



Trace Metal Levels in Sediments and Muscle of Edible Fish Species from the Kasai River, Democratic Republic of the Congo

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Abstract Kasai River receives *inter alia* discharges of mining wastewaters, resulting in occasionally massive fish kills. This study quantified trace metals, including Hg, Pb, Cd, Cu, Sc, Zn, Ni, Cr, As, and Co, in surface sediments and edible fish collected on a stretch of the Kasai River near the city of Bandundu. Metal analysis were performed using inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700x) and an Advanced Mercury Analyzer (AMA-254) for total Hg. The river sediments showed an enrichment in metal concentrations, with Cu concentrations up to 57 mg kg⁻¹, Zn up to 279 mg kg⁻¹, Ni up to 70 mg kg⁻¹, Pb up to 69 mg kg⁻¹, and

Hg < 0.17 mg kg⁻¹, exceeding at some sites the Sediment Quality Guidelines adopted by Canada. Sediments acted as significant reservoirs for trace metals, with retention strongly influenced by organic matter and calcium carbonate content, while metal bioavailability and accumulation in fish reflected both geochemical and anthropogenic factors. Species-specific selenium-to-mercury molar ratios (0.5–31.7) indicated differential protective effects against Hg toxicity. Ecological risk indices indicated moderate to considerable risk (RI ≈ 170–207), with Hg, Cd, and Pb as major contributors. In fish muscle, Pb concentrations reached 1.6 mg kg⁻¹, Cd 0.7 mg kg⁻¹, and Hg 1.0 mg kg⁻¹, while other elements remained below safety thresholds. Human health risk assessment, including Estimated Daily Intake (EDI), Target Hazard Quotients (THQ), Hazard Index (HI ≤ 1.9), and Cancer Risk (CR ≤ 4.6 × 10⁻¹⁰), generally suggested low health risk for the moment. These findings highlight the need for continued monitoring of ecological and dietary exposure risks in the Kasai River basin.

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1 Introduction

The contamination of aquatic ecosystems by inorganic micropollutants, such as trace metals, has

become a major environmental concern worldwide due to their toxicity, bioaccumulation, persistence, and non-biodegradability (Akonga et al., 2025; Tarigan et al., 2025). Sources of these micropollutants include untreated industrial and mining effluents, domestic and hospital wastewater, agricultural runoff, and accidental chemical releases. Natural inputs of trace metals may occur also via mineral weathering (Balaram et al., 2023; Das & Raj, 2025; Sigue et al., 2025). In aquatic systems, sediments act both as sinks and secondary sources of inorganic micropollutants, controlling micropollutants storage, release, and bioavailability to aquatic organisms (Afahnwie et al., 2025; Hu et al., 2025; Jean-Lavenir et al., 2025; Tarigan et al., 2025; Yiika, et al., 2022).

Fish, positioned high in the aquatic food chain, can accumulate considerable levels via uptake from water and diet (Kipelo et al., 2025; Ray & Vashishth, 2024). Human consumption of contaminated fish is thus a potential exposure route to micropollutants with public health consequences (Abera & Adimas, 2024; Zhuzzhassarova et al., 2024). In humans, chronic exposure can damage vital organs (liver, kidneys, brain, lungs, and gonads), leading to hepatic, renal, neurological, cardiovascular, and reproductive disorders, as well as cancers (Qu & Zheng, 2024; Rajpoot et al., 2025).

Although several studies have examined contamination of aquatic ecosystems in Africa, Democratic Republic of the Congo (DRC) included (Kipelo et al., 2025; Lundemi et al., 2022), data on the pollution of Kasai River, a tributary to the Congo River, is scarce. The Kasai River is ecologically and socio-economically important, sustaining fisheries, agriculture, and navigation in the southwest of DRC (Mbimbi Mayi Munene et al., 2021; Lesani et al., 2024). Yet, increasing human activities exert growing pressure on Kasai River ecosystems. As an example, the environmental crisis of July 2021, linked to mining discharges from Angola into this river, affected nearly two million people through water contamination, fish kills, disease outbreaks, and disruption of fishing and navigation activities, which illustrates the scale of the problem (CRREBaC, 2021). Those mining discharges spreaded for many kilometers along the Kasai River and reached the Bandundu region, Kwilu Province, well inside the DRC. Bandundu city and neighborhoods have a population of near 150 000 inhabitants while the Kwilu Province has near 7 million inhabitants, which heavily rely on fisheries, from the Kasai

and other rivers in the region, as a source of animal protein.

This study aimed to (i) determine trace metal concentrations (Hg, Pb, Cr, As, Cd, Cu, Ni, Zn) in the sediments and in edible tissues of fish collected from the Kasai River near Bandundu city; (ii) compare concentrations of these trace elements with international safety standards for the protection of aquatic biota; and (iii) assess the potential ecological and human health risks associated with the consumption of fish from Kasai River.

