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Research Article

Distribution of Potentially Toxic Elements in Sediments of the Subarnakhali River, Bangladesh: Ecological Risks Assessment

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ABSTRACT

There are major ecological and health risks associated with the accumulation of toxic metals in river sediments, particularly in regions where industrial and agricultural activities are prevalent. This study measured the concentrations of six toxic metals (Cr, Ni, Cu, Cd, Pb, and As) in the sediments of the Subarnakhali River at Jamalpur district of Bnagladesh using ICP-MS and evaluated the associated risks. The mean concentrations (mg/kg) of the toxic metals were as follows: Ni (41.01 ± 4.65) > Cu (29.01 ± 3.77) > Cr (20.18 ± 3.40) > Pb (17.59 ± 3.45) > Cd (1.29 ± 0.19) > As (1.18 ± 0.11). Notably, Ni and Cd levels exceeded the allowable limits set by sediment quality guidelines, indicating potential ecological concerns. Multivariate analyses (Pearson correlation, principal component analysis, and cluster analysis) revealed that Pb and As had both natural and anthropogenic origins, whereas Cu, Cr, and Ni were primarily derived from industrial sources. Pollution assessment indicated that the sediments were moderately to severely contaminated based on the geo-accumulation index (Igeo) and severely enriched (EF = 8.02). Moderate to high pollution levels were also reflected in the pollutant load index (PLI), modified contamination degree (mCD), and contamination degree (CD). Potential ecological risk evaluations (PER = 379.42 to 537.43) suggested significant threats, particularly from Cd. Although toxic unit (TU) values were below acute toxicity thresholds, the long-term presence of these metals could harm aquatic ecosystems and pose risks to human health. These findings underscore the urgent need for stricter regulation of industrial and agricultural discharges, improved waste management, and enhanced public awareness to prevent further contamination and protect the ecological integrity of the river.

Introduction

Sediments are ecologically vital components of aquatic habitats and reservoirs of pollutants, playing a crucial role in preserving the trophic status of any water body (Ali *et al*., 2016). Generally, sediments provide valuable information about the extent of geochemical and environmental pollution (Proshad *et al*., 2019). Toxic metals (e.g., heavy metals) are poisonous, abundant, and persistent in the environment, and their contamination of river water and sediments is a major global concern (Islam *et al*., 2020). Heavy metals undergo various speciation changes as a result of dissolution, precipitation, sorption, and complexation processes (Islam *et al*., 2018) and can occur in sediments in a wide variety of chemical forms (Islam *et al*., 2017). In addition to natural sources (e.g., atmospheric precipitation, geological weathering), significant amounts of heavy metals are released from anthropogenic activities such as leachates, brick kilns, chemical fertilizers and pesticides, industrial emissions, municipal waste, and traffic emissions, all of which contribute to metal pollution in aquatic ecosystems (Alahabadi and Malvandi, 2018; Kinimo *et al*., 2018; Lee *et al*., 2017). Heavy metal accumulation disrupts natural equilibrium and can move up the food chain, leading to bioaccumulation and biomagnification in aquatic species. These organisms may eventually enter the human food chain (Haque *et al*., 2021; Ahmed *et al*., 2015). Therefore, monitoring toxic metals in river sediments is crucial for maintaining riverine ecological balance.

In Bangladesh, approximately 1,176 enterprises discharge 0.4 million m^3 of untreated wastewater into

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rivers daily (Islam *et al*., 2015). Long-term heavy metal deposits in benthic sediments serve as indicators for assessing ecological risk, pollution sources, and distribution patterns (Zhang *et al*., 2018; Proshad *et al*., 2021). Sediment analysis is therefore a valuable approach for understanding metal contamination and formulating environmental risk management strategies (Kormokar *et al*., 2019). Environmental risk posed by heavy metals is often evaluated using indices such as the contamination factor (CF), enrichment factor (EF), geo-accumulation index (Igeo), pollution load index (PLI), and potential ecological risk (PER) (Yu *et al*., 2011; Proshad *et al*., 2019). Multivariate statistical techniques, including the Pearson correlation coefficient (PCC), principal component analysis (PCA), and cluster analysis (CA), are also useful for identifying pollution sources and trends (Ustaoğlu and Islam, 2020; Varol, 2011). The combined application of these indices and statistical tools is essential for assessing the extent of sediment pollution.

Bangladesh, as a developing nation, faces increasing contamination of aquatic habitats due to unregulated industrialization and growing human activities (Kabir *et al*., 2020). One such river system under threat is the Subarnakhali River in the Jamalpur District, which has recently drawn attention for signs of significant environmental degradation. Extensive illegal encroachment, siltation and pollution from various sources (domestic and commercial etc.) killing Subarnakhali River in Jamalpur (The Daily Star, 2023). Despite its ecological and socioeconomic importance, no scientific study has yet evaluated heavy metal contamination in this river's sediments. This lack of systematic research highlights a critical knowledge gap, particularly regarding potential ecological hazards posed by toxic substances in riverine sediments. Therefore, the primary objective of this study was to determine the concentrations of key heavy metals (Cr, Ni, Cu, As, Cd, and Pb) in surface sediments of the Subarnakhali River and assess their potential ecological risks in order to evaluate the river's pollution status. The specific aims were to: i) determine the concentrations of heavy metals in the sediments of the Subarnakhali River, ii) assess the ecological risks and pollution levels of these metals, and iii) identify their potential sources using multivariate statistical tools. The results of this integrated approach will contribute to developing effective regulatory strategies for similar ecosystems worldwide. Furthermore, the findings will support policymakers and environmental managers in advancing several Sustainable Development Goals (SDGs-2030), particularly those related to sustainable ecosystems (SDG 15), clean water and sanitation (SDG 6), and responsible consumption and production (SDG 12).

