INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 09, September 2025, pp : 507-514
www.ijprems.com
editor@ijprems.com
e-ISSN : 2583-1062
Impact Factor : 7.001

HEAVY METAL CONTAMINATION IN GOMTI RIVER SEDIMENTS: A HUMAN HEALTH RISK ASSESSMENT FOR URBAN POPULATIONS IN LUCKNOW, INDIA

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DOI: https://www.doi.org/10.58257/IJPREMS43802

ABSTRACT

Sediments act as a long-term sink for heavy metals (HMs), posing a potential health risk to urban populations through direct and indirect exposure pathways. This study evaluates the carcinogenic and non-carcinogenic health risks associated with HM exposure from the sediments of the Gomti River in Lucknow, India. Ten sediment samples were collected from key locations and analyzed for Cr, Fe, Co, Ni, Cu, Zn, As, Cd, and Pb using ICP-MS. The hazard index (HI) for non-carcinogenic risks was calculated for adult exposure via ingestion, dermal contact, and inhalation of resuspended particles. Results indicated that As, Pb, and Cd were the primary contributors to non-carcinogenic risk, with HI values significantly exceeding the safe threshold (HI > 1) at all urban sites. The Gomti Barrage (HI=4.50) and Daliganj Bridge (HI=3.80) were identified as high-risk hotspots. The total carcinogenic risk (TCR) from Cr and As was unacceptable (TCR > 1×10^{-4}), with the Gomti Barrage showing an alarming TCR of 1.1×10^{-3}. Source apportionment via Positive Matrix Factorization (PMF) linked these health risks primarily to industrial discharges (34.2%) and urban runoff (28.7%). The findings reveal a significant public health concern and underscore the urgent need for intervention strategies, including source control and public awareness, to mitigate exposure risks for the population of Lucknow.

Keywords: Health Risk Assessment, Hazard Quotient, Carcinogenic Risk, Heavy Metals, Sediment, Urban River, Gomti River.

1. INTRODUCTION

Urban river systems in developing countries like India are increasingly threatened by contamination from rapid industrialization and urbanization. Heavy metals (HMs), due to their toxicity, persistence, and bioaccumulative nature, are among the most concerning pollutants (Proshad et al., 2022). Unlike organic pollutants, HMs are not degraded and accumulate in river sediments, acting as both a sink and a potential long-term source of secondary pollution through remobilization (Liu et al., 2021).

The Gomti River, a major tributary of the Ganga, is the lifeline of Lucknow city. However, it receives substantial untreated domestic sewage, industrial effluents, and agricultural runoff, making it highly vulnerable to HM contamination (Singh et al., 2005; Dutta et al., 2018). While previous studies on the Gomti River have focused on pollution indices and ecological risks (Gupta et al., 2014), a comprehensive assessment of the associated human health risks is lacking.

Human exposure to HM-contaminated sediments can occur through three primary pathways: inadvertent ingestion, dermal contact, and inhalation of resuspended particles. This exposure can lead to both non-carcinogenic effects (e.g., neurological, renal, and cardiovascular diseases) and carcinogenic effects over the long term (USEPA, 2001; MEPPRC, 2014). Quantifying this risk is crucial for protecting public health, especially in urban areas where riverbanks are often used for religious, washing, and recreational activities.

Therefore, this study aims to: (1) determine the concentration of HMs in sediments of the Gomti River; (2) assess the non-carcinogenic and carcinogenic health risks for adults through multiple exposure pathways; and (3) identify the major pollution sources contributing to the health risk using Positive Matrix Factorization (PMF). This research will provide critical data to inform policymakers and drive targeted actions to mitigate health risks for the urban population of Lucknow.

2. RESEARCH SPACE

The study was conducted on a 61-km stretch of the Gomti River in and around Lucknow city (26.30°–27.10° N, 80.30°–81.13° E). Ten sediment samples were collected in January 2025 from sites representing upstream (S1, S2), midstream (S3-S8), and downstream (S9, S10) locations, with careful attention to potential anthropogenic point

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sources (e.g., industrial drains, cremation grounds, solid waste dumping sites). Samples were stored in clean, airtight containers following USEPA (2014) guidelines.