2 Materials and Methods

2.1 Description of the Study Area

The sampling of fishes and sediments was conducted in a section of the Kasai River near Bandundu city, Kwilu Province, in the southwestern Democratic Republic of the Congo. The Bandundu city lies near the confluence of the Kasai and Kwilu rivers, within the Congo River basin (3°19'S; 17°22'E; altitude 324 m). The Kasai River has experienced visible pollution episodes, including water coloration and fish mortality episodes related with mining waste discharges (CRREBaC, 2021) (Fig. 1).

2.2 Sample Collection

Three sampling sites were selected in the Kasai River based on their accessibility and fishing activity: Bendela (B), Dima Lumbu (D) and Kutumuke (K), in a sequence from upstream to downstream (Fig. 2).

Between September and October 2024, edible fish from three common species were collected using gill-nets (9 specimens per sampling site, 27 specimens in total) representing small, medium, and large fish typically consumed by local populations. Fish species were: the elephant fish (*Marcusenius angolensis* Boulenger, 1905), a demersal species feeding upon aquatic invertebrates; the sharktail distichodus (*Distichodus fasciolatus* Boulenger, 1898), a bottom dweller mainly herbivorous, and the squeaker (*Synodontis congicus* Max Poll, 1971), a bottom feeder with omnivorous diet (FishBase, 2025). Fish were dissected and the muscle tissue (fish filet) was removed, minced, homogenized, and frozen (−20 °C) for analysis.

Fig. 1 Pollution of the Kasai river with high fish mortality (Source: CRRE-BaC, N Ref: CRREBaC/RTM/046/082021, Kinshasa 13 August 2021)

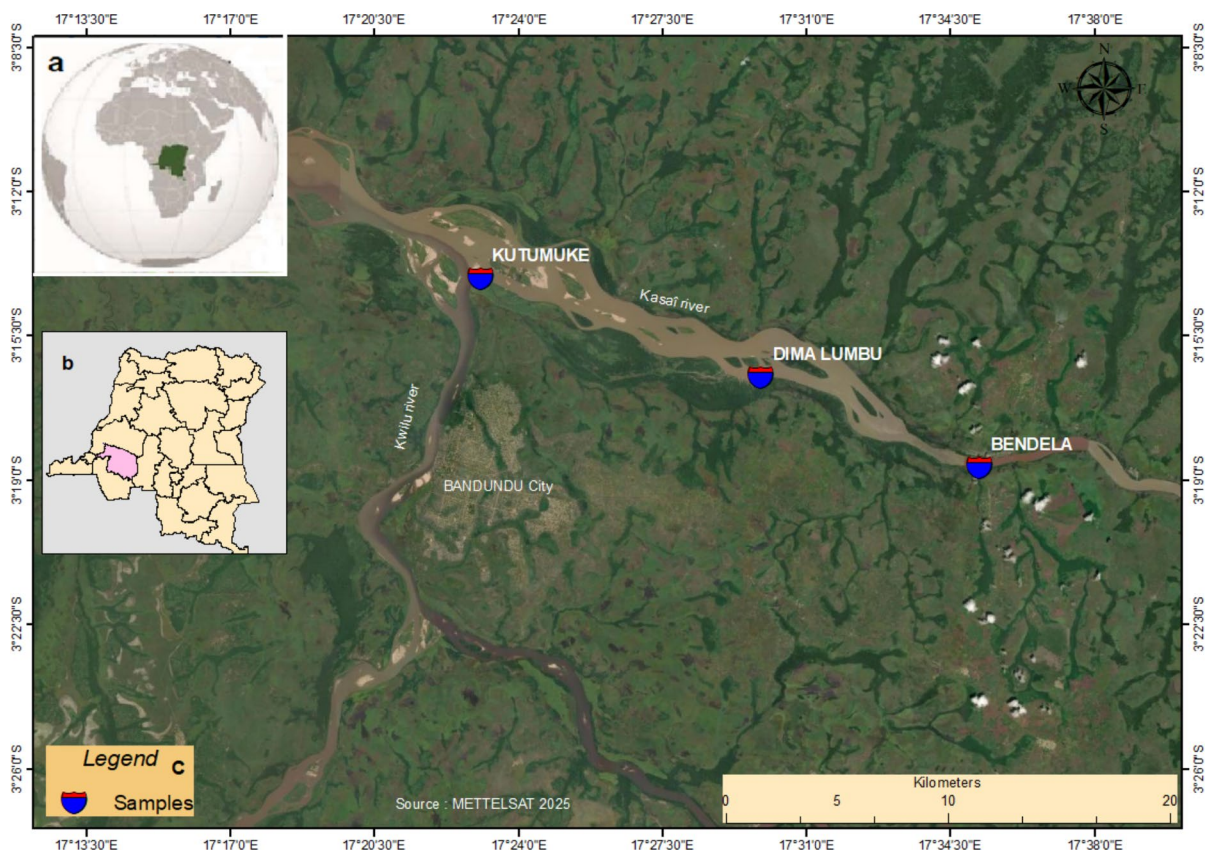


Fig. 2 **a** Location of the DR Congo in Africa; **b** Location of Kivu Province within the DR Congo; **c** Study area with sediment and fish sampling sites (half-circles in red and blue) along the Kasai River

In parallel, nine surface sediment samples of about 50 g each were collected from the 0–8 cm sediment top layer, at ~5 m off the river bank and by <2 m water depth. Three sediment samples were collected per sampling site and coded SB1, SB2, SB3 for Bendela; SD1, SD2, SD3 for Dima Lumbu, and SK1, SK2, SK3 for Kutumuke.