Materials and Methods

Study area

The Subarnakhali River, located in Sharishabari Upazila of Jamalpur District (24°46'30.99"N 89°50'22.69"E to 24°44'43.13"N89°49'09.58"E), north-central Bangladesh, was selected as the study site (Fig. 1). This serpentine river is approximately 16 km long and 33 m wide on average, originating from the ancient Brahmaputra River and flowing through Jamalpur and Mymensingh districts before joining the Khiro River (Razzak, 2015). Historically used for domestic purposes, livestock rearing, and irrigation, the river has experienced declining utility in recent years due to increasing pollution, resulting in reduced agricultural productivity and loss of aquatic biodiversity. Without timely intervention, its pollution levels may reach critical thresholds.

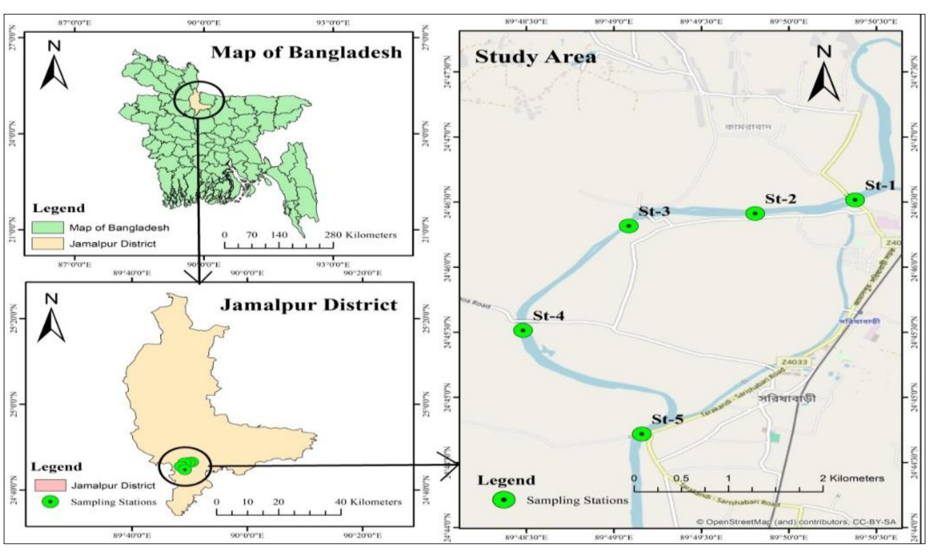

Figure 1. Map of the study showing all the sampling stations in the Subarnakhali River, Jamalpur

Sample collection and processing

A total of 15 composite sediment samples were taken from five specific locations along the Subarnakhali River in the Jamalpur area of Bangladesh during the pre-monsoon season (February, 2025). The sampling was carried out in accordance with the standard protocol described by Proshad *et al*. (2019) and USEPA (2011). Using a portable Ekman Dredge grab sampler (20 x 20 × 20 cm), three composite sediment samples (~500 g each) were taken from the riverbed at a depth of 0–10 cm at each station. To avoid metal contamination from the grab sampler, the top 5 cm of each sample was carefully removed from the middle of the catcher using a plastic spatula that had been acid-washed (Ustaoglu and Islam, 2020). All samples were immediately packed into sterile polyethylene plastic bags and kept in the lab at a low temperature (4°C) until they were processed further. Sediment samples were allowed to air dry at room temperature in a dust-free, hygienic setting in the lab. To eliminate organic matter and debris, the dried samples were pulverized with a porcelain mortar and pestle, homogenized, and then sieved through a 2 mm screen. Until chemical analysis, the homogenized sediment powders were stored at 8°C in sealed Ziploc bags.

Sediment digestion, analysis, and quality control

Samples of sediments were examined at Bangabandhu Sheikh Mujibur Rahman Agricultural University's Laboratory of Soils Science, Department of Soil Science (BSMRAU). About 0.5 g of each powdered sediment sample was digested for chemical analysis in a 100 mL Pyrex glass beaker (Merck, Germany) using a 15 mL solution of ultra-pure perchloric acid ($HClO_4$) and nitric acid (HNO_3) in a 1:2.5 ratio. For around five hours, the beakers were heated to 130°C on a hot plate until the volume was down to two or three milliliters. Until the digested solution turned clear or light in color, more 5 mL volumes of the di-acid combination were added repeatedly and brought to a boil. After cooling, the digested solutions were diluted to 25 mL with deionized water for further analysis after being filtered through Whatman No. 41 filter paper (Islam *et al*., 2017). An Inductively Coupled Plasma Mass Spectrometer (ICP-MS, Agilent 7500i, USA) was used to measure the amounts of heavy metals (Cr, Ni, Cu, As, Cd, and Pb). Strict quality control procedures were used to guarantee the analytical methodologies' correctness and precision. Before being used, all glassware and plastic containers were rinsed with deionized water after being pre-soaked in 5% HNO_3. For sample preparation and analysis, only high-purity reagents (99.98%, Merck, Germany) were utilized. The analytical reagent blanks and sediments reference materials were generated and added to each batch of five sediment samples for analysis in order to track the precision and accuracy of the analytical techniques utilized.

Environmental and ecological risk assessment

Contamination factor (CF), geo-accumulation index (Igeo), enrichment factor (EF), contamination degree (CD), modified contamination degree (mCD), toxic unit (TUs), pollution load index (PLI) and potential ecological risk index (PER) were calculated to assess sediment contamination levels and related ecological risks in the study area. Key characteristics of these indices are summarized in Table 1.