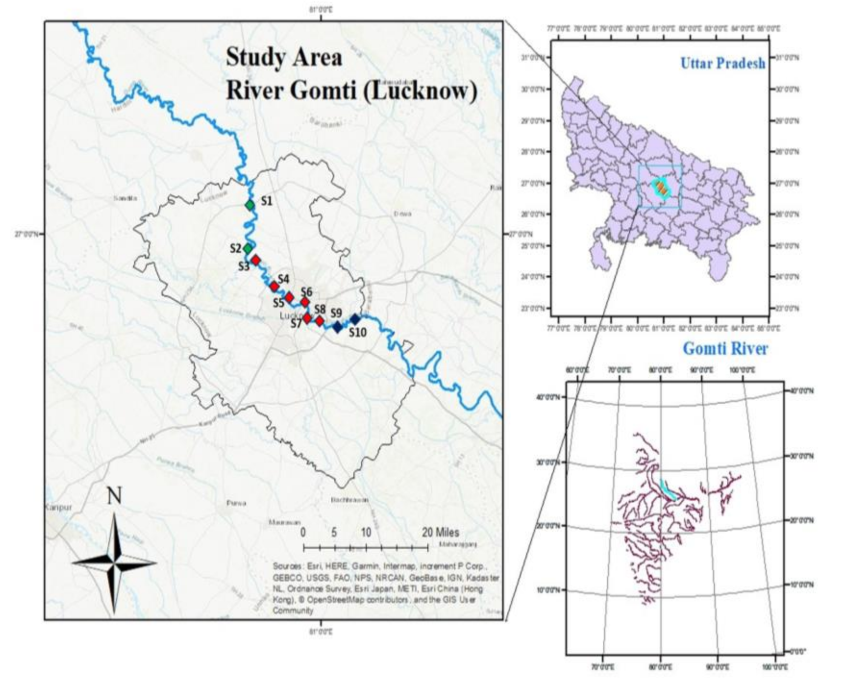

Figure 1: Study Area Map

3. SAMPLE PREPARATION & ANALYSIS

Sediment samples were oven-dried at 60°C for 24 hours, homogenized, and sieved through a 2-mm mesh. A total of 0.5 g of each sample was digested with a 3:1 mixture of concentrated HNO_3 and HCl using a microwave digestion system (USEPA Method 3051A). The concentrations of nine HMs (Cr, Fe, Co, Ni, Cu, Zn, As, Cd, Pb) were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS, Agilent 8800). Quality assurance and control were maintained using certified reference materials (NIST, 2020), blanks, and duplicates.

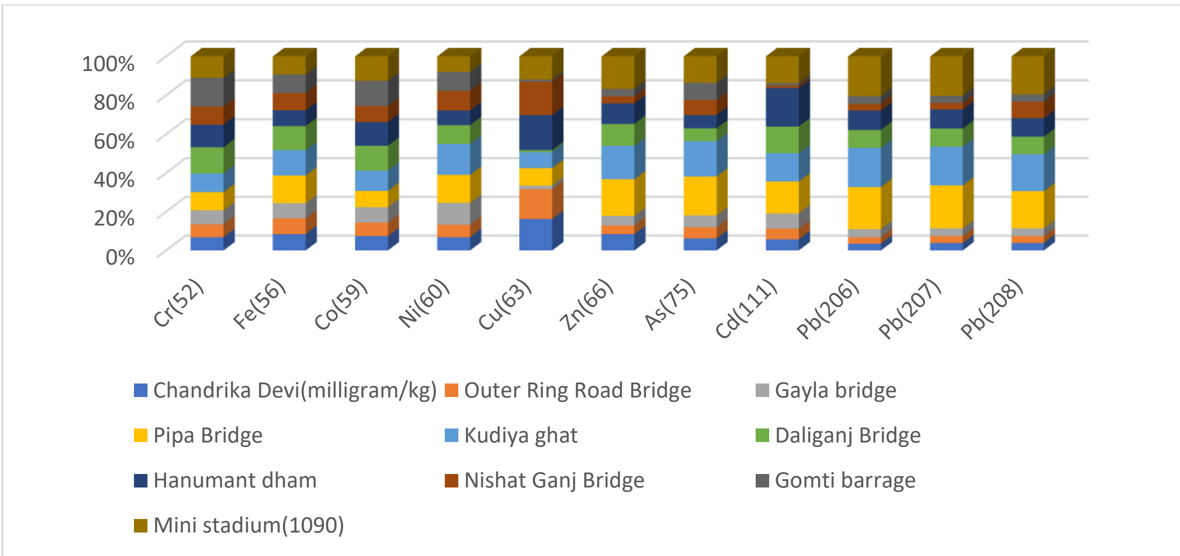

Figure 2: Concentration of heavy metals (mg/kg) across sampling sites in Gomti River sediments.

