatic system.

The contamination status of individual metals was further assessed using the contamination factor (CF), and the results are illustrated in figure 3(a). The mean CF values of the elements did not exceed 1 (low contamination) for As, Pb, Cr, Co, and Mn. The mean CF values of these metals were between 0.21 (As) and 0.47 (Cr) and the maximum values were below or close to 1.08, indicating that the concentrations of these metals were mainly controlled by natural geochemical processes and are low in terms of anthropogenic contribution. Some sampling sites were significantly contaminated as evidenced by the maximum CF of Cd (3.53), Ni (5.98), and Cu (3.46). The metals Zn and Hg had the highest contamination rates when compared to all other metals analyzed. The mean CF value for Zn was 2.12 and the maximum was 6.52, this suggests moderate contamination. The highest contamination among all metals was found for Hg, a mean CF value of 7.79 and CF values ranging from 0.15 to 19.25, indicating very high contamination. There is a significant anthropogenic influence, possibly due to industrial effluents, metal processing, waste disposal, or other anthropogenic sources, with the extremely high levels of Hg. According to the CF, the contaminant that was most abundant in the sediment collected in the winter was Hg followed by Zn, Cu, Ni and Cd, while As, Pb, Cr, Co and Mn were low as shown in figure 3(a).

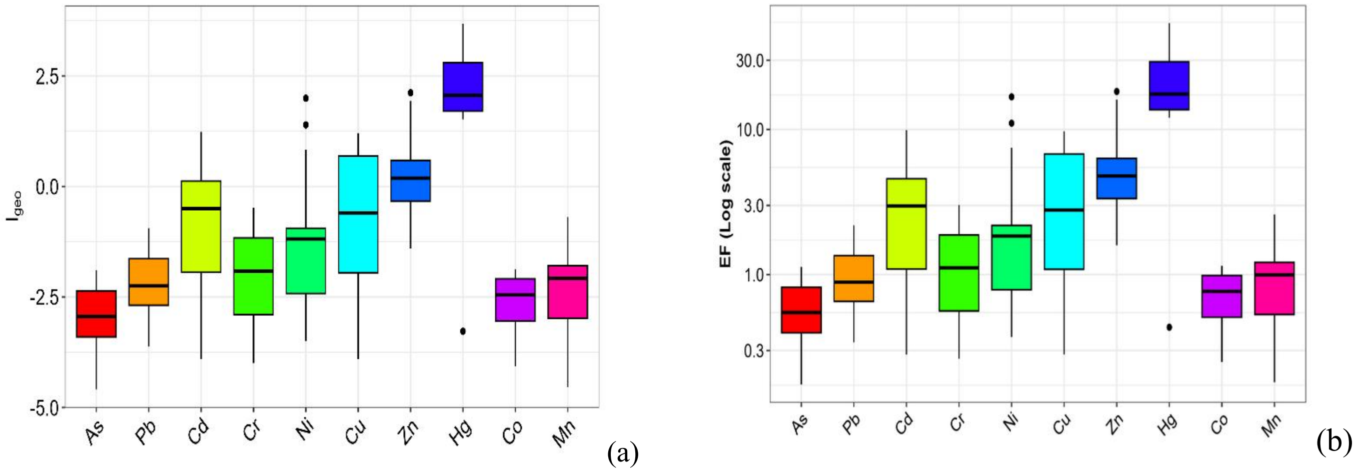


Figure 2. Boxplot of (a) geo-accumulation index (I_{geo}) and (b) enrichment factor (EF) values potentially toxic elements (PTEs) in Tongi Khal sediments.