Table 1. Description of the sediment pollution and ecological risk assessment indices

Index and Formula	Description	Standards	References
Geo-accumulation index (I_{geo}) $$I_{geo} = log_2\left(\frac{C_n}{1}.5 \times B_n\right)$$	I_{geo}, broadly used for assessment of metal contamination in soils by comparing the measured concentrations to background concentrations. C_n is the measured concentration of examined metal (n); B_n is the geochemical background concentration of that corresponding metal (n); The factor 1.5 is applied for the probable deviations in background values because of lithological effect.	class 0 (I_{geo} ≤0): uncontaminated, class 1 (0≤I_{geo} ≤1): uncontaminated to moderately contaminated, class 2 (1≤ I_{geo} ≤2): moderately contaminated, class 3 (2≤I_{geo}≤3): moderately to strongly contaminated, class 4 (3≤I_{geo}≤4): strongly contaminated, class 5 (4≤I_{geo}≤5): strongly to extremely contaminated, and class 6 (5<I_{geo}): extremely contaminated.	Muller (1969) Proshad *et al*. (2019) Turekian and Wedepohl (1961) Rudnick and Gao (2014) Nikolaidis *et al*. (2010)
Enrichment factor (EF) $$EF = \frac{\left(C_M/C_{Al}\right)Sample}{\left(C_M/C_{Al}\right)Background}$$	EF, a significant tool in assessing the degree of anthropogenic heavy metal contamination. $(C_M$ and $C_{Al})_{Sample}$ is the average concentration of the examined metal in soil sample, $(C_M$ and $C_{Al})_{Background}$ is the background concentrations used as the reference element; Al is used as the reference element in this study due to its geochemistry.	EF <1 (no enrichment), EF <3 (mild enrichment), EF =3-5 (moderate enrichment), EF =5-10 (moderately intense enrichment), EF =10-25 (severe enrichment), EF =25-50 (very severe enrichment), and EF >50(extremely severe enrichment)	Ustaoğlu and Islam (2020) Aminiyan *et al*. (2018) Varol (2011) Idris *et al*. (2019)
Contamination factor (CF) & Contamination degree (CD)	CF to investigate the contamination level of heavy metals in sediments, C_m is the measured concentration of heavy	CF <1: low, 1≤ CF <3: moderate, 3≤ CF <6: considerable,	Varol (2011) Idris et al. (2019)

$CF = (C_m)/(B_m)$	metal in sediment; B_n is the background concentration of concerned metal; CD was computed by the sum of the six heavy metals in soils of the study area.	and CF ≥6: very high. CD <6: low, 6≤ CD <12: moderate, 12≤ CD <24: considerable, and CD ≥24: very high.	Aminiyan *et al.* (2018) Kabir *et al.* (2020)
Modified degree of contamination (mCD) $mCD = \frac{1}{n}\sum_{i=n}^{1} CF_i$	degree of contamination index which integrates a single pollution index to evaluate each sediment sample. mCD is the modified contamination degree, n is the total number of metal elements considered if it is a pollutant, CF_i is the contamination factor of ith heavy metals	mCD <1.5: Nil to very low, 1.5≤mCD<2.0: low, 2.0≤ mCD<4.0: moderate, 4.0≤ mCD <8.0: high, 8.0≤ mCD <16.0: very high, 16.0≤ mCD <32.0: Extremely, mCD>32: ultra-high	Hakanson, (1980) Zhang *et al.* (2018)
Pollution load index (PLI) $PLI = \sqrt[n]{(CF_1 \times CF_2 \times CF_3 \times \ldots CF_n)}$	PLI evaluates mutual pollution weight at dissimilar locations through the dissimilar metals in soils and sediments and provided an evaluation of the inclusive toxicity grade of each single sampling location. PLI value of 0, 1 and above 1 means perfection, existence of only baseline levels of pollutants and progressive deterioration of site quality, respectively.	PLI>1 specifies pollution exists, conversely, if PLI<1 designates there are nonexistence metal pollution.	Proshad *et al.* (2019) Tomlinson *et al.* (1980) Varol (2011)
Toxic unit analysis $TU = C_M / PEL$ $\sum TU_S = TU_{metal\,(1)} + TU_{metal\,(2)} + TU_{metal\,(3)} + \cdots + TU_{metal\,(n)}$	The sum of toxic units (ΣTU_S) is referred to as the potential acute toxicity of hazardous elements in sediment samples. Toxic unit (TU), the ratio of the weighted concentration of toxic metals in sediments to the probable effect level (PEL). C_M is the measured concentration of heavy metal in sediments, PEL is the probable effect levels value of corresponding heavy metals, and $\sum TU_S$ is the product of toxic units (TUs) for heavy metals in urban river sediment samples.	If the sum of toxic units (TUs) for all investigated sediments samples is greater than 4, then moderate to serious toxicity of toxic metals happen	Islam *et al.* (2018) Bai *et al.* (2011) Proshad *et al.* (2019)
Ecological risk factor (E_r^i) and Potential ecological risk (PER) $E_r^i = T_f^i \times C_f^i$ $PER = \sum_{i=1}^{n} E_r^i$ $C_f^i = \frac{C_m^i}{C_n^i}$	E_r^i, indicates sensitivity of the biotic community to the toxic elements and exemplifies the PER caused by the overall contamination. E_r^i is the potential ecological risk coefficient of a single metal; C_f^i is the accumulating coefficient of metal (i); T_f^i is the toxic-response factor of metal (i); C_m^i is the value of heavy metal concentration in the dust samples; C_n^i is background values in soils; toxic-response factors for Pb, Cu, Cr, Cd, Ni and As were considered 5, 5, 2, 30, 4 and 10, respectively.	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 sediments.	Håkanson (1980) Ustaoğlu and Islam (2020) Chen and Zhou (1992)

Statistical analysis

Using IBM SPSS Statistics 20.0, statistical procedures such as principal component analysis, cluster analysis, and Pearson's correlation coefficient analysis were used in this study to determine the likely sources of the heavy metals in the sediments and to reveal the relationships between the metals under examination. ArcGIS 14.1 was used to create the spatial distribution maps.