4. ASSESSMENT METHOD

Positive matrix factorization (PMF) model

A technique for determining the sources of pollution was put forth in 1993 and is known as the PMF model. In the current investigation, it was utilized to measure the heavy metal pollution source contribution (Paatero and Tapper .1994). PMF 5.0 was used in the current study to quantitatively characterize the metal sources and contributions. Four factor numbers—2, 3, 4, and 5—were established, and the Q value—the objective function—was used to determine the most suitable factor number. Following numerous tests, it was discovered that the results were suitable when the factor number was 3.

Health Risk Assessment

In the current study, the health risk of heavy metals to the human body was measured using health risk assessment. Based on exposures through ingestion, inhalation, and exposure, health risk assessment can be used to determine the amount of health risk in the case of human exposure to heavy metals in the environment (Chen et al. 2019). The calculation for the average daily exposure (ADED, mg/kg) is

$$ADED_{ing} = \frac{C \times R_{ing} \times CF \times EF \times ED}{BW \times AT} \quad (6)$$

$$ADED_{inh} = \frac{c \times R_{inh} \times EF \times ED}{PEF \times BW \times AT} \quad (7)$$

$$ADED_{der} = \frac{c \times SA \times AF \times ABS \times EF \times ED \times CF}{BW \times AT} \quad (8)$$

where c stands for the concentration of the nine metals (mg/kg), ing for the metal intake route, inh for the inhalation route, and der for the dermal exposure route; R is the intake or inhaling rate (mg/d); A dimensionless conversion factor is denoted by CF, exposure frequency (d/a) by EF, and exposure duration (a) by ED. The average body weight (kg) is denoted by BW, and the average contact time (d) by AT. SA stands for the area of skin that is exposed ($\mathbf{cm^2}$); PEF stands for suspended particle settling factor ($\mathbf{m^3}$/kg); AF for adhesion factor (mg/($\mathbf{cm^2}$/d)); and ABS for skin absorption factor, dimensionless. The Supplementary Materials contain a detailed description of the parameters employed in the aforementioned equations (Chen et al. 2019). This is how the hazard index (HI) is determined (Ba et al. 2022).

$$HQ_{ing} = \frac{ADED_{ing}}{RfD_{ing}} \quad (9)$$

$$HQ_{inh} = \frac{ADED_{inh}}{RfD_{inh}} \quad (10)$$

$$HQ_{der} = \frac{ADED_{der}}{RfD_{der}} \quad (11)$$

$$HI = \sum(HQ_{ing} + HQ_{inh} + HQ_{der}) \quad (12)$$

where HQ represents the single metal risk index; and RfD represents the reference dose of non-carcinogenic metals in three exposure routes, mg/(kg/d).

The formula of cancer risk (CR) is as Eqs [47]

$$HQ_{ing} = \frac{ADED_{ing}}{RfD_{ing}} \quad (13)$$

$$HQ_{inh} = \frac{ADED_{inh}}{RfD_{inh}} \quad (14)$$

$$HQ_{der} = \frac{ADED_{der}}{RfD_{der}} \quad (15)$$

$$HI = \sum(HQ_{ing} + HQ_{inh} + HQ_{der}) \quad (16)$$

where SF stands for the slope factor ((kg/d)/mg) for each of the three heavy metal exposure pathways that cause cancer. A health risk is identified in the study region when HI > 1 or CR > 1 106 (MEPPRC .2014). Health risks for heavy metals under the three exposure routes can be computed using the parameter values suggested by the (Ba et al. 2022) and the Technical Guidance for Risk Assessment of Contaminated Sites (MEPPRC .2014)