Fish muscle and sediment samples were stored frozen during transfer to the University of Geneva for analysis.

2.3 Sediment Physicochemical Characteristics

Physicochemical parameters of the sediment, including organic matter (OM) and calcium carbonate (CaCO_3) content, were analysed. The organic matter of sediment samples was assessed by determining the weight loss of dry sediment aliquots after combustion for 1 h at 550°C in a muffle furnace (Salvis AG, Lucerne, Switzerland). The carbonate content (expressed as CaCO_3 equivalent) was determined using the loss-on-ignition method (Heiri et al., 2001). Dried sediment aliquots were ignited in a muffle furnace (Salvis AG, Luzern, Switzerland) at 1000 °C for one hour, and the resulting weight loss recorded. The mass loss corresponding to CO_2 release was converted to CaCO_3 using the calcite conversion factor (2.273), as the exact carbonate mineralogy (calcite or dolomite) was not known.

2.4 Trace Metal Analysis

2.4.1 Pretreatment of Sediment Samples

The collected sediment samples were freeze-dried, finely ground into a homogeneous powder, and sieved through a 63 µm mesh nylon sieve. Aliquot-*sof* the homogenized sediments were taken for trace metal analysis. The procedure of aliquots digestion in acids followed the protocols described by Atibu et al. (2023). In brief, approximately 10–15 mg of powdered sample were fully digested using ultrapure acids in Teflon vessels placed on a ceramic hot plate. The acid digestion consisted of three successive steps: (i) addition of 1 mL HNO_3 (suprapur, 65%); (ii) treatment with a mixture of 0.5 mL HClO_4 (suprapur, 70%) and 0.5 mL HF (suprapur, 40%); and (iii) addition of 0.5 mL HNO_3 (suprapur, 65%). The acids were completely evaporated between steps. The final

residues were diluted in 10 mL of 1% HNO_3 prior to analysis. Chemical analyses were performed within 24 h after dilution.

2.4.2 Analysis of Trace Metals in Sediments

Trace metal concentrations were determined using inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700×series), optimized for complex matrices. To minimize spectral interferences, the instrument was operated in collision cell mode (helium) with interference correction equations applied. Calibration of the instrument was performed using multi-element standard solutions at different concentrations (0, 0.02, 1, 5, 20, 100, and 200 mg L^{-1}) (Thevenon et al., 2013).

The analytical accuracy and sensitivity of the method were checked with the certified reference material (CRM) STSD1 (stream sediment, Canadian Certified Reference Materials Project, Canada). Standard deviations of triplicate measurements were below 10%, and procedural blanks were less than 2% of the sample signal. Results were expressed in mg kg^{-1} dry weight.

2.4.3 Analysis of Total Mercury in Sediments

Total mercury concentrations were determined using a dedicated atomic absorption spectrometer (Advanced Mercury Analyzer, AMA 254; Altec s.r.l., Czech Republic) following the procedure described in Bravo et al. (2011). This method involves combustion of the sediment sample, amalgamation of mercury in a gold trap, and detection of the released mercury vapor by atomic absorption spectrometry.

The method validation and quality control were carried out using the certified reference material SRM 2702 (Inorganics in Marine Sediment) from the National Institute of Standards and Technology, USA. The detection limit, calculated as three times the standard deviation of blanks, was 0.005 mg kg^{-1} . Trace element concentrations were reported in mg kg^{-1} dry weight.

2.4.4 Analysis of Trace Metals in Fish

The protocol for heavy metal analysis in fish was adapted from Suami et al. (2019), which originally was designed for oysters and crayfish, and modified

based on methods described by Rashed (2001) and Sivaperumal et al. (2007). In brief, fish tissues were freeze-dried (Adolf Kühner, Birsfelden, Switzerland) and ground into a fine powder. Accurately weighed aliquots with approximately 1 g of the powdered samples were digested in 10 mL of a 3:1 mixture of suprapur HNO₃ (65%, Merck KGaA, Darmstadt Germany) and HClO₄ (70%, Merck KGaA, Darmstadt Germany) in Teflon digestion vessels and heated overnight at 110 °C. After cooling to room temperature, the digests were centrifuged, diluted with 1% suprapur HNO₃, and analyzed by ICP-MS. Ultrapure water (Millipore, Milli-Q, 18 MW, Merck, Darmstadt, Germany) was used for all acid dilutions.

As an analytical quality control, aliquots of the certified reference standard DORM-4 (Fish protein, National Research Council of Canada) were prepared and analyzed alongside the samples. Results for trace metal concentrations were expressed in mg kg⁻¹ dry weight.

