`Vol. 6, No. 4, pp. 375-387, (December2025)
DOI: 10.21608/aujes.2025.412070.1359
Aswan University Journal of Environmental Studies (AUJES)
Online ISSN: 2735-4237, Print ISSN: 2735-4229
Journal homepage: https://aujes.journals.ekb.eg/ E-mail: AUJES@aswu.edu.eg

Original research

Heavy Metals in River Jega Northwestern Nigeria: Ecological and Human Health Risk Assessment

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Received: 08/08/2025 Accepted: 07/11/2025

Abstract:

River Jega in Kebbi State, Nigeria, provides essential ecosystem services such as water for drinking and domestic use, agriculture, transportation, and fishing. However, these activities contribute to pollution and pose health risks, yet the river's safety has not been assessed in recent years. This study evaluated water samples from the river for levels of heavy metals including cadmium (Cd), copper (Cu), chromium (Cr), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn). Cd concentrations exceeded the NSDWQ and WHO limit of 0.003 mg/L in all months except December. Fe surpassed the 0.3 mg/L threshold in all months except February whereas Mn concentrations remained below the safe limit of 0.4 mg/L except in September, October, November, and December. Ni exceeded its limit (0.001 mg/L) in September, October, February, March, and April, while Pb was undetectable from September to December but exceeded safe limits of 0.001 mg/L in other months. Cu, Cr, and Zn remained within safe limits (2.0 mg/L, 0.3 and 3 mg/L, respectively) throughout the year. Average daily ingestion (ADI) and dermal contact (ADC) with the heavy metals were within acceptable ranges. However, their hazard quotient (HQ) indicated potential non-carcinogenic risks from Cr ingestion and dermal exposure to Ni and Pb. Carcinogenic risk (CR) and heavy metal pollution index (HPI) values were below critical thresholds. These results suggest that the water may pose a significant health risk. It is imperative to implement routine monitoring programs and enforce stricter regulations on pollutant discharge.

Keywords: Chromium (Cr), Hazard quotient (HQ), Heavy metal pollution index (HPI), Jega, Lead (Pb).

1- Introduction

Rivers are vital for numerous ecological, social, and economic reasons. They provide critical ecosystem services, including freshwater resources essential for drinking, agriculture, and industrial processes, while also supporting diverse plant and animal life.

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Beyond their ecological roles, rivers are fundamental in shaping landscapes, facilitating transportation, and generating hydroelectric power.

Historically, rivers have been central to the development of major cities and civilizations, offering a reliable water source and fertile lands for agriculture (Yahaya *et al*., 2024a). Rivers serve as dynamic connectors, linking people, places, and ecosystems, and have long inspired diverse cultural beliefs, values, and ways of life (Anderson *et al*., 2019). They also function as natural corridors that enhance urban ventilation and mitigate urban heat by creating localized cooling effects around riverbanks (Guo *et al*., 2023). Furthermore, rivers are valuable for tracing ancient human migration patterns and understanding the geographical distribution of populations, as they often acted as natural guideposts for migratory routes (Nagel *et al*., 2023). The role of rivers extends even to physiological processes. Water derived from rivers is critical in maintaining internal homeostasis across humans, animals, and plants. It supports vital bodily functions such as temperature regulation, fluid balance, nutrient transport, and waste removal (Seleiman *et al*., 2021; Robayo-Amortegui *et al*., 2024).

However, the benefits that rivers provide are increasingly under threat due to pollution. Anthropogenic activities such as urbanization, industrialization, and population growth are major drivers of river contamination. Globally, approximately two million tons of sewage, industrial effluent, and agricultural runoff are discharged into water bodies daily (du Plessis, 2022). This pollution leads to the proliferation of infectious waterborne diseases such as diarrhea, cholera, dysentery, and typhoid, which collectively cause more deaths annually than war and other forms of violence (du Plessis, 2022). Degradation of river water quality not only jeopardizes human health but also diminishes ecosystem functioning and impedes socioeconomic development. Poor water quality can affect the health sector by reducing labor productivity, impact agriculture by lowering food quality and yields, and harm industries like tourism, real estate, and aquaculture that depend on healthy ecosystems (Russ *et al*., 2022). The economic repercussions are measurable: moderate river pollution can reduce downstream economic growth by approximately 1.4%, while severe pollution can result in a 2% decline in growth (Russ *et al*., 2022). Protecting rivers is therefore critical, not just for preserving biodiversity and ecosystem services, but also for safeguarding human health, cultural heritage, and sustainable economic development.