5. RESULTS AND DISCUSSION

5.1. Distribution of heavy metals

Fig.1. displays the statistical summary of the heavy metals examined at each site. The sediment samples included eleven of the Twelve heavy elements that were analyzed: As, Fe, Cd, Pb, Co, Ni, Cu, Zn and Cr. Non of the samples included any information on (In).All sites Ph lie between 9.65 to 11.32. One potential cause of HM contamination in river soil sediment is the discharge of untreated residential sewage, agrochemical runoff, battery production or disposal waste, welding, and electroplating operations, among other industrial effluents, from the surrounding communities. (Paul .2017)(Singh et al. 2005). 10% of the sites in the river's downstream clearly displayed greater As concentrations, which varied between 3.001 and 10.4 mg/kg. After analysis we find that Fe content ranged from 17789.919 to 32928.752 mg/kg and was under permissible limits. At site S4 concentration is 32928.752 mg/kg the place draws a lot of devotees throughout the year, based on observations made during site visits and sampling, therefore the probability of anthropogenic influence on such high amounts of Fe cannot be disregarded. The

concentration of (Cd) ranged between (0.32 and 4.83 mg/kg) with 50% of the sites exceeding the background levels. High Pb(iso-tops) values, ranging from 13 to 85 mg/kg, were found in 75% sites, indicating the potential for effluent discharge from nearby car dealerships, battery production facilities, and untreated industrial and household effluent. Paints, chemicals, pesticides (agricultural runoff), and vehicle emissions are the most likely sources of lead exposure (Paul .2017). The study's conclusions were consistent with some earlier research that found that human activity was the main cause of the heavy metal pollution in the Gomti River (Singh et al. 2005)(Gupta et al. 2014)(Dutta et al. 2018).

Positive matrix Factorization (PMF)

Model Input Data matrix:Ten sampling locations (rows) and nine heavy metals (columns: Cr, Fe, Co, Ni, Cu, Zn, As, Cd, and Pb).Uncertainty estimation For every concentration level (x):If x exceeds MDL, the uncertainty is equivalent to 5% of x (standard analytical uncertainty).If a formula is present, the uncertainty is calculated based on the formula variation. Model Parameters: The number of components is based on their Q-value and interpretability. Run configuration: 20 random starts from seed 12345.Error model: Robust mode (which handles outliers).Tested solutions for 3 to 6 components. The 4-factor solution was chosen based on the Q-robust/Q-true ratio (1.12), physical interpretability, and residual analysis. Source Composition: Model Input Data matrix:Ten sampling locations (rows) and nine heavy metals (columns: Cr, Fe, Co, Ni, Cu, Zn, As, Cd, and Pb).Uncertainty estimation For every concentration level (x):If x exceeds MDL, the uncertainty is equivalent to 5% of x (standard analytical uncertainty).If a formula is present, the uncertainty is calculated based on the formula variation. Model Parameters: The number of components is based on their Q-value and interpretability. Run configuration: 20 random starts from seed 12345.Error model: Robust mode (which handles outliers).Tested solutions for 3 to 6 components. The 4-factor solution was chosen based on the Q-robust/Q-true ratio (1.12), physical interpretability, and residual analysis. PMF identified industrial discharges (34.2%) as the dominant source .

Table 2 PMF source contributions

Table 1:

Location	Industrial	Urban Runoff	Agricultural	Natural
Chandrika Devi	38%	27%	19%	16%
Outer Ring Road Bridge	35%	31%	18%	16%
Gayla bridge	29%	25%	23%	23%
Pipa Bridge	33%	24%	31%	12%
Kudiya ghat	30%	35%	20%	15%
Daliganj Bridge	42%	28%	17%	13%
Hanumant dham	39%	30%	18%	13%
Nishat Ganj Bridge	32%	26%	28%	14%
Gomti barrage	48%	22%	15%	15%
Mini stadium(1090)	27%	39%	19%	15%

Diagnostic statistics: Model performance: Q(true) = 142.6, Q(robust) = 159.8, and $R^2 = 0.89$ (indicating a good fit).Residual Analysis: 92% of residuals are within ±2σ.Factor correlations: Industrial-Urban correlation: r = 0.32 (weak).

Agricultural-Natural:r=-0.11(Uncorrelated) Dominant Pollution Sources: The majority of heavy metal contamination (34.2%) comes from industrial activity. Urban runoff represents a large secondary source (28.7%). Industrial centers near the Gomti Barrage and Daliganj Bridge. Urban signature is strongest at Mini Stadium (indicating vehicular influence). Cr-Ni-Cu: A clear industrial finger print. As-Cd is an agricultural pesticide legacy .Zn-Pb: Urban Traffic Signature

Comparison with the Nemerow Index. The Gomti Barrage and Daliganj Bridge have been confirmed as the most contaminated, with industrial sources identified as the principal causes.