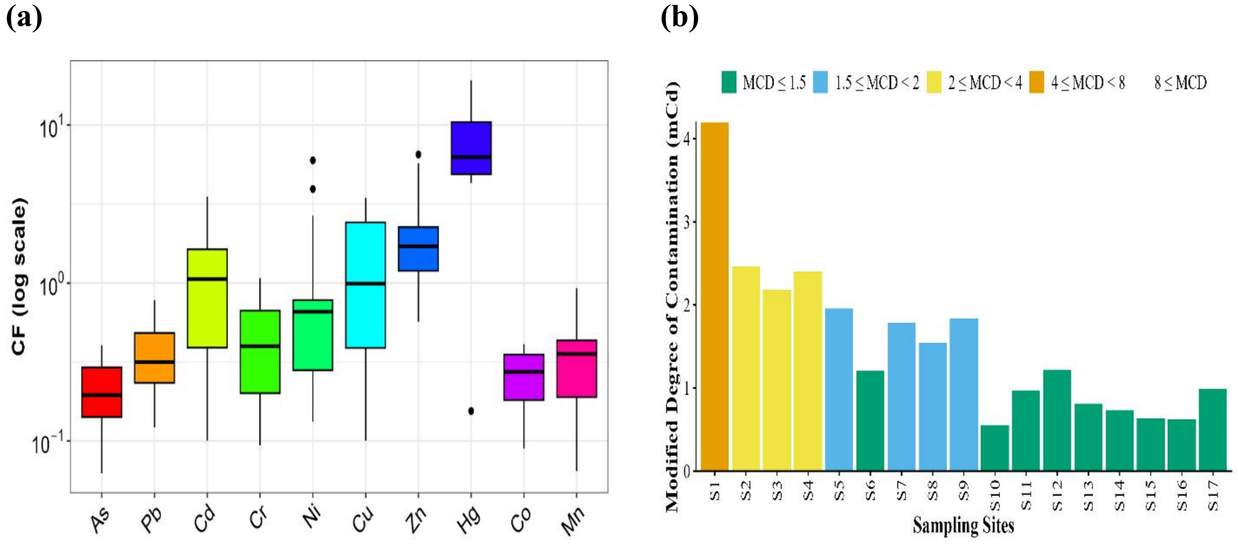
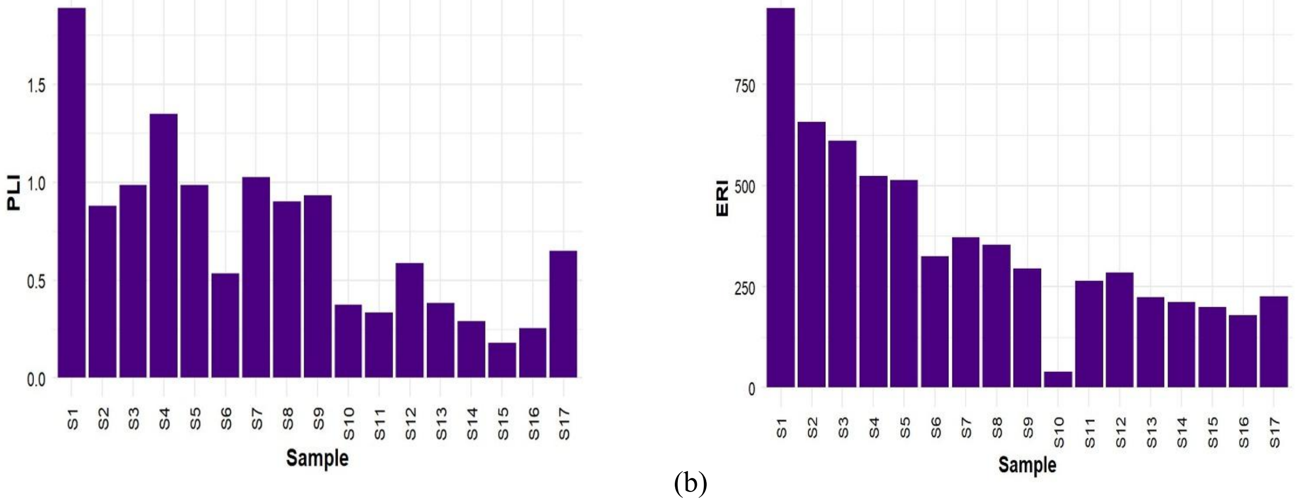


Figure 3. Distribution of (a) Boxplot of Contamination factor (CF) values and (b) Modified degree of contamination (MCD) values for PTEs in Tongi Khal sediments.