Among the various classes of pollutants released into rivers, heavy metals are among the most intensively studied due to their non-biodegradable nature, persistence in the environment, and toxicity even at trace concentrations (Ogbeide and Henry, 2024). The most commonly detected heavy metals in river systems include lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), arsenic (As), and mercury (Hg) (Kadim and Risjani, 2022; Xu *et al*., 2024). Heavy metal contamination poses substantial risks to both ecological integrity and human health. Due to their inability to degrade naturally, heavy metals accumulate in aquatic organisms through bioaccumulation and biomagnification, eventually entering the human food chain and causing a range of adverse health effects such as neurological disorders, kidney damage, and cancer (Niampradit *et al*., 2024). Ecologically, the presence of heavy metals disrupts aquatic ecosystems by reducing species diversity, impairing reproduction, and causing physiological and behavioral changes in aquatic organisms (Ahamad *et al*., 2024). To safeguard the functions and services provided by rivers, it is essential to monitor heavy metal concentrations regularly. This is typically achieved by analyzing heavy metal levels in river water and comparing the results against international guidelines such as those established by the World Health Organization (WHO) or national environmental standards. In addition to concentration assessments, recent approaches emphasize evaluating the potential health and ecological risks associated with detected heavy metals. Such risk assessments help identify threats to ecosystem services and public health before irreversible damage occurs.

In Kebbi State, northwestern Nigeria, the Jega River in Jega town provides crucial ecosystem services, including drinking and domestic water supply, transportation, animal grazing along its banks, fishing, and irrigation. However, these activities may be contributing to the river's pollution, as evident by visible water discoloration and accumulated waste along the banks. Moreover, the Jega River discharges directly into the River Niger—the largest and most vital river system in Nigeria—serving numerous downstream communities. Consequently, contamination of the Jega River could have far-reaching environmental and public health implications. Periodic safety assessments of the river are therefore critical to prevent potential health crises and ecological degradation. Although a recent study evaluated the concentrations of heavy metals in the Jega River, the associated health and ecological risks were not previously assessed. Such evaluations are necessary to generate comprehensive data that can inform policymakers, stakeholders, and local communities about the state of the river and guide effective management interventions. Accordingly, the present study aims to employ standard mathematical models to evaluate the health and ecological risks posed by heavy metals in the Jega River. This approach will provide an evidence-based foundation for developing policies and strategies to ensure the sustainable management of the river and the protection of the communities depending on it.

2. Materials and Methods

2.1 Description of study site

Jega is a prominent town located in Kebbi State, northwestern Nigeria, positioned at approximately latitude 12°13'19.88" N and longitude 4°22'46.67" E (Figure 1). It serves as a major transportation hub, strategically situated at the crossroads of routes leading to Sokoto, Birnin Kebbi, Yauri, and Kamba. The town lies within the Sudan savanna zone, characterized by grassland interspersed with scattered trees, reflecting the typical vegetation of this climatic region. The climate in Jega is marked by extreme temperatures. The wet season, which extends from June to October, is hot and humid, while the dry season, dominated by the harmattan winds, brings extremely hot days and cooler nights. Temperatures often exceed 40°C during the peak of the dry season, and can drop below 20°C during the harmattan period. As of 2025, the estimated population of Jega town is approximately 73,495 residents (World Population Review, 2025). The majority of the inhabitants belong to the Hausa and Fulani ethnic groups, although a significant number of settlers from the Yoruba and Igbo ethnic groups also reside in the town, contributing to its cultural diversity.