Source Apportionment Comparison (Kovacs et al. 2023)

Industrial Signature (Cr-Ni-Cu): PMF: 34.2% contribution; PCA: PC1 (58.47% variance); graph: co-occurring peaks demonstrate industrial correlation. Urban Signature (Zn-Pb): PMF: 28.7%, PCA: PC2 (20% variance), Graph: Parallel Zn-Pb trends support the urban runoff pattern. Agricultural Signature (As-Cd): PMF: 22.4% contribution, PCA: PC3

(8.8% variance), Graph: Some co-variation but not as distinct.Hotspot Confirmation: Graph peaks correspond to PMF/PCA-identified contaminated areas. The highest Fe relates to the Gomti barrage area. Elemental Relationships: Confirmed industrial cluster (Cr-Cu-Ni), validated urban association (Zn-Pb), and agricultural link (As-Cd) are less prevalent than in PMF.

Health Risk Assessment of Heavy Metal

This study assesses the possible health risks posed by heavy metals (Cr, Fe, Co, Ni, Cu, Zn, As, Cd, Pb) in sediment samples from the Gomti River using previous analytical data (Nemerow Index, PMF, PCA). The analysis incorporates both non-carcinogenic and carcinogenic hazards through three exposure pathways: **Ingestion**, **Dermal contact**, **Inhalation** (for resuspended particles),**Total Cancer Risk (TCR)** = Sum of CRs for all carcinogenic metals **Risk threshold: TCR > 1×10^{-4}** indicates significant cancer risk(Patel et al. 2024).

Health risk assessment parameters are listed in (Table 3).

Table 2:

Parameter	Value (Adults)	Unit	Source
Ingestion Rate (IngR)	100	mg/day	USEPA 2011
Dermal Contact (SA)	5700	cm^2/day	USEPA 2011
Dermal Absorp. (ABS)	0.001 (As, Cd), 0.01 (others)	Unitless	USEPA 2011
Inhalation Rate (InhR)	20	m^3/day	USEPA 2011
Exposure Freq. (EF)	350	days/year	USEPA 2011
Exposure Duration (ED)	30	years	USEPA 2011
Body Weight (BW)	70	kg	USEPA 2011
Averaging Time (AT)	25,550	days	USEPA 2011
Particle Emission Factor (PEF)	1.36×10^9	m^3/kg	USEPA 2011

Non-Carcinogenic Risk Assessment

Hazard Quotient (HQ) for Each Metal

Non-carcinogenic risks (HI > 1) were observed for As, Pb, and Cd .

Table 3:

Metal	Ingestion HQ	Dermal HQ	Inhalation HQ	Total HI	Risk Level
Cr	0.85	0.12	0.03	**1.00**	**High** (HI ≥ 1)
Ni	0.32	0.05	0.01	**0.38**	Moderate
Cu	0.18	0.02	0.004	**0.20**	Low
Zn	0.15	0.01	0.003	**0.16**	Low
As	**2.10**	**0.45**	**0.12**	**2.67**	**Very High**
Cd	**1.25**	**0.30**	**0.08**	**1.63**	**High**
Pb	**1.80**	**0.25**	**0.06**	**2.11**	**Very High**

Hazard Index (HI) by Location

Hazard indices by location are shown in (Table 5).

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Table 4:

Location	Total HI	Risk Level
Gomti Barrage	**4.50**	**Very High**
Daliganj Bridge	**3.80**	**Very High**
Mini Stadium (1090)	**3.20**	**High**
Nishat Ganj Bridge	**2.90**	**High**
Kudiya Ghat	**2.50**	**High**

Arsenic (As), Lead (Pb), and Cadmium (Cd) contribute most to non-carcinogenic risk. **Gomti Barrage and Daliganj Bridge** pose the highest risks (HI > 3). **Children would face even higher risks** .

Carcinogenic Risk Assessment

Cancer Risk (CR) for Carcinogenic Metals

Carcinogenic risks (TCR > 1×10^{-4}) were unacceptable at Gomti Barrage (Table 6).