(a)

(b)

Figure 4. Spatial variation of (a) Pollution Load Index (PLI) and (b) Ecological Risk Index (ERI) across sediment sampling sites in Tongi Khal.

MCD value for S1 was the highest (4.19) and was classified as high contamination, indicates high anthropogenic influence, high accumulation of heavy metals at S1 among all the sampling sites. Contamination levels were moderate at S2 (2.47), S3 (2.18), and S4 (2.40), suggesting that there are some degree of metal enrichment, possibly linked to urban activities, industry, traffic emissions, or other anthropogenic sources in figure 3(b). S5 (1.96), S7 (1.78), S8 (1.54), and S9 (1.84) indicated low levels of contamination but with metals still present. The other sites (S6, S10, S11, S12, S13, S14, S15, S16 and S17) showed MCD values of less than 1.5, which suggested relatively safer environmental conditions in these areas as no significant contamination was found. The majority of sampling locations were either uncontaminated or somewhat contaminated, while a small number showed moderate to high contamination.

The overall pollution status due to the synergistic effect of PTEs and ecological risk associated with sediment contamination were evaluated using PLI and ERI, respectively (Figure 4). Pollution load index (PLI) values over the winter sediments in the Tongi khal were clearly different from one spot to another, suggesting the presence of specific zones of high contamination. Pollution levels are generally low (most samples with PLI < 1), however, a number of locations have relatively high PLI values, including S1 (1.89), S4 (1.35), S7 (1.02) and S3 (0.98, near threshold). This indicates a patchy distribution of contamination sources and indicates that they are likely related to point-source discharges, as shown in figure 4(a). Similar PLI patterns have been reported by Hassan et al. [59], where low to moderate pollution indicated in Hatirjheel Lake. Rahman et al. [43] reported all the sampling sites in Dhaleshwari River had a low degree of pollution based on PLI assessment. In contrast Islam et al. [62] reported majority of the sampling sites in Buriganga River under high degree of pollution category.

ERI values have a large variation among the sampling sites with values ranging from 40.738 to 940.801. S1 (940.801) showed very high ecological risk, followed by S2 (658.458) and S3 (613.158), which also indicate very high-risk levels. S4 (526.628) and S5 (516.007) fall under considerable ecological risk, while S6 (326.553), S7 (374.714), and S8 (356.207) also indicate considerable risk. Most remaining samples, including S9 (296.958), S11 (264.535), and S12 (286.937), show moderate ecological risk. On the other hand, S10 (40.738) is the ecological risk category of low, which indicates relatively favorable ecological conditions. As indicated in figure 4(b), majority of the sampling sites are under moderate to very high ecological risk. The results from the PLI and ERI indicate that there is a high pollution pressure and ecological threat at upper and mid-reach stations and these levels are lower at downstream stations. The pattern is indicative of high anthropogenic influence from the industrial and municipal effluents into the Tongi khal in the winter season. Rahman et al. [43] observed relatively lower ecological risk levels in Dhaleshwari River sediments; Islam et al. [62], however, reported that a majority of sediment samples from the Buriganga River exhibited high ecological risk owing to severe industrial pollution.