A prominent natural feature of Jega is River Jega, which traverses the southern part of the town. This river is an important component of the Sokoto-Rima basin and a major tributary of the Zamfara River, eventually discharging into the River Niger. River Jega plays a critical role in the local economy and daily life, supporting intensive agricultural activities along its banks. Residents also rely on the river for fishing, bathing, laundry, and as a source of drinking and domestic water. During the wet season, when the river's volume increases, it also serves as a means of transportation. Despite its importance, the river faces significant environmental challenges. Open defecation, waste dumping, and other forms of pollution are common along its course. These practices have the potential to degrade water quality, posing serious health risks to the community and threatening aquatic ecosystems. Regular monitoring and assessment of the river's water quality are therefore essential to mitigate potential health hazards and preserve the river's ecological integrity.

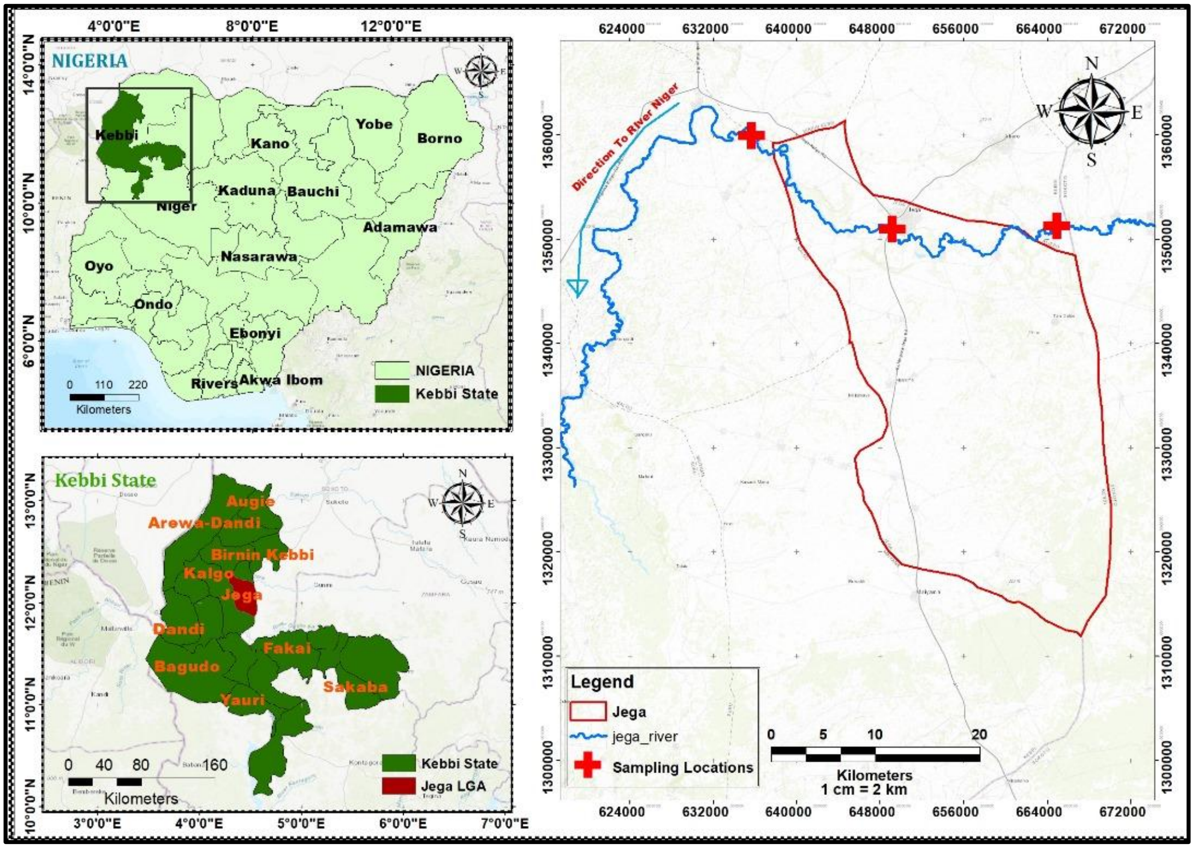

Figure 1: map of the study area.