Results and Discussion

Occurrence and abundance of heavy metals in sediments

The descriptive data of the discovered amounts of heavy metals (Cr, Pb, Cd, Cu, As, and Ni) in sediments taken from the Subarnakhali River in the Jamalpur area of Bangladesh is summarized in Table 2. In potentially disturbed sediments, the concentrations of Cr, Pb, Cd, Cu, As, and Ni varied from 16.48 to 25.18; 13.61 to

21.14; 1.08 to 1.56; 23.90 to 33.17; 1.06 to 1.35; and 35.02 to 47.57 mg/kg, respectively (Table 2). The average concentrations (mg/kg) of these heavy metals followed a decreasing order: Ni (41.01±4.65) > Cu (29.01±3.77) > Cr (20.18±3.40) > Pb (17.59±3.45) > Cd (1.29±0.19) > As (1.18±0.11). These concentrations were found to be very assorted across the inspected state. Large transportation loads, construction operations in the Jamalpur area, residential debris, agricultural runoff, discarded items, and native trash disposal could all be causing the wide range of metal concentrations (Kabir *et al*., 2020; Shorna *et al*., 2021). Additionally, Ni, Cr and Pb are significantly higher than other metals and are linked to galvanizing and melting processes in riverbank production costs (Kormoker *et al*., 2019). A lower concentration of some potentially hazardous compounds in exposed sediments is probably linked to a lower level of production discharge (Proshad *et al*., 2019).

Table 2. Concentration (mg/kg) of heavy metals in sediments of the Subarnakhali River at Jamalpur in Bangladesh

Descriptive Statistics	Cr	Ni	Cu	Cd	Pb	As
Mean	20.18	41.01	29.01	1.29	17.59	1.18
SD	3.40	4.65	3.77	0.19	3.45	0.11
VC (%)	16.83	11.34	13.01	14.92	19.59	9.22
Minimum	16.48	35.02	23.90	1.08	13.61	1.06
Maximum	25.18	47.57	33.17	1.56	21.14	1.35
Skewness	0.75	0.25	-0.42	0.65	-0.38	0.82
Kurtosis	-0.20	0.46	-1.40	-1.14	-2.89	0.60
Reference/Literature data						
BV (Rudnick and Gao, 2014)	92	47	28	0.09	17	4.8
UCC (Taylor and McLennan, 1995)	35	20	25	0.09	20	1.5
TRV (USEPA, 1999)	26	16	16	0.6	31	6
ASV (Turekian and Wedepohl, 1961)	90	68	45	0.3	20	13
TRF (Hakanson, 1980)	2	6	5	30	5	10
PEC (MacDonald *et al*., 2000)	111	48.6	149	4.98	128	33

N.B.: SD = Standard Deviation, VC= Coefficient of variance. BV= Background value, UCC= Upper continental crust, TRV= Toxicity reference value, ASV= Average shale value, TRF= Toxic response factor, PEC= Probable effect concentration.

The study revealed that when the concentrations of these heavy metals were compared with the background values, the mean concentration of Ni was higher than the pertinent background levels. Conversely, the concentrations of Cd, Cu, Cr, Pb, and As were much lower. With the exception of Ni, Cu, and Cd, all of the heavy metals had mean concentrations below the upper continental crust (UCC); nevertheless, the toxicity reference value (TRV) for Cu, Ni, and Cd was greater (Table 2). The average shale value (ASV) was exceeded by the concentrations of Cd, Cu, and As, but not by the concentrations of Cr, Ni, or Pb. With the exception of Cd and As, all heavy metal concentrations were higher than the toxic response factor (TRF), while the average concentrations of Cr, Ni, Cu, Cd, Pb, and As were lower than the likely effect concentration (PEC). The calculated coefficient of variance (VC) values for Cr, Ni, Cu, Cd, Pb, and As in sediment samples were 16.83, 11.34, 13.01, 14.92, 19.59, and 9.22%, in that order (Table 2). Anthropogenic activities produce more metal pollution when the VC is higher; while natural sources produce more metal pollution when the VC is lower (Han *et al*., 2013). Depending on the values of VC, the current study showed that human activity dominated the level of metal pollution across the sample locations. All of the heavy metals' skewness and kurtosis values were found to be near to one, indicating both left- and right-handed skewness and leptokurtic kurtosis (Table 2).

Spatial distribution of heavy metals in sediments

In the Subarnakhali River's sediments, the spatial distribution of heavy metals is shown in Fig. 2 and Table 2. Different levels of contamination are shown by the spatial distribution of these elements across several locations, which represent the influence of both natural and anthropogenic processes. With the highest concentration at Site-2 (25.18 mg/kg) and the lowest at Site-4 (16.48 mg/kg), the mean concentration of chromium (Cr) was 20.18±3.40 mg/kg. The observed human influence suggests that Cr may have come from industrial operations. In comparison to international rivers like the Yellow River in China and other Bangladeshi rivers including the Karatoya, Old Brahmaputra, and Halda (Table 3), the average Cr content was lower. All sediment quality guideline (SGQ) levels (LEL, TEL, SEL, PEL, ERL, ERM, and TET) were likewise below Cr values (MacDonald *et al*., 2000). With a maximum concentration of 47.57 mg/kg at Site-1 and a minimum of 35.02 mg/kg at Site-4, the mean concentration of nickel (Ni) was 41.01±4.65 mg/kg (Fig. 2). Ni levels were lower than those in the Korotoa and