2.5 Statistical Analyses

Each sample was analyzed in triplicate and the results averaged. The statistical treatment of data, including Spearman's rank correlation, was carried out using XLSTAT software (Addinsoft, 2020; New York, USA, <https://www.xlstat.com>).

2.6 Nature and Degree of Sediment Pollution

The extent of sediment pollution was assessed using the Enrichment Factor (EF) and the Geoaccumulation Index (I_{geo}) as described by Akonga et al. (2025).

The Enrichment Factor (EF) was calculated as follows:

$$EF = (\text{metal}/Sc)_{\text{sample}} / (\text{metal}/Sc)_{\text{background}}$$

where “metal” is the concentration of a given heavy metal in the sample or in the background, and “Sc” is the concentration of scandium. Scandium was chosen as the normalizing element due to its conservative behavior. The Upper Continental Crust (UCC) concentration values for trace elements reported by McLennan (2001) were used as the geochemical background values.

The Geoaccumulation Index (I_{geo}) was calculated as:

$$I_{geo} = \log_2(C_m) / 1.5(B_m)$$

where « C_m » is the concentration of a given metal in the sample, « B_m » is its background concentration in the UCC, and 1.5 is a correction factor accounting for natural variability of trace elements in lithogenic materials (Mabidi et al., 2024).

2.7 Ecological Risk Parameters

To evaluate the extent of heavy metal contamination in sediment samples, the Contamination Factor (CF) was calculated. It is expressed as:

$$CF = (C_n / B_n)$$

where C_n denotes the concentration of a given heavy metal (n) in the sediment sample, and B_n corresponds to its natural geochemical background level (Mudinga et al., 2024; Rubio et al., 2000).

The overall level of contamination from multiple metals in each sample was then estimated using the Contamination Degree (CD), defined as the sum of all contamination factors (Håkanson, 1980):

$$CD = \sum CF_i$$

where CF_i is the contamination factor for metal « i ». In this study, eight trace metals (Hg, Cd, As, Co, Cu, Pb, Cr, and Zn) were included in the CD calculation.

To further determine the potential ecological threats posed by these elements, the Ecological Risk Index (Eri) was calculated. This parameter accounts for both the contamination level and the toxicity of each heavy metal and it was computed as:

$$Eri = Tr_i \times CF_i$$

where Tr_i represents the toxic-response coefficient (or biological toxicity factor) specific to each element. The coefficients applied in this study were: Hg (40), Cd (30), As (10), Co (5), Cu (5), Pb (5), Cr (2), and Zn (1) (Islam et al., 2014).

The Potential Ecological Risk Index (RI), which integrates the combined effects of multiple metals, was obtained by summing the risk indices of all metals analyzed:

$$RI = \sum Er_i$$

This index provides an overall measure of the cumulative ecological risk, taking into account metal concentrations, toxicity, and the sensitivity of aquatic ecosystems (Singh et al., 2002).

Finally, the ecotoxicological significance of heavy metal levels in sediments was evaluated by comparing the measured concentrations against threshold values established in Sediment Quality Guidelines (SQGs) and Probable Effect Levels (PELs) in aquatic biota as adopted by the Canadian Council of Ministers of the Environment (CCME, 1999). These guidelines indicate threshold concentrations of heavy metals in sediments above which adverse biological effects are expected to occur.

2.8 Assessment of Human Health Hazards from Consumption of Fish

To evaluate the human health hazards associated with the consumption of fish from Kasai River, contaminated with heavy metals, several internationally recognized toxicity parameters were calculated as follows.

2.8.1 Estimated Daily Intake (EDI)

The estimated daily intake represents the amount of a metal absorbed by an individual through fish consumption and is calculated as:

$$EDI = \frac{C_m \times IR}{BW}$$

where « C_m » is the metal concentration in the fish (mg/kg), « IR » is the fish ingestion rate (3.90 kg/year = 0.0107 kg/day), and « BW » is the average body weight of the individual (57.8 kg) (FAOSTAT, 2023; Ngweme et al., 2020; USEPA, 2000; FAO/WHO, 2011).

2.8.2 Target Hazard Quotient (THQ) and Hazard Index (HI)

The THQ estimates the non-carcinogenic risk:

$$THQ_i = \frac{EDI_i \times EF \times ED}{RfD_i \times AT} \times 10^{-3}$$

where RfD_i (mg/kg body weight/day) is the oral reference dose for metal i , EF is the exposure frequency (365 days/year), ED is the exposure duration

(70 years), AT is the averaging time (25,550 days = 70 years $\times$ 365 days/year). The following RfD (mg/kg/day) values were used: As (0.0003), Cd (0.001), Pb (0.0035), Hg (as MeHg: 0.0001), Cr (as Cr(III): 1.5), Ni (0.02), Cu (0.04), Zn (0.3), Fe (0.7) (USEPA, 2023).

$THQ < 1$ indicates insignificant non-carcinogenic risk.