2.2 Sample collection

Water samples were collected monthly from three designated points along the Jega River: upstream (approximately 5 km before Jega town), midstream (within Jega town), and downstream (approximately 5 km after Jega town). Sampling was carried out over a 12-month period, from September 2021 to August 2022, to capture seasonal variations in water quality across both the rainy and dry seasons. These locations were strategically selected to provide a comprehensive spatial representation of the river's water quality, accounting for natural influences and anthropogenic activities in and around Jega town. At each sampling point, water samples were randomly collected in triplicate using clean, pre-rinsed 1000 mL polyethylene terephthalate (PET) bottles. The bottles were immediately sealed to prevent contamination. Each month, three samples from each location were collected and pooled, resulting in a total of nine samples per month. Over the course of the study, 108 water samples were collected. To preserve sample integrity, the bottles were placed in opaque black polyethylene bags to minimize light exposure, properly sealed, and transported under cool conditions to the laboratory. Upon arrival, the samples were stored at 4 °C in a refrigerator until physicochemical and heavy metal analyses were performed.

2.3 Heavy metal analysis

Heavy metal analysis was conducted following a modified standard acid digestion procedure adapted from Yahaya *et al*. (2024b). Prior to analysis, each water sample was thoroughly homogenized to ensure uniform distribution of constituents. A 100 mL aliquot of the sample was measured and transferred into a pre-cleaned 250 mL beaker. To initiate digestion, 5 mL of concentrated nitric acid (HNO_3) was added to the sample. The mixture was gently heated on a hot plate in a fume hood until near dryness to oxidize organic matter and concentrate the metals. After cooling, an additional 5 mL of concentrated HNO_3 was added to enhance complete digestion, and the sample was reheated until a light-colored residue remained, indicating sufficient mineralization. To dissolve the residue, 1 mL of concentrated HNO_3 was added, followed by gentle heating at a low temperature. The resulting solution was allowed to cool, then quantitatively transferred into a 100 mL volumetric flask. The beaker was rinsed several times with deionized water, and the rinses were added to the flask, which was then brought up to volume with deionized water. The final digested samples were filtered using Whatman No. 42 filter paper to remove any remaining particulates. The concentrations of cadmium (Cd), copper (Cu), chromium (Cr), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn) in the digests were determined using a UNICAM 969 atomic absorption spectrophotometer (AAS), operated according to the manufacturer's guidelines. Appropriate blanks and calibration standards were run to ensure accuracy and precision.

2.4 Quality control and assurance

To ensure the accuracy and reliability of the analytical results, rigorous quality control and quality assurance (QC/QA) protocols were implemented throughout the study. Only high-purity, analytical-grade reagents and chemicals were used in all procedures to minimize the risk of contamination. All glassware and plastic containers were thoroughly decontaminated before use by soaking them in concentrated nitric acid (HNO_3) for 24 hours. After acid treatment, the containers were thoroughly rinsed multiple times with ultrapure deionized water to remove any residual acid or contaminants. To avoid the introduction of extraneous metals, all sample collection, handling, and preparation were performed using non-metallic tools and surfaces. Contact with metallic instruments was strictly avoided during all stages of analysis. Blank samples, prepared using ultrapure deionized water and subjected to the same digestion and analysis procedures as the actual samples, were run periodically alongside test samples. These blanks served to detect and correct for any potential background contamination or systematic errors. Each water sample was analyzed in triplicate to assess analytical precision, and the results were evaluated for consistency by ensuring that variations among replicates remained within acceptable limits (typically less than 5% relative standard deviation).