3.4 Source Identification of PTEs

Pearson correlation analysis

Pearson's correlation matrix of physicochemical parameters and PTEs of the sediment samples collected from Tongi Khal shows the significant correlation among the physicochemical parameters and PTEs which suggests common sources and geochemical behaviour of the PTEs (Figure 5). There is very high positive correlation among Electrical conductivity (EC), Total dissolved solids (TDS) and Salinity (r = 0.78–1.00, $p < 0.001$), indicating these three variables are closely related, and are controlled by the concentration of dissolved ions in sediments. The pH, however, has weak mostly negative correlations with most heavy metals, which indicate that metal accumulation in the study area is influenced by pH to a lesser extent. Positive correlations are seen among various toxic elements and are thought to represent common anthropogenic sources for some elements. The high correlations with Cd ($r = 0.96$, $p < 0.001$), Cr ($r = 0.92$, $p < 0.001$) and Cu ($r = 0.85$, $p < 0.001$) indicate that these metals may be from similar industrial or urban discharge sources [63].

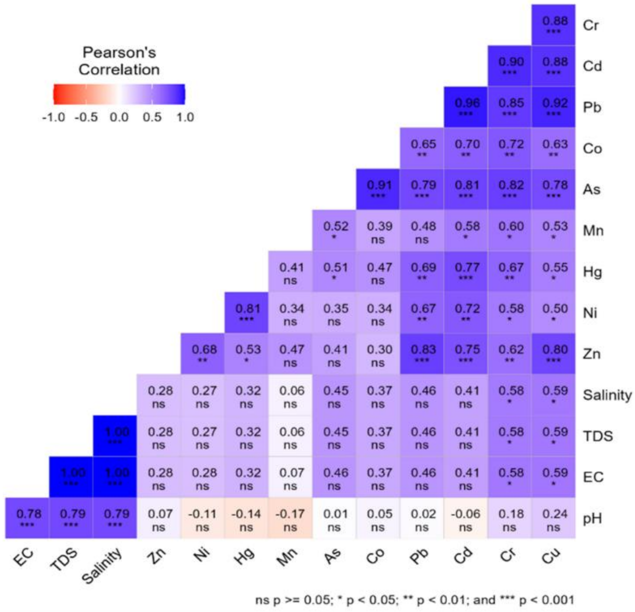
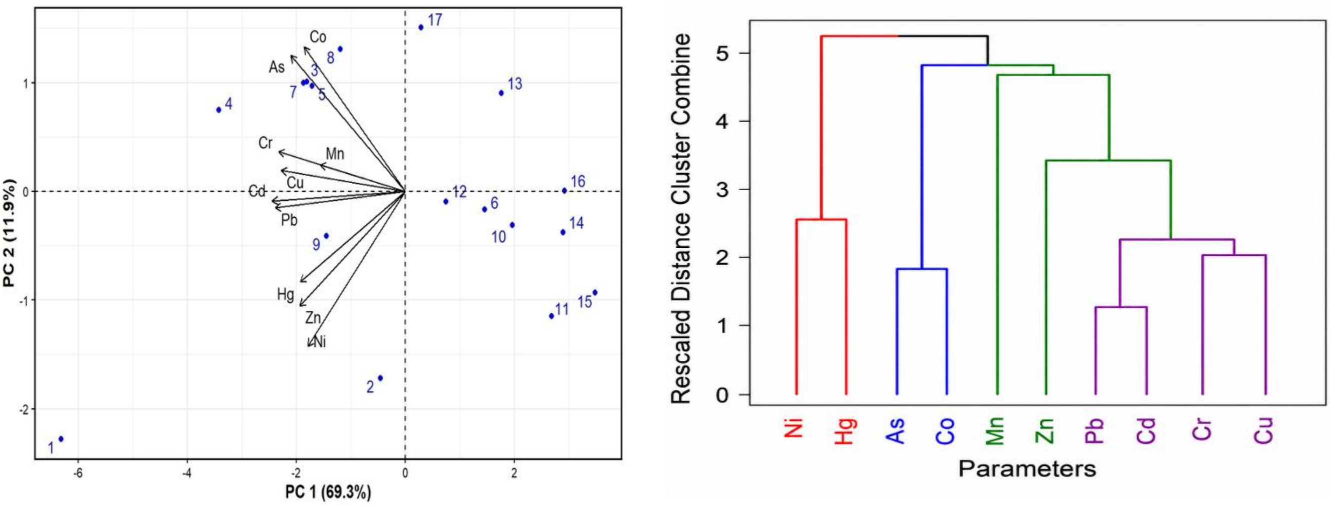


Figure 5. Pearson's correlation matrix showing relationships among physicochemical parameters and PTEs.