Rupsha, but greater than those in the Halda, Dhaleshwari, Bangshi, and Louhajang Rivers (Table 3). Ni concentrations were below SEL, ERM, and TET but over LEL, TEL, ERL, and PEL criteria (Table 3). According to Proshad *et al*. (2019), the higher Ni value in the sediment may have come from industrial and urban trash. The average concentration of copper (Cu) found was 29.01±3.77 mg/kg. The levels were lowest at Site-4 (23.90 mg/kg) and highest at Site-1 (33.17 mg/kg). Both natural processes (Kabir *et al*., 2020) and human activities (Ali *et al*., 2018; Bhuyan *et al*., 2017) were cited as the causes of the Cu content. Compared to all SGQ thresholds and the Korotoa and Rupsha rivers, Cu concentrations were lower (Table 3). The current study's Cu content is below recommended values for TEL, ERL, SEL, PEL, ERM, and TET (MacDonald *et al*. 2000). The mean concentration of cadmium (Cd) was 1.29±0.19 mg/kg. At 1.56 mg/kg, Site-2 had the greatest amount, while at 1.08 mg/kg, Site-3 had the lowest (Fig. 2). With the exception of Rupsha and Korotoa, the levels of Cd in the current research were higher than those in the majority of other rivers (Table 3). Although Cd levels were lower than SEL, PEL, ERM and TET levels, while higher than LEL, TEL and ERL, suggesting a potential industrial origin (Ali *et al*., 2016; Proshad *et al*., 2019). The average concentration of lead (Pb) was 17.59±3.45 mg/kg, with the highest value at Site-1 being 21.14 mg/kg and the lowest at Site-5 being 13.61 mg/kg (Fig. 2). The battery industry, industrial paints, and household garbage were among the sources of lead (Shorna *et al*., 2021). Pb levels were below those seen in Yellow Rivers, Halda, and Korotoa (Table 3). The Pb concentration in the current study is below recommended values such as LEL, TEL, ERL, SEL, PEL, ERM, and TET, per sediment quality guidelines (Table 3). The mean amount of arsenic (As) was 1.18±0.11 mg/kg, with Site-2 having the lowest level (1.06 mg/kg) and Site-4 having the highest (1.35 mg/kg) (Fig. 2). Mining, wood preservation, and agricultural practices were also possible sources (Acharjee *et al*., 2022). In the present study, river sediment's arsenic concentration is found to be relatively lower than that of previous studies (Liu *et al*., 2009; Rahman *et al*., 2013; Hasan *et al*., 2015; Kormokar *et al*., 2019; Proshad *et al*., 2019; Islam *et al*., 2020; Kabir *et al*., 2020; Hoque *et al*., 2021; Proshad *et al*., 2021; Shorna *et al*., 2021) and below sediment quality guidelines such as LEL, TEL, SEL, PEL, and TET (SGQs) (Table 3).

Table 3. Concentration (mg/kg) of heavy metals in sediments of the Subarnakhali River along with a comparison to other studies for rivers and sediments quality guidelines (SGQs)

River Name	Cr	Ni	Cu	Cd	Pb	As	References
Subarnakhali	20.18	41.01	29.01	1.29	17.59	1.18	Present study (2025)
Korotoa	165.8	114.1	76.00	1.49	64.67	12.18	Proshad *et al*. (2021)
Old Brahmaputra	30.25	43.49	NF	0.03	14.29	3.74	Shorna *et al*. (2021)
Shitalakhya	38.39	NF	24.60	0.64	13.16	NF	Kabir *et al*. (2020)
Halda	90.7	37.0	17.8	0.42	18.2	6.51	Islam *et al*. (2020)
Rupsha	25.26	42.40	68.81	3.78	32.57	9.31	Proshad *et al*. (2019)
Dhaleshwari	64.7	18.2	6.8	0.73	15.4	NF	Hoque *et al*. (2021)
Dakatia	31.09	NF	23.99	0.07	3.70	NF	Hasan *et al*. (2015)
Bangshi	98.10	25.67	31.01	0.61	59.99	1.93	Rahman *et al*. (2013)
Louhajang	9.21	7.68	17.73	0.08	4.60	9.00	Kormoker *et al*. (2019)
Ganges, India	4.10	NF	2.69	0.77	6.35	NF	Gupta *et al*. (2009)
Yellow, China	84.5	NF	66.00	NF	52.00	31.00	Liu *et al*. (2009)
			SQGs				
LEL	26	16	16	0.6	31	6	MacDonald *et al*. (2000)
TEL	37	18	36	0.59	35	5.9	MacDonald *et al*. (2000)
SEL	110	75	110	10	250	33	MacDonald *et al*. (2000)
PEL	90	36	197	3.5	91	17	MacDonald *et al*. (2000)
ERL	81	20.9	34	1.2	46.7	NA	MacDonald *et al*. (2000)
ERM	370	51.6	270	9.6	218	NA	MacDonald *et al*. (2000)
TET	100	61	86	3	170	17	MacDonald *et al*. (2000)

N.B.: NF = Not Found; NA = Not Available; LEL (Lowest effect level), TEL (Threshold effect level), SEL (Severe effect Level), PEL (Probable effect level), ERL (Effect range low), ERM (Effect range medium), TET (Toxic effect threshold): MacDonald *et al*. (2000).