$THQ \geq 1$ suggests a potential health risk.

For combined exposure to multiple metals, the Hazard Index (HI) was calculated as:

$$HI = \sum THQ_i$$

$HI \geq 1$ indicates potential overall risk (Suresh et al., 2012).

2.8.3 Calculation of Cancer Risk using Estimated Fractions

Only the total concentrations of arsenic (As) and chromium (Cr) were available. The calculation of cancer risk (CR) requires information on the toxic forms of inorganic arsenic and hexavalent chromium (Cr(VI)). The toxic forms fractions were estimated using literature-based conversion factors.

The inorganic arsenic concentrations were estimated using the following equation:

$$[As]_{inorg} = [As]_{total} \times f_{inorg}$$

where « f_{inorg} » is the fraction of inorganic arsenic. Literature reports that this fraction is generally 1–10% (therefore, 10% was assumed in this study, as it represents a conservative assumption for freshwater fish) of total arsenic in fish (EFSA, 2009; Santonen et al., 2003).

Total chromium in fish includes Cr (III) (essential, low toxicity) and Cr (VI) (carcinogenic).

If only total Cr is available, the Cr (VI) fraction can be estimated as:

$$[Cr(VI)] = [Cr]_{total} \times f_{Cr(VI)}$$

where « $f_{Cr(VI)}$ » is the fraction of hexavalent chromium. Typical values reported in the literature are 1–5% of total chromium (therefore, 1% was assumed for the calculation, as it represents a conservative/moderate assumption for freshwater fish) (EFSA, 2011; USEPA, 2000).

The lifetime cancer risk can then be calculated as:

$$CR = EDI \times CSF = \frac{[M]_{est} \times IR}{BW} \times CSF$$

where $[M]_{est} = [M]_{total} \times f_{toxic}$, with f_{toxic} representing either f_{inorg} for As or $f_{Cr(VI)}$ for chromium.

CSF represents the cancer slope factor. Values $1.5 \text{ (mg/kg.day)}^{-1}$ and $0.5 \text{ (mg/kg.day)}^{-1}$ were considered respectively for inorganic As and Cr(VI). It should be considered that values.

$CR > 10^{-4}$ is considered high risk, while $10^{-6} < CR < 10^{-4}$ is considered acceptable or low risk (USEPA, 2000).

Therefore, the CR values for As and Cr calculated herein are estimates only based on literature fractions. For a more precise risk assessment, speciation analyses by HPLC-ICP-MS for arsenic and the selective extraction for Cr(VI) determination would be needed.

2.8.4 Selenium/Mercury (Se/Hg) Concentrations Ratio

This ratio provides a complementary metrics to evaluate human health risk and the biochemical interaction of Hg and Se in fish species (Suami et al., 2018).

The Se/Hg concentrations ratio was calculated to assess the potential protective effect of selenium against mercury toxicity:

$$\frac{Se}{Hg} = \frac{C_{Se}}{C_{Hg}}$$

It must be considered that $Se/Hg > 1$ indicates that selenium is in excess and there is a reduced risk despite the presence of mercury. If $Se/Hg < 1$, this indicates that mercury predominates and there is a potential higher risk.

3 Results and Discussion

3.1 Sediment Organic Matter and Calcium Carbonate Content

The content of organic matter (OM) and calcium carbonate (CaCO_3) in sediments from the Kasai River is presented in Table 1.

Sediment OM content varied markedly among the three sites, ranging from 1.26% to 12.42%. The most

Table 1 Sampling sites, organic matter (OM) and calcium carbonate (CaCO_3) content of sediment samples

Site name	Geographical coordinates	Sample ID	OM	CaCO_3
Bendela	S 3° 18' 41.43''	SB1	12.42	2.40
	E 17° 35' 12.92''	SB2	10.33	2.13
		SB3	11.37	2.72
Dima Lumbu	S 3° 16' 30.27''	SD1	6.05	8.19
	E 17° 29' 53.85''	SD2	1.26	0.37
		SD3	4.53	1.36
Kutumuke	S 3° 14' 6.08''	SK1	1.75	0.00
	E 17° 23' 5.25''	SK2	2.30	0.02
		SK3	3.86	0.47

upstream site, Bendela, exhibited the highest OM values (10.33–12.42%, mean = 11.37%), reflecting substantial organic inputs from natural vegetation and anthropogenic sources, such as agricultural runoff and domestic effluents. At the middle station Dima Lumbu, OM content showed intermediate values (1.26–6.05%, mean = 3.95%), suggesting a dilution effect and partial organic matter degradation along the flow path. The downstream site, Kutumuke, displayed the lowest OM content (1.75–3.86%, mean = 2.64%), indicating reduced organic inputs and sedimentation, possibly due to higher water flow velocity and lower deposition potential.

The sediment OM content decreased progressively downstream, in the sequence Bendela > Dima Lumbu > Kutumuke. Elevated OM at the upstream site suggests that the river receives significant organic inputs near Bendela, which are progressively diluted and degraded downstream. High OM concentrations may enhance sediment fertility and benthic productivity, but they can also indicate organic pollution in densely populated or cultivated zones (Nazir et al., 2024).