The result of Cadmium and Chromium shows a strong correlation with each other ($r = 0.88$, $p < 0.001$) which also indicates that they share the same source. Arsenic (As) shows strong correlation with cobalt (Co) ($r = 0.91$, $p < 0.001$), cadmium ($r = 0.81$, $p < 0.001$) and chromium ($r = 0.82$, $p < 0.001$), suggesting possible co-transport and similar source of contamination. Zinc (Zn) shows strong positive correlations with lead ($r = 0.83$, $p < 0.001$), cadmium ($r = 0.75$, $p < 0.001$), and copper ($r = 0.80$, $p < 0.001$), suggesting industrial or mixed anthropogenic sources. There are moderate to strong positive relationships between several metals including nickel (Ni) and mercury (Hg), suggesting partial commonality in sources of contamination [64]. The correlations of manganese (Mn) with most metals are smaller, indicating a combination of lithogenic and anthropogenic sources.

PCA results of the sediment-metal data from Tongi Khal shows that the major component is PC1 which accounts for 69.25% of the total variance. PC1 has high positive loadings for almost all metals especially Cd (0.979), Pb (0.955), Cr (0.930), Cu (0.912), As (0.840), Zn (0.774), Hg (0.771), Ni (0.717), and Co (0.743). This pattern suggests a high common source, possibly industrial effluents, electroplating, battery waste, and metal processing, in which several metals are impacted at a time [65]. The results of PC1 reveal the overall pollution intensity of Tongi Khal. The variance of 11.92% is explained by PC2 which separates metals into contrasting groups. Trace elements with positive loadings (Ni 0.571, Zn 0.423 and Hg 0.333) represent a combination of industrial and municipal/domestic waste, and negative loadings for As (–0.500) and Co (–0.532) suggest another geochemical pattern or minor sources. Figure 6(a) may then be interpreted as secondary pollution pathways or geochemical variations associated with sediments. PC3 has a high positive loading of the element Mn (0.527) and a moderate positive loading of the element Zn (0.321). The source of this component is presumably natural geochemical sources, particularly Mn-bearing minerals and weathering, and a small anthropogenic contribution of Zn. PC4 (6.25%) is also predominantly influenced by Mn (0.563), and moderately by Hg (0.285) and Ni (0.139) indicating variation in redox sensitive elements and/or local sediment conditions (Table S2). The PCA results show that industrial pollution is the most significant factor in metal deposition in Tongi Khal sediments (PC1), whereas PC2–PC4 account for minor variations in response to a mixture of anthropogenic, natural and sediment geochemical factors.



(a) (b)

Figure 6. (a) Principal Component Analysis (PCA) and (b) Hierarchical cluster Dendrogram of PTEs in winter-season sediment samples showing the distribution of metals across major principal components.