2.5 Health risk assessment of the heavy metals

2.5.1 Non‑ carcinogenic health risk assessment

The non-carcinogenic risk assessment involved the calculation of average daily intake (ADI), average dermal contact (ADC) and hazard quotients via ingestion and dermal contact (HQ) of the individual water samples. Employing the guidelines presented by Duggal et al. (2017), the CDI and HQ risks posed by ingesting a single trace of element are computed for the children and adult.

$$ADI = \frac{Cn\ x\ EF\ x\ ED\ x\ IR}{BW\ x\ AT} \quad (1)$$

$$ADC = \frac{Cn\ x\ Sa\ x\ Pc\ x\ EF\ x\ ED\ x\ Et}{BW\ x\ AT} \quad (2)$$

$$HQ = \frac{ADI\ /ADC}{RFD} \quad (3)$$

where CDI is the chronic daily intake otherwise referred to as the exposure dose (mg/kg/day); Cn signifies the concentration of heavy metal in water (mg/L); EF is used to denote the exposure frequency (EF is equivalent to 365 days per year); ED signifies the exposure duration (adult ED = 55 years while children ED = 6 years) average life time of a Nigerian (Yahaya *et al.*, 2019); BW is the body weight (equivalent to 65 kg and 15 kg for adult and children, respectively); AT represents the average time (equivalent to 20075 days and 2190 days for adult and children, respectively) (Yahaya *et al.*, 2019). From equation 2, *SSA* = 28,000, *DPC* = 0.0002 for Ni, 0.001 for Cd, Cu, Fe, and Mn, 0.002 for Cr, and 0.004 for Pb, where *SSA* stands for skin surface area (cm^3) and *PC* denotes dermal permeability constant (cm/h) (Yahaya *et al*., 2020).

In equation 3, *RFD* represents the oral/dermal reference dose (mg/L/day). According to Yahaya *et al*. (2020), *RFD* (oral and dermal) for Pb = 0.0035, 0.00525; Ni = 0.02, 0.0054; Cd = 0.005, 0.0005; Cr = 0.0003, 0.002; Zn = 0.3, 0.3; Cu = 0.150, 0.12; Mn = 0.14, 0.046 = Fe = 0.700, 0.007 (Mgbenu and Egbueri 2019).

2.5.2 Carcinogenic health risk assessment

To assess the carcinogenic risks associated with the use of the groundwater, the heavy pollution index (HPI), summation of heavy metal pollution index (HPI) and probability of cancer risk (PCR) were calculated using the formulae given in Equation 3, 4 and 5.

$$HPI = \frac{Cn}{MPC} \quad (3)$$

$$\sum HPI = Cd + Cu + Cr + Fe + Mn + Ni + Pb + Zn \quad (4)$$

$$PCR = CDI \times SF \quad (5)$$

Where Cn is the concentration of heavy metal, MPC is the maximum permissible concentration of each heavy metals (Equation 3). Where CDI is the chronic daily intake and SF is the slope factor (mg/kg/day) (Equation 4). The acceptable limit for individual heavy metal index is <2, whereas the acceptable limit for summation of the heavy metal index is <100.

An acceptable PCR value is $\leq 1\times10^{-6}$, which means on average, the probability is that approximately 1 per 1,000,000 will develop cancer as a consequence of the exposure to a carcinogen (Yahaya *et al.*, 2021). However, risk in the range of 1×10^{-6} to 1×10^{-4} typically has been reported to be acceptable. In this study, the SF values for calculating the CR of the heavy metals (carcinogens) are given as: Pb (0.0085), Cr (0.05), Cd (0.38), and Ni (0.91)

2.6 Data analysis

Data were statistically analyzed and presented as mean ± standard deviation (SD) using the Statistical Package for the Social Sciences (SPSS), version 21. In addition, health risk assessment parameters, including the Average Daily Intake (ADI), Hazard Quotient (HQ), Heavy Metal

Index and Cancer Risk (CR), were computed to evaluate potential human health risks associated with exposure to the heavy metals. These risk metrics were calculated using standard equations integrated into the SPSS environment.