The sediment CaCO_3 content ranged from 0.00% to 8.19%, showing notable spatial variability. The upstream sediments at Bendela had moderate carbonate contents (2.13–2.72%, mean = 2.42%), possibly linked to both detrital inputs and limited carbonate precipitation. Dima Lumbu exhibited the highest variability (0.37–8.19%, mean = 3.31%), with the maximum value recorded at SD1, suggesting localized carbonate accumulation related to micro-environmental conditions. In contrast, the downstream site, Kutumuke, was nearly devoid of carbonates (0.00–0.47%, mean = 0.16%), implying either leaching or the

predominance of siliciclastic sediments. These observations indicate that carbonate distribution along the river is influenced primarily by local lithology and water chemistry, rather than by a simple longitudinal gradient.

At certain points, OM and CaCO_3 contents appeared correlated. For instance, at Dima Lumbu (SD1), high OM coincided with high CaCO_3 , suggesting localized sediment enrichment. Conversely, at Kutumuke, OM accumulation occurred despite negligible CaCO_3 , while at Bendela, high OM was not accompanied by proportionally high carbonate content. This pattern suggests that OM deposition is mainly driven by biological productivity and anthropogenic inputs, whereas carbonate content is controlled by geological and geochemical processes (Indraswari et al., 2025).

The observed downstream decline in OM content emphasized the attenuation of organic inputs and self-purification capacity of the river along its course. Meanwhile, the presence of moderate CaCO_3 at Bendela may help buffer sediment acidity, while its near absence at Kutumuke could make sediments more susceptible to pH fluctuations. Zones with simultaneously high OM and CaCO_3 may undergo localized enrichment, potentially affecting benthic biodiversity and nutrient cycling (Neves et al., 2025).

3.2 Trace Metal Concentrations in Sediment Samples

Accuracy and precision of the analytical procedure were verified using the reference materials STSD1 and SRM2702. For STSD1, the measured values of Cu, Cd, Co, Cr, Ni, Zn, As, and Pb closely matched the certified reference values, with deviations generally below 5%. Similarly, the total mercury concentration determined in SRM2702 ($0.4468 \text{ mg kg}^{-1}$) was nearly identical to the certified value ($0.4474 \text{ mg kg}^{-1}$). This agreement confirmed the accuracy and precision of the analytical method, thereby ensuring the credibility of the environmental data.

The concentrations of selected trace metals (Cu, Sc, Cd, Co, Cr, Ni, Zn, As, Pb, and Hg) in sediments from the Bendela, Dima Lumbu, and Kutumuke sites are shown in Table 2. These values are compared with the Sediment Quality Guidelines (SQG) and Probable Effect Levels (PEL) adopted by Canada to evaluate potential ecological risks.

Upstream at Bendela, sediments exhibited the highest concentrations of most metals. Copper ranged from 48.61 to 56.74 mg kg^{-1} (mean = 51.68 mg kg^{-1}), systematically exceeding the SQG value of 35.7 mg kg^{-1} . Zinc concentrations were similarly elevated (263.7 – 279.0 mg kg^{-1} ; mean = 272.6 mg kg^{-1}),

Table 2 Concentrations of trace metals in sediments (mg kg^{-1} dry weight)

Site	Sediment Sample ID	Cu	Sc	Cd	Co	Cr	Ni	Zn	As	Pb	Hg
STSD1	Ref. value	36	-	0.8	14	28	18	165	17	34	-
	Det. Value	34.5	-	0.7	13.4	27.5	17.2	163.7	15.8	32.9	-
SRM2702	Ref. value	-	-	-	-	-	-	-	-	-	0.4474
	Det. Value	-	-	-	-	-	-	-	-	-	0.4468
Kutumuke	SK1	16.11	0.81	0.02	2.03	11.42	5.18	133.6	0.14	42	0.02
	SK2	19.48	1.94	0.04	4.52	23.99	16.69	143.3	0.28	43.8	0.02
	SK3	16.48	2.24	0.05	6.01	27.69	14.34	144.3	0.32	46.9	0.04
	SD1	39.59	1.89	0.08	4.99	44.59	14.48	147.2	0.29	44	0.09
Dima Lumbu	SD2	37.21	1.27	0.03	2.83	46.74	8.24	136.5	0.14	42.9	0.01
	SD3	36.35	2.13	0.04	6.2	46.38	16.28	139.5	0.35	43.6	0.07
	SB1	49.69	6.94	0.14	22.24	78.75	66.44	275.1	0.67	64.9	0.16
Bendela	SB2	56.74	5.49	0.1	14.75	62.07	46.71	263.7	0.58	68.9	0.13
	SB3	48.61	7.91	0.14	22.91	81.30	70.41	279	0.65	61.6	0.16
	SQG	35.7		0.6		37.3		123.0	5.9	35.0	0.17
	PEL	197.0		3.5		90.0		315.0	17.0	91.3	0.486