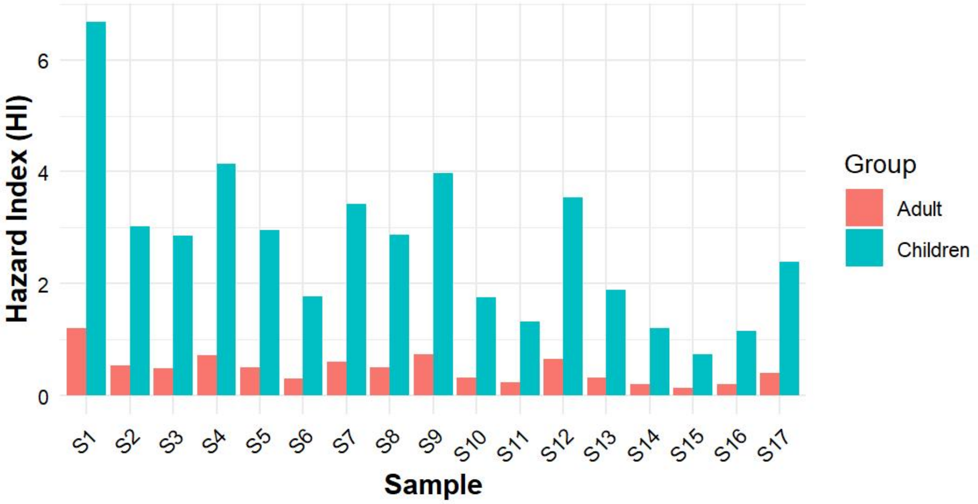


Figure 7. Comparison of non-carcinogenic health risk (Hazard Index, HI) values for adults and children across the sampling sites.

The Dendrogram of the metals from sediment of Tongi Khal shows the formation of three distinct clusters, which indicate the variations in the sources and geochemical behaviour of these metals. The first cluster includes Ni and Hg that are grouped together, suggesting similar sources, likely from a more minor or different source than the other metals, such as mixed low level pollution or atmospheric deposition. The second cluster consists of As and Co, which are moderately similar, and may have a partially shared industrial or natural source. The most significant and well-defined cluster is for the elements Mn, Zn, Pb, Cd, Cr, and Cu that are grouped at fairly low rescaled distances, suggesting high similarity between them. In this group, Cd, Cr, Cu, and Pb are grouped closely suggesting that these metals are strongly correlated with industrial effluents, electro-plating industries, and metal-processing industries in the industrial zone of Tongi–Gazipur. The Mn and Zn are a bit further from this cluster, suggesting that they are provided by similar sources, but that they may also be affected by natural geochemical processes or inputs from municipal waste. The clustering pattern indicates a high industrial pollution signature in Tongi Khal sediments during winter, as the majority of metals are highly linked and a small number of metals (Ni, Hg, As, Co) are associated with either a different or secondary pollution pathway in figure 6(b).

3.4. Health risk assessment

3.4.1. Non-carcinogenic risk

The results for the non-carcinogenic health risk assessment show that children are always at a health risk higher than adults for all sampling locations (Figure 7). The hazard index (HI) for adults ranges from 0.13 to 1.20, while those for children are between 0.74 and 6.67, indicating that children are much more vulnerable. S1 is the most hazardous of all sites for adults (1.20) and children (6.67) with a possible non-carcinogenic health problem (HI>1), particularly for children. Likewise, S4 (Adult: 0.73; Children: 4.14) and S9 (Adult: 0.73; Children: 3.98) have high child-specific risk scores indicating high levels of contaminant exposure at these sites. Moderate health risks for children are also observed in S7 (3.42), S12 (3.55), S5 (2.95), S3 (2.87), and S8 (2.87). Most sampling sites have HI values < 1 for adults which indicate relatively low non-carcinogenic risk levels, although HI slightly exceeds the safety threshold at S1. S15 is the lowest health risk (0.13 for adults and 0.74 for children) which suggests relatively good environmental conditions.

3.4.2. Carcinogenic risk

The carcinogenic risks of sediment in Tongi Khal were performed for both adults and children. The CR_{ing} values for adults were in the range of 2.37×10^{-6} to 6.25×10^{-4} which are generally low to moderate, with the exception of Nickel (Ni) in Sample S1 which it is considered to pose a potential health risk with a CR_{ing} value of 6.25×10^{-4} (exceeds acceptable). In contrast, the values for children were consistently high ranging from 8.35×10^{-6} to 4.47×10^{-3} reflecting the higher vulnerability of children, because of their lower body weight and higher exposure per unit body mass. Nickel (Ni) was the most significant carcinogenic agent, the highest risk being for children with values in some samples (S1, S2 and S4) being greater than the acceptable limit of 1×10^{-4}. Potential carcinogenic risk was also greatly driven by Chromium (Cr) and Lead (Pb) with particular risks for children while Arsenic (As) and Cadmium (Cd) generally resulted in low-to-moderate risks. The highest CR_{ing} values can be considered localized contamination hotspots, while the lowest CR_{ing} values would be considered to have little health risk. The findings indicate that the risk of cancer related effects to the children is significantly higher from the sediment of Tongi Khal with regards to the presence of certain metals like Ni, Cr, and Pb. Therefore, these elements have the potential to exert long-term carcinogenic effects for children's health. These results highlight the importance of targeted measures for risk reduction to protect vulnerable populations in the region (Table S3).