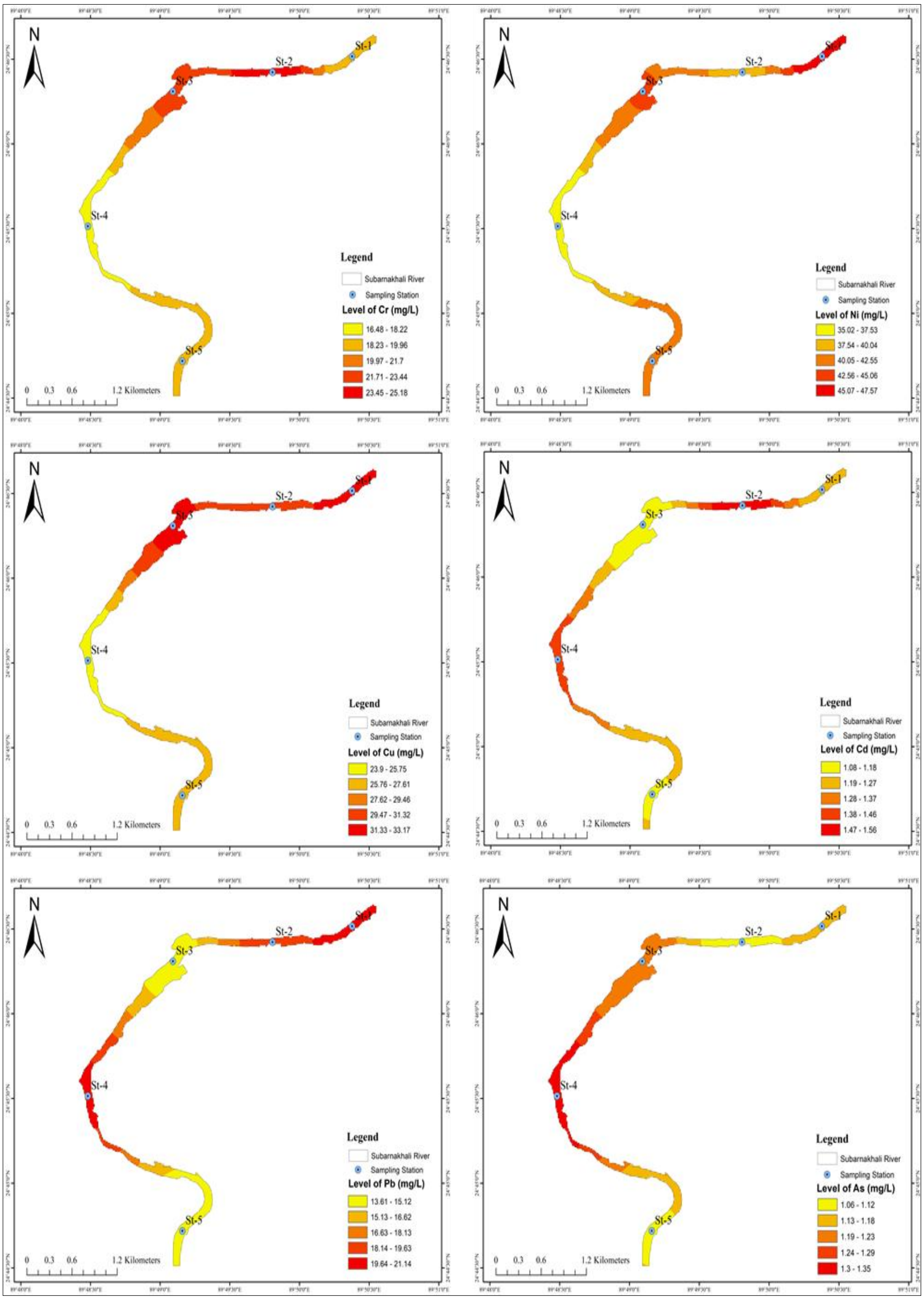

Figure 2. Spatial distribution of toxic element concentrations of heavy metals in sediments of the Subarnakhali River at Jamalpur in Bangladesh

Identification of the sources of heavy metals in surface sediments

Pearson's correlation coefficient analysis (CCA), Principal Component Analysis (PCA) and Cluster Analysis (CA), which are frequently employed in related studies (Suryawanshi *et al*., 2016; Jiang *et al*., 2017; Zglobicki *et al*., 2018; Jose and Srimuruganandam, 2020), were used to clarify the relationships between the heavy metals and to identify their potential sources in surface sediments. Significant positive correlations between the majorities of the heavy metals under study were found by the CCA results (Table 4). Anthropogenic activities were the primary cause of the significantly strong positive correlations ($p<0.05$) that were seen between the Cu-Cr pair (0.420*), Pb-Cd pair (0.584*), and Ni-Cu pair (0.874*). Additionally, Proshad *et al*. (2019) carried out a similar investigation in Bangladesh's Rupsa River. However, there were notable negative correlations between As-Cr (-0.718), As-Cd (-0.107), and As-Cu (-0.439), which were probably lithogenic. Overall, the findings showed that the Subarnakhali River's distinct heavy metal sources were complicated. The PCA was used to determine the sources of metal pollution, which supports these findings. According to eigenvalues, two significant components were identified (Fig. 3); PC-1 explained 57.884% of the variation and had a strong positive loading for Ni (0.634) and Cu (0.390), both of which were linked to human activities such plating processes (Pandey *et al*., 2016). The PC-2, which accounted for 24.682% of the variance, displayed poor loading for As, Pb, Cd, and Cr, suggesting lithogenic origin and geochemical dependence. Additionally, the sampling sites were categorized using cluster analysis (CA) according to how similar the patterns of metal deposition were. Out of the five sampling locations, the findings (Fig. 4) revealed two significant clusters. Sites 3, 5, 2, and 1 were all part of Cluster 1, however only site 4 was part of Cluster 2. These groups show comparable degrees of pollution, accumulation patterns, and maybe shared metal contamination sources.

Table 4. Pearson correlation coefficients among heavy metals in sediments

Metals	Cr	Ni	Cu	Cd	Pb	As
Cr	1					
Ni	0.033	1				
Cu	0.420*	0.874**	1			
Cd	0.310	-0.586	-0.350	1		
Pb	-0.236	0.011	0.457*	0.584**	1	
As	-0.718	-0.371	-0.439	-0.107	0.281	1

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

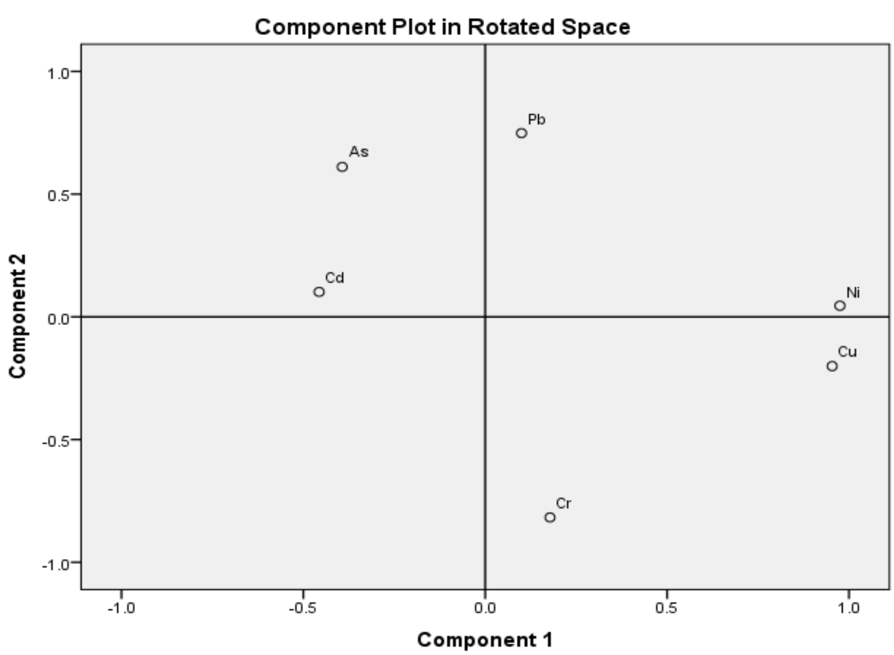

Figure 3. Principal component analyses (PCA) of heavy metals in sediments samples