3. Results and Discussion

3.1 Concentrations of heavy metals in the water samples

The concentrations of heavy metals in the river, monitored from the beginning of the study in September 2023, are presented in Table 1. With the exception of December, cadmium (Cd) levels consistently exceeded the Nigerian Standard for Drinking Water Quality (NSDWQ, 2020) and the World Health Organization (WHO, 2022) permissible limit of 0.003 mg/L, peaking at 0.02 mg/L in February, March, and July. Copper (Cu) concentrations remained within the safe limit (1.00 mg/L for NSDWQ and 2.0 mg/L for WHO) throughout the year, ranging from a minimum of 0.01 mg/L in June to a maximum of 0.6 mg/L in May. Chromium (Cr) levels, with a permissible threshold of 0.05 mg/L for NSDWQ and 0.3 mg/L for WHO, stayed within acceptable limits all year. The lowest Cr concentration (0.01 mg/L) was recorded in March, April, and May, while the highest (0.06 mg/L) was observed in January. Iron (Fe) concentrations exceeded the recommended limit of 0.3 mg/L in all months except February (0.1 mg/L), with the highest level recorded in December (1.4 mg/L). Manganese (Mn) concentrations remained below the safe limit (0.2 mg/L for NSDWQ and 0.4 mg/L for WHO), except in September, October, November, and December, when they exceeded this threshold. Nickel (Ni) levels surpassed the permissible limit of 0.001 mg/L and 0.02 mg/L (WHO and NSDWQ, respectively) in September, October, February, March, and April, but were below detectable levels in the other months. Lead (Pb) was undetectable from September through December, but exceeded the tolerable limit (0.01 mg/L for NSDWQ and 0.001 mg/L for WHO) in the remaining months, reaching a peak of 0.13 mg/L in August. Zinc (Zn) levels remained well below the permissible limit of 3 mg/L throughout the study period, with the highest concentration (0.14 mg/L) recorded in November.

The monthly variations and non-permissible levels of heavy metals in the river suggest that both natural processes and human activities are contributing to the river's heavy metal burden. Our results align with the findings of Shabanda *et al*. (2013), who reported chromium (Cr) and manganese (Mn) concentrations above permissible limits in River Jega. Similarly, Yahaya *et al*. (2024a) documented intolerable levels of Fe, Cd, and Pb in River Bunza, a nearby waterbody subjected to similar anthropogenic pressures and land-use practices. In contrast, Bawa *et al*. (2018) reported no significant heavy metal contamination in River Jega, while Ibrahim *et al*. (2024) found heavy metal concentrations, particularly Fe, Pb, and Cd, within acceptable limits in the Augie River, another adjacent river system. These discrepancies may be attributed to spatial variations in pollution sources, the intensity of human activities, and seasonal sampling differences. Although River Jega, River Bunza, and Augie River are located within the same ecological zone, the nature and intensity of human activities vary significantly. Unlike Augie River, both Jega and Bunza Rivers receive substantial input from artisanal mining, industrial waste, and poorly managed urban runoff, which likely contribute to the elevated concentrations of heavy metals observed in this study.

The sources of heavy metals in the river may vary. Cadmium contamination may originate from various sources including small-scale mining, improper disposal of batteries, municipal landfills, fossil fuel combustion, and industrial effluents (Wang *et al*., 2020). Around River Jega, intensive farming practices, waste dumping, and dust emissions from vehicular traffic are prevalent and likely contribute to Cd accumulation. Iron presence in the river may be attributed to both geogenic and anthropogenic factors. The riverbed comprises iron-rich rocks whose weathering can release Fe into the water. Additional inputs may come from agricultural runoff, industrial discharges, and the erosion of iron-bearing soils and construction materials. Sarkar and Shekhar (2018) identified these as common sources of Fe in river systems. Manganese concentrations may be elevated due to natural weathering of Mn-bearing rocks, leachate from nearby landfills, and mining activities in the surrounding region (Usman *et al*., 2021). Similarly, Ni contamination may result from emissions of poorly maintained vehicle engines, industrial discharges, and leaching from nickel-containing consumer products such as coins, jewelry, and metal-plated items (Begum *et al*., 2022). Lead (Pb) contamination in river systems can stem from a wide range of sources including corroded plumbing materials, industrial effluents, deteriorating lead-based paints, and weathering of Pb-rich geological formations (Wei *et al*., 2023). In the context of River Jega, frequent disposal of household waste containing lead-based materials and unregulated artisanal mining are likely contributors.