Carcinogenic risk due dermal exposure (CR_{der}) was assessed for adults and children in Tongi Khal. Adults' CR_{der} values were between 2.83×10^{-7} and 7.48×10^{-5}, which are generally low to negligible risk. Children were more susceptible than adults with higher CR_{der} ranged from 7.01×10^{-7} to 3.75×10^{-4}. Children were more susceptible with higher CR_{der} ranging from 7.01×10^{-7} to 3.75×10^{-4}, which was due to lower body surface area to body weight ratio compared to adults and higher dermal exposure per body mass in children. Out of all the metals Nickel (Ni) had the highest dermal carcinogenic risk, especially for children with sample S1 having the highest value at 3.75×10^{-4}. As a result, moderate dermal risk was identified for chromium (Cr) and lead (Pb) and minimal risk for both adults and children were identified for arsenic (As) and cadmium (Cd). Samples from hotspots with elevated dermal chromium (CR) concentrations were samples S1, S2 and S4 and the lowest dermal chromium (CR_{der}) concentrations were in samples S15 and S16 where there was a low risk of dermal exposure. The results indicate that adults are unlikely to be exposed to a high level of carcinogens from dermal exposure to metals present in the sediment of Tongi Khal. Children are at higher risk from Ni, and should have minimal direct exposure to contaminated sediments to minimize the potential for long-lasting health impacts (Table S4).

4. Conclusion

This study assessed the extent of potential toxic element (PTE) contamination in the urban river sediments of Tongi Khal, located near industrial zones. The results indicated the presence of Cd, Ni, Cu, Hg and Zn levels, which indicated significant industrial pollution. The sediments were identified to be highly contaminated using I_{geo} and EF. The combined effects of toxic metals indicated significant contamination by the MCD and PLI. The pollutants were considered for their potential ecological risk in the study and moderate to high risks were found in some sites. The main pollution sources of toxic metals in sediment were found to be anthropogenic and industrial activity by PCA and hierarchical cluster analysis. Children were determined to be at a higher risk than adults to carcinogenic and non-carcinogenic risk through the health risk index. It is strongly recommended to have a long-term monitoring scheme in place with ecological risk and geo-accumulation indices to help monitor temporal changes in sediment quality. The study's results highlighted the need for stringent pollution control measures and better management of industrial waste. The study results provide insight into the environmental risks associated with industrial activities and call for pollution control and risk management in urban rivers.

Author contributions

Md. Rakibul Hassan: Writing-original draft, Methodology, Data Analysis, Visualization, Statistical Analysis, Tasnim Farzana: Writing-review & editing, Supervision, Mohammad Moniruzzaman: Formal Analysis, review and editing, Md. Shahariar Mahmud: Writing-review & editing, Software, Investigation, Lokibur Rahaman: Sample collection, analysis, Abdus Samad: Conceptualization, writing, review & editing, Resources, Supervision, Funding acquisition. All authors have read and agreed with the published version of the manuscript.

Ethical approval

Not applicable.

Conflicts of Interest

The authors report no conflicts of interest.

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Data availability statement

All the data used here are mentioned either in the manuscript or in the supplementary information.

Supplementary material

The Supplementary Material for this article can be found online at:
https://www.jspae.com/index.php/jce/article/view/929/383

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