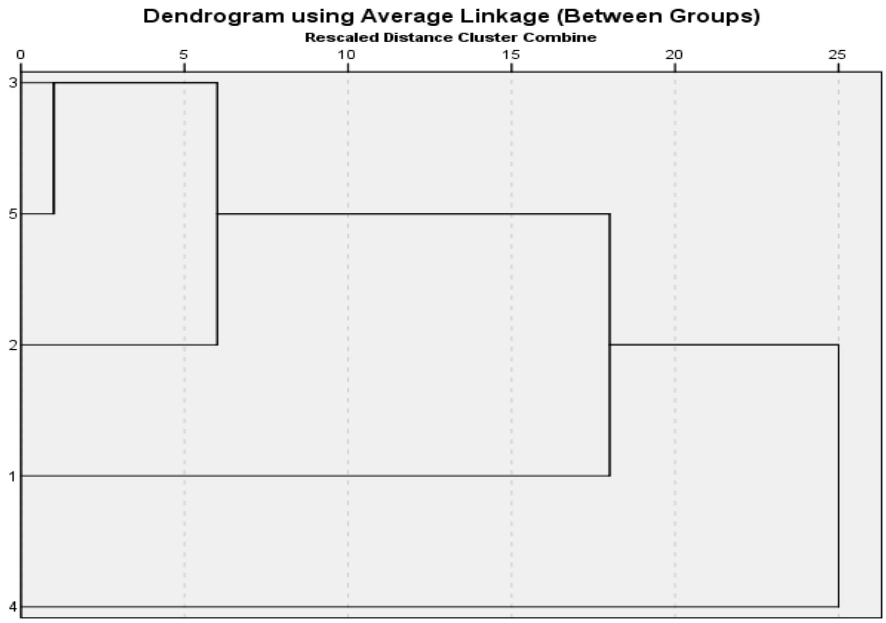

Figure 4. Cluster Analysis (CA) among the sampling sites of study area

Pollution level and ecological risk assessment of river sediment

The geo-accumulation index (Igeo) was used to evaluate the degree of heavy metal pollution in sediment samples taken from the Subarnakhali River. The average Igeo scores showed a decreasing order of Cd (3.24) > Cu (-0.54) > Pb (-0.56) > Ni (-0.79) > Cr (-2.61) > As (-2.79), as shown by the Igeo values in Table 5. The research area has significant sediment pollution, as shown by the highest Igeo values found for Cd. The Pb, Ni, Cu, Cr and As all have Igeo values below 0, which is considered uncontaminated. The location with the highest Igeo level of Cd (3.53) and the lowest for As (-2.76) was located at location-2. Phosphate fertilizers, industrial discharges, sewage sludge, battery leachates, and atmospheric emissions may all be connected to the elevated Cd level (Krishnamurti *et al*., 2005; Proshad *et al*., 2019). An efficient method for determining the extent of contaminants in the sites is the enrichment factor (EF) (Franco-Uria *et al*., 2009; Proshad *et al*., 2019; Kabir *et al*., 2020). The computed EF values for each of the metals under study are displayed in Table 6. The heavy metals under analysis show a decreasing trend in their average EF values, with Cd (8.02) > Pb, Cu (0.58) >Ni (0.49) > As (0.14) > Cr (0.12). The largest EF value in the current investigation indicates that Cd is severely enriched. Rather than human intervention, this could be due to the anoxic or sub-oxic conditions of the sediment (Islam *et al*., 2018; Proshad *et al*., 2019). For Pb, Ni, Cu, Cr, and As, the average EF values are less than 1, indicating neither background concentration nor enrichment.

According to the contamination factor (CF) values shown in Table 7, Cd had a very high average CF of 14.30, followed by moderately contaminated Cu (1.04) and Pb (1.03). Low contamination was suggested by CF values less than 1 for Ni (0.87), Cr (0.22), and As (0.25). At Site-2, the highest CF value for Cd was 17.30. Site-2 had the highest degree of contamination (CD), while Site-3 had the minimum. The CD ranged from 15.41 to 20.78. With an average of 0.94, the pollutant load index (PLI), which measures the integrated metal pollution, varied from 0.86 (Site-5) to 1.00 (Site-1 and Site-2) and the modified degree of contamination (mCD) ranged from 2.57 to 3.46 suggested that the Subarnakhali River is moderately contaminated. The cumulative acute toxicity risks of sediment samples were estimated by calculating the toxic units (TUs) of particular metals. Table 8 indicates that the decreasing order of average hazardous units was as follows: Ni (1.14) > Cd (0.37) > Cr (0.22) > Pb (0.19) > Cu (0.15) > As (0.07). The ecological risk factor ($\mathbf{E_r^i}$) and potential ecological risk index (PER), which are summarized in Table 9, were used to assess the ecological risk. In the Subarnakhali River's sediments, the average possible ecological risk factor for heavy metals is as follows: Cd (428.89) > Ni (5.24) > Cu (5.18) > Pb (5.17) > As (2.46) > Cr (0.44). With a range of 361.11 to 518.89 across the sites, Cd exhibited the highest ecological risk, with Site-2 recording the highest risk. With PER scores ranging from 379.42 to 537.43, every station was classified as being at considerable ecological risk.