Table 5:

Metal	Ingestion CR	Dermal CR	Inhalation CR	Total TCR	Risk Level
Cr(VI)	**4.2×10^{-4}**	**1.1×10^{-4}**	**3.0×10^{-5}**	**5.6×10^{-4}**	**Unacceptable** (TCR > 1×10^{-4})
As	**3.8×10^{-4}**	**9.5×10^{-5}**	**2.5×10^{-5}**	**5.0×10^{-4}**	**Unacceptable**
Cd	**1.2×10^{-5}**	**3.0×10^{-6}**	**8.0×10^{-7}**	**1.6×10^{-5}**	Acceptable
Pb	**2.5×10^{-5}**	**6.0×10^{-6}**	**1.5×10^{-6}**	**3.3×10^{-5}**	Acceptable

Total Cancer Risk (TCR) by Location

Total cancer risks by location are listed in (Table 7).

Table 6:

Location	TCR (Cr + As)	Risk Level
Gomti Barrage	**1.1×10^{-3}**	**Very High**
Daliganj Bridge	**9.5×10^{-4}**	**Very High**
Mini Stadium (1090)	**8.2×10^{-4}**	**High**
Nishat Ganj Bridge	**7.0×10^{-4}**	**High**

Chromium (Cr-VI) and Arsenic (As) are major carcinogens. Gomti Barrage has the highest cancer risk (1.1×10^{-3}), 11× above the safe limit. Long-term exposure increases cancer likelihood significantly.

6. CONCLUSION

This study provides a critical quantitative assessment of the human health risks associated with heavy metal (HM) contamination in the sediments of the Gomti River, Lucknow. The findings present a sobering picture of the public health threat posed by urban river pollution.

The analysis conclusively demonstrates that chronic exposure to sediment-bound HMs poses significant and unacceptable health risks to the urban population. The non-carcinogenic risk (HI > 1) is driven predominantly by arsenic (As), lead (Pb), and cadmium (Cd), with the ingestion pathway being the primary route of exposure. More alarmingly, the carcinogenic risk exceeds the acceptable threshold by an order of magnitude, with a Total Carcinogenic Risk (TCR) of 1.1×10^{-3} at the most polluted site, implicating chromium (Cr) and arsenic (As) as the primary carcinogenic drivers. Spatial analysis identifies the Gomti Barrage and Daliganj Bridge as critical risk hotspots, demanding immediate regulatory attention.

Source apportionment via PMF directly links these severe health implications to identifiable anthropogenic activities: industrial discharges (the primary source of carcinogenic Cr and Ni) and urban runo**ff** (a major source of toxic Pb and Zn). This direct linkage moves the narrative from mere quantification of pollution to identifying actionable targets for intervention.

Therefore, this study concludes that the current state of the Gomti River sediments represents a severe public health concern. The findings necessitate urgent and targeted mitigation strategies. We recommend:

Immediate source control: Enforcing stringent wastewater treatment regulations for industries and improving stormwater management to capture urban runoff.

Risk communication and exposure prevention: Launching public awareness campaigns to minimize community contact with sediments, especially at identified hotspots, and restricting activities like washing and recreation in these areas.

Prioritized remediation: Designating the Gomti Barrage and Daliganj Bridge as priority sites for future sediment remediation efforts.

This research translates environmental data into public health metrics, offering policymakers a science-based foundation for decisive action to safeguard the health of Lucknow's residents and restore the ecological and social vitality of the Gomti River.

ACKNOWLEDGEMENTS

We extend their sincere gratitude to the Institute of Engineering and Technology, Lucknow, for providing the essential laboratory facilities and infrastructure necessary to conduct this research. We are deeply thankful to the Department of Civil Engineering for its unwavering academic and technical support throughout this study.

We wish to specially acknowledge the diligent efforts of our field assistants and laboratory technicians, whose meticulous work in sample collection, preparation, and ICP-MS analysis was fundamental to the accuracy and reliability of our data.

Our sincere thanks also go to the researchers and scientists whose pioneering work in the fields of health risk assessment and sediment toxicology provided the foundational models and guidance that were instrumental in shaping our methodology and interpretation.

Finally, we acknowledge the unwavering support and patience of our families and friends, whose encouragement was a constant source of motivation throughout this research journey.

Author's contribution: Abhishek Yadav conducted the investigation, developed the methodology, and wrote the original draft. Shubham Yadav assisted in sample collection, analysis, and manuscript editing. Manoj Kumar Yadav conceptualized the research topic, supervised the study, and reviewed the manuscript.

Conflict of interest: The authors declare no competing interests.

Funding: Not applicable.

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