In bold, values of the heavy metal's concentration higher than the recommended probable effect concentration according to Sediment Quality Guidelines (SQG) for the Protection of Aquatic Life (CCME, 1999). PEL -probable effect levels (dry weight)

while nickel levels (46.71–70.41 mg kg⁻¹; mean = 61.2 mg kg⁻¹) also exceeded the SQG threshold of 35 mg kg⁻¹. Chromium concentrations were the highest at this site (62.07–81.30 mg kg⁻¹), and cobalt reached up to 22.91 mg kg⁻¹. Cadmium, though present at lower levels (< 0.15 mg kg⁻¹), approached the SQG value (0.6 mg kg⁻¹) at Bendela. These elevated metal concentrations at Bendela reflect strong anthropogenic inputs near the upstream section, potentially from agricultural, domestic, and mining activities, as well as favorable geochemical conditions for metal retention in sediments due to high organic matter (11.37%) and moderate CaCO₃ content (2.13–2.72%).

At the middle site, Dima Lumbu, metal concentrations decreased compared to Bendela but remained relatively elevated in some samples. Copper ranged from 36.35 to 39.59 mg kg⁻¹, Cr from 44.59 to 46.74 mg kg⁻¹, and Ni from 8.24 to 16.28 mg kg⁻¹. The variability among samples (e.g., SD1 vs. SD3) suggested localized metal accumulation, potentially related to zones of enhanced organic matter (up to 6.05%) and carbonate deposition (up to 8.19%). Such localized enrichment may be linked to inputs from riparian vegetation, domestic effluents, or sediment resuspension.

In contrast, the downstream site, Kutumuke, displayed the lowest metal concentrations: Cu (16.11–19.48 mg kg⁻¹), Zn (133.6–144.3 mg kg⁻¹), Ni (5.18–16.69 mg kg⁻¹), and Cr (11.42–27.69 mg kg⁻¹). Cobalt ranged from 2.03 to 6.01 mg kg⁻¹, and Cd remained extremely low (0.02–0.05 mg kg⁻¹). These reduced concentrations corresponded to the lower organic matter (mean = 2.64%) and very low CaCO₃ content (mean = 0.16%), which limit the sediment's capacity to adsorb and retain metals. The relatively high water flow and sediment dilution downstream likely contribute to metal dispersion.

The distribution of metals along the Kasai River revealed a clear upstream-to-downstream depletion pattern: Bendela > Dima Lumbu > Kutumuke. This trend mirrors the decreasing gradient in organic matter (OM) and CaCO₃ contents observed in Table 1, suggesting that sediment geochemistry exerts a strong influence on metal retention. Organic matter enhances the adsorption and complexation of trace metals through humic substances, while CaCO₃ can increase pH buffering and promote metal precipitation as carbonates or hydroxides (Jokinen et al., 2020; Li et al., 2020; Yan et al., 2022). Thus, sites with sediments

with higher OM and CaCO₃ contents tend to accumulate more metals.

The elevated Cr and Co concentrations at Bendela may also reflect the combined effects of carbonate buffering and organic complexation, which reduce metal mobility (Bastianini et al., 2024). Conversely, the low CaCO₃ content at Kutumuke limits such stabilization, favoring metal dispersion downstream. Arsenic and mercury concentrations were generally low across all sites (As: 0.14–0.67 mg kg⁻¹; Hg: < 0.16 mg kg⁻¹), though both showed slightly higher values at Bendela, consistent with OM enrichment and possible anthropogenic inputs (Terrón et al., 2025).

The heavy metal distribution along the Kasai River sediments highlighted the influence of both natural and anthropogenic factors on sediment quality. The upstream accumulation at Bendela indicates higher metal loading and retention due to enhanced organic and carbonate interactions, while downstream dilution at Kutumuke reflects natural self-purification processes. However, since several metals at Bendela (Cu, Zn, Ni, Cr, Pb) exceeded the SQG limits, potential ecological risks cannot be excluded, particularly for benthic organisms sensitive to trace metals exposure.

3.3 Spearman's Rank Correlation Analysis

To further elucidate the relationships between trace metal concentrations and key physicochemical parameters (organic matter and calcium carbonate), a Spearman's rank correlation analysis was performed (Table 3). The results revealed several strong and statistically significant correlations ($p < 0.05$), reflecting common sources and/or similar geochemical behaviors among the studied elements.