Table 1: Concentrations of heavy metals in the water samples

Month	September	October	November	December	January	February	March	April	May	June	July	August	Mean	WHO Standards (2022)	Nigerian Standard Limit (NSDWQ, 2020)
Cd	0.01	0.01	0.01	0.003	0.01	0.02	0.02	0.01	0.01	0.01	0.02	0.01	0.012±0.005	0.003	0.003
Cu	0.08	0.07	0.06	0.05	0.20	0.30	0.40	0.51	0.60	0.01	0.03	0.03	0.195±0.207	2.00	1.00
Cr	0.03	0.03	0.02	0.03	0.06	0.02	0.01	0.01	0.01	0.05	0.05	0.02	0.028±0.169	0.3	0.05
Fe	1.20	1.20	1.20	1.40	0.40	0.10	0.34	0.40	0.42	0.80	1.10	0.98	0.795±0.439	0.3	0.3
Mn	0.70	0.68	0.73	0.70	0.31	0.21	0.30	0.30	0.20	0.20	0.10	0.10	0.377±0.249	0.1-0.4	0.2
Ni	0.10	0.10	0.00	0.00	0.00	0.10	0.10	0.10	0.00	0.00	0.00	0.00	0.042±0.051	0.001	0.02
Pb	0.00	0.00	0.00	0.00	0.03	0.10	0.02	0.03	0.05	0.06	0.08	0.13	0.041±0.043	0.001	0.01
Zn	0.13	0.12	0.14	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.041±0.061	0.1-3	3.0

Note: Values were presented as mean ± SD (n=3) and mg/L; Cd = Cadmium, Cu = Copper, Cr = Chromium, Fe = Iron, Mn = Manganese, Ni = Nickel, Pb = Lead, and Zn= Zinc

3.2 Potential health risks of the heavy metals in the water

3.2.1 Non-carcinogenic health risk

Table 2 presents the average daily intake (ADI) and average dermal contact (ADC) values for heavy metals in the water. Both ADI and ADC values for all the assessed heavy metals remained within the recommended safety threshold of 1, indicating low risk from exposure through ingestion and skin contact. Except for chromium (Cr), which had a hazard quotient (HQ) of 3, all metals had ingestion HQ values within the recommended limit of 1 (Table 3). Similarly, dermal exposure HQ values were within acceptable limits for most metals, except for nickel (Ni) and lead (Pb), which showed elevated HQs of 1.85 and 34.29, respectively, indicating potential health concerns through skin contact.

These results indicate a potential risk of non-carcinogenic health effects associated with regular use or exposure to the river water. Prolonged exposure to even low concentrations of Cr can adversely affect the skin, eyes, and respiratory and immune systems. It has also been linked to oxidative stress, DNA damage, and tumorigenesis due to its ability to generate reactive oxygen species and interfere with cellular processes (Georgaki *et al*., 2023). Dermal exposure to Ni, especially when prolonged or repetitive, may result in allergic contact dermatitis, contact urticaria, ocular hypersensitivity, oral mucosal allergic reactions, and granulomatous skin responses (Roach *et al*., 2024). Similarly, chronic exposure to lead, particularly through occupational or environmental contact, has been associated with dermatological issues such as skin inflammation, reduced elasticity, pigmentation changes, and impaired skin hydration (Rerknimitr *et al*., 2019).