Table 5. Geo-accumulation index (I_{geo}) values of heavy metals in sediment samples

Station	Cr	Ni	Cu	Cd	Pb	As
St-1	-2.91	-0.57	-0.34	3.18	-0.27	-2.62
St-2	-2.45	-0.86	-0.50	3.53	-0.44	-2.76
St-3	-2.66	-0.72	-0.40	3.00	-0.84	-2.57
St-4	-3.07	-1.01	-0.81	3.38	-0.34	-2.42
St-5	-2.86	-0.78	-0.66	3.11	-0.91	-2.70
Mean	-2.79	-0.79	-0.54	3.24	-0.56	-2.61
SD(±)	0.24	0.16	0.19	0.21	0.29	0.13
Min.	-3.07	-1.01	-0.81	3.00	-0.91	-2.76
Max.	-2.45	-0.57	-0.34	3.53	-0.27	-2.42

Table 6. Enrichment factor (EF) values of heavy metals in sediment samples

Station	Cr	Ni	Cu	Cd	Pb	As
St-1	0.11	0.57	0.66	7.61	0.70	0.14
St-2	0.15	0.46	0.59	9.71	0.62	0.12
St-3	0.13	0.51	0.64	6.76	0.47	0.14
St-4	0.10	0.42	0.48	8.77	0.66	0.16
St-5	0.12	0.49	0.53	7.28	0.45	0.13
Mean	0.12	0.49	0.58	8.02	0.58	0.14
SD(±)	0.02	0.06	0.08	1.20	0.11	0.01
Min.	0.10	0.42	0.48	6.76	0.45	0.12
Max.	0.15	0.57	0.66	9.71	0.70	0.16

Table 7. Contamination factor (CF), contamination degree (CD), modified degree of contamination (mCD), and pollution load index (PLI) values of heavy metals

Station	Cr	Ni	Cu	Cd	Pb	As	CD	mCD	PLI
St-1	0.20	1.01	1.18	13.56	1.24	0.24	17.44	2.91	1.00
St-2	0.27	0.83	1.06	17.30	1.11	0.22	20.78	3.46	1.00
St-3	0.24	0.91	1.13	12.04	0.84	0.25	15.41	2.57	0.92
St-4	0.18	0.75	0.85	15.63	1.18	0.28	18.87	3.15	0.92
St-5	0.21	0.87	0.95	12.96	0.80	0.23	16.02	2.67	0.86
Mean	0.22	0.87	1.04	14.30	1.03	0.25	17.70	2.95	0.94
SD(±)	0.04	0.10	0.13	2.13	0.20	0.02	2.18	0.36	0.06
Min.	0.18	0.75	0.85	12.04	0.80	0.22	15.41	2.57	0.86
Max.	0.27	1.01	1.18	17.30	1.24	0.28	20.78	3.46	1.00

Table 8. Toxic unit (TU) and sum of toxic units (ΣTUs) of heavy metals

Station	TU						ΣTUs
	Cr	Ni	Cu	Cd	Pb	As	
St-1	0.20	1.32	0.17	0.35	0.23	0.07	2.34
St-2	0.28	1.08	0.15	0.44	0.21	0.06	2.22
St-3	0.24	1.19	0.16	0.31	0.16	0.07	2.13
St-4	0.18	0.97	0.12	0.40	0.22	0.08	1.98
St-5	0.21	1.14	0.14	0.33	0.15	0.07	2.03
Mean	0.22	1.14	0.15	0.37	0.19	0.07	2.14
SD (±)	0.04	0.13	0.02	0.05	0.04	0.01	0.15
Min.	0.18	0.97	0.12	0.31	0.15	0.06	1.98
Max.	0.28	1.32	0.17	0.44	0.23	0.08	2.34

Table 9. Ecological risk factor (E_r^i) and potential ecological risk index (PER) of heavy metals

Station	Ecological Risk Factor (E_r^i)						PER	
	Cr	Ni	Cu	Cd	Pb	As	Value	Status
St-1	0.40	6.07	5.92	406.67	6.22	2.44	427.72	Considerable
St-2	0.55	4.96	5.29	518.89	5.53	2.22	537.43	Considerable
St-3	0.48	5.45	5.67	361.11	4.19	2.53	379.42	Considerable
St-4	0.36	4.47	4.27	468.89	5.92	2.81	486.71	Considerable
St-5	0.41	5.23	4.75	388.89	4.00	2.31	405.60	Considerable
Mean	0.44	5.24	5.18	428.89	5.17	2.46	447.38	Considerable
SD (±)	0.07	0.59	0.67	64.01	1.01	0.23	64.04	-
Min.	0.36	4.47	4.27	361.11	4.00	2.22	379.42	Considerable
Max.	0.55	6.07	5.92	518.89	6.22	2.81	537.43	Considerable

Conclusion

This study provides the first comprehensive assessment of heavy metal contamination in the sediments of the Subarnakhali River, revealing moderate level pollution but considerable ecological risk driven primarily by cadmium enrichment. While most metals (Cr, Ni, Cu, Pb, and As) were below international sediment quality guideline thresholds, Ni exceeded background levels and Cu, Ni, and Cd surpassed toxicity reference values, indicating both anthropogenic and lithogenic contributions. Cu and Cd in Subarnakhali River sediments are more strongly linked to nearby anthropogenic sources (agriculture, domestic, and commercial waste), whereas Ni can have both geogenic (upstream) and anthropogenic (local commercial/domestic waste) contributions. Multivariate statistical analyses confirmed mixed sources, with plating, industrial discharges, agricultural runoff, and urban waste identified as major drivers. Spatial variability across sites highlighted localized contamination hotspots, particularly at Site-2, where Cd concentrations, contamination factors, and ecological risk indices were highest. Although the integrated pollution load index suggested moderate contamination, the potential ecological risk index classified all sites as being under considerable risk, underscoring the urgent need for targeted mitigation measures, stricter waste management regulations, and continuous monitoring to safeguard the river's ecological integrity and dependent communities. However, this study is based on a single season's sampling data, which represents a major limitation in capturing the complete pollution scenario of the river. Therefore, comprehensive and periodic monitoring is recommended to better understand the long-term pollution dynamics.

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Data availability statement

The data will be made available on request to corresponding author.

Declaration of interest's statement

The authors declare no conflict of interest.

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