Table 2: Average daily intake and average dermal contact of heavy metals

Heavy metals	ADI	ADC	RDI
Cd	0.0004	0.0013	0.060
Cu	0.006	0.021	0.900
Cr	0.0009	0.006	0.200
Fe	0.025	0.086	10.00
Mn	0.012	0.041	-
Ni	0.001	0.001	0.500
Pb	0.001	0.018	0.210
Zn	0.001	0.004	8.000

ADI= average daily intake, ADC= average dermal contact, RDI= recommended daily intake (Yahaya *et al.*, 2022)

Table 3: Hazard quotient via ingestion and dermal contact of heavy metals

Heavy metals	HQ (ingestion)	HQ (dermal)	RDL
Cd	0.80	0.20	
Cu	0.15	0.18	
Cr	3.00	0.002	
Fe	0.04	0.123	<1
Mn	0.08	0.919	
Ni	0.07	1.85	
Pb	0.37	34.29	
Zn	0.004	0.013	

RDI= recommended daily limit

3.2.2 Carcinogenic health risk of the heavy metals

Table 4 summarizes the heavy metal index (HMI) while Table 5 reveals the carcinogenic risk (CR) associated with the metals.

Chromium (Cr), Cd, Ni, and Pb are classified by the International Agency for Research on Cancer (IARC) as known or probable human carcinogens (Aendo *et al*., 2022). Their presence in drinking or surface water can pose long-term cancer risks if concentrations exceed permissible thresholds. Nevertheless, in this study, the calculated carcinogenic risk (CR) values for all heavy metals were within the acceptable benchmark (CR < 1), indicating that the current levels may not pose significant carcinogenic threats to human health. Additionally, the Heavy Metal Pollution Index (HPI) for River Jega was found to be within the critical value of 100, suggesting that the overall metal contamination level is within acceptable environmental standards and may not yet pose serious threats to aquatic life or ecological functions. However, it is important to acknowledge a limitation of this assessment: not all potential heavy metals were included in the evaluation. The presence of other undetected or unmeasured metals could elevate the HPI beyond the critical threshold, thus increasing ecological and human health risks. Furthermore, while regulatory agencies provide permissible limits for heavy metals, it is widely recognized that in a strict environmental and toxicological context, there are no truly “safe” levels for heavy metals. Even trace concentrations can accumulate over time in biota, sediments, and human tissues, leading to chronic exposure risks. Therefore, the detection of Cr, Ni, Pb, and Cd above WHO and national safety standards in some samples underscores the need for caution, ongoing monitoring, and mitigation measures to protect both public health and environmental integrity.

Table 4: Heavy metal index

Heavy metals	HMI
Cd	4.00
Cu	0.098
Cr	0.093
Fe	2.65
Mn	0.928
Ni	42.00
Pb	41.00
Zn	0.014
∑HMI	90.79
Permissible limit	<100

Table 5: Carcinogenic risk assessment

Heavy metals	PCR
Cd	1.52×10^{-4}
Cu	-
Cr	4.5×10^{-5}
Fe	-
Mn	-
Ni	9.1×10^{-4}
Pb	1.52×10^{-6}
Zn	-
Permissible	10^{-4}-10^{-6}

4. Conclusion

The results revealed the presence and potential risks of heavy metal contamination in River Jega. Cadmium (Cd) and iron (Fe) consistently exceeded World Health Organization (WHO) limits during most of the sampling period, while manganese (Mn), nickel (Ni), and lead (Pb) appeared at elevated levels in some months. These patterns suggest that both geogenic factors and intensified anthropogenic activities such as artisanal mining, industrial discharge, agricultural runoff, and improper waste disposal are significant contributors to the river's heavy metal burden. The estimated average daily intake (ADI), dermal contact levels (ADC), and carcinogenic risk (CR) values for the detected heavy metals were below the critical threshold (CR < 1). However, hazard quotient (HQ) analysis revealed potential non-carcinogenic health risks associated with ingestion of Cr and dermal exposure to Ni and Pb. The Heavy Metal Pollution Index (HPI) was below the environmental concern level of 100, indicating that the overall contamination may not yet pose serious ecological threats. Nonetheless, the detection of several metals above recommended limits, and the possibility of unmeasured metals contributing additional risk, highlight the need for continued vigilance.

Given these findings, it is imperative to implement routine monitoring programs, enforce stricter regulations on pollutant discharge, and promote public awareness on the dangers of heavy metal pollution. Comprehensive mitigation strategies must be adopted to safeguard both human health and the ecological integrity of River Jega and its surrounding ecosystems.

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