Organic matter (OM) exhibited very strong positive correlations with almost all trace metals, including Cd ($r = 0.95$), Pb ($r = 0.85$), Hg ($r = 0.99$), As ($r = 0.95$), and Co ($r = 0.92$). These findings confirmed the crucial role of OM in regulating metal distribution within sediments. The high affinity of heavy metals for organic ligands promoted complexation and adsorption, thus enhancing metals retention in OM-rich upstream sediments (Bendela). This observation aligns with the spatial trend previously described, where Bendela, characterized by the highest OM

Table 3 Spearman's rank correlation matrix between trace metals and physicochemical parameters in sediment samples

Variables	CaCO ₃	Cu	Sc	Cd	Co	Cr	Ni	Zn	As	Pb	Hg
OM	0.833	0.767	0.85	0.95	0.917	0.717	0.85	0.917	0.946	0.85	0.992
CaCO ₃		0.75	0.6	0.84	0.733	0.683	0.617	0.817	0.703	0.667	0.84
Cu			0.633	0.79	0.717	0.867	0.733	0.767	0.703	0.767	0.748
Sc				0.891	0.967	0.75	0.883	0.883	0.946	0.867	0.84
Cd					0.908	0.756	0.857	0.992	0.903	0.924	0.936
Co						0.817	0.883	0.883	0.979	0.833	0.916
Cr							0.733	0.733	0.762	0.65	0.723
Ni								0.867	0.862	0.783	0.824
Zn									0.862	0.917	0.908
As										0.845	0.932
Pb											0.824

Statistically significant coefficients ($p < 0.05$) are shown in bold

content (11.37%), also exhibited the highest concentrations of most trace metals.

Calcium carbonate (CaCO₃) displayed also significant positive correlations with several metals, namely Cd ($r=0.84$), Zn ($r=0.82$), Pb ($r=0.84$), and Cu ($r=0.75$). These relationships suggested that carbonates contributed to metal retention, possibly through co-precipitation or adsorption onto carbonate surfaces (Li et al., 2020). However, the correlations between CaCO₃ and trace metals were slightly weaker than those with OM, indicating that carbonate buffering exerts a secondary, although complementary influence on metal accumulation compared to organic matter.

Strong inter-metal correlations were also evident, reflecting possible shared origins or similar geochemical pathways. For example: Sc, Cd, and Co showed strong mutual associations ($r > 0.89$), pointing to a common source or a similar sedimentary behavior. Zn and As were highly correlated ($r=0.92$), implying possible co-enrichment from anthropogenic inputs such as agricultural or domestic effluents. Hg was strongly correlated with almost all other metals ($r > 0.90$), consistent with its well-known affinity for organic matter and fine-grained particles (Akonga et al., 2025; Atibu et al., 2023).

The overall pattern of correlations suggested that organic matter acted as the dominant control on heavy metal accumulation along the Kasai River, while CaCO₃ provides additional stabilization through pH buffering and surface adsorption. The interdependence of trace metals further supports the hypothesis of common anthropogenic influences, especially near the upstream area (Bendela) where domestic, agricultural, and possibly mining-related inputs are most

pronounced. Downstream at Kutumuke, the lower OM and CaCO₃ levels reduce adsorption capacity, favoring metal dispersion and dilution along the flow path.

3.4 Pollution and Ecological Risk Parameters

3.4.1 Geoaccumulation Index (I_{geo}) and Enrichment Factor (EF)

The Geoaccumulation Index (I_{geo} , Table 4) revealed a clear upstream-to-downstream decline in sediment contamination levels along the Kasai River.

At the upstream site (Bendela), I_{geo} values were the highest for most metals, including Cu (0.4–0.6), Ni (1.1–1.2), Zn (1.3–1.4), Pb (1.0–1.2), and Hg (0.6–0.9), corresponding to Classes 2–3 (unpolluted to heavily polluted). Chromium and cobalt also showed moderate enrichment ($I_{geo} \approx 0.6$). These results indicated significant anthropogenic influence near Bendela, likely from domestic discharges, agricultural runoff, and small-scale mining residues, combined with favorable geochemical conditions for metal retention due to high organic matter (11.37%) and moderate CaCO₃ content (2.42%).

At the middle site (Dima Lumbu), I_{geo} values decreased slightly but remained within Classes 1–2 for Cu, Zn, Pb, and Hg ($I_{geo} \approx 0.4$ –0.6). Other metals, such as Cr, Ni, and Co showed negative or near-zero values (Classes 0–1), suggesting a moderate level of enrichment linked to localized anthropogenic inputs. The site's higher variability in OM (1.26–6.05%) and CaCO₃ (0.37–8.19%) suggested that sediment composition and depositional microenvironments significantly affect the spatial distribution of contaminants.

Table 4 Calculated I_{geo} and EF pollution indices: results for trace metals in sediment samples

Igeo	Cu	Cd	Co	Cr	Ni	Zn	As	Pb	Hg	
SB1	0.4	-0.1	0.6	0.6	1.1	1.4	-1.7	1.1	0.9	Igeo classification
SB2	0.6	-0.6	0.0	0.2	0.6	1.3	-2.0	1.2	0.6	$I_{\text{geo}} \leq 0$ Class 0 – practically unpolluted
SB3	0.4	-0.1	0.6	0.6	1.2	1.4	-1.8	1.0	0.9	$0 < I_{\text{geo}} < 1$ Class 1 – unpolluted to moderately polluted
SD1	0.1	-0.9	-1.6	-0.2	-1.1	0.5	-3.0	0.6	0.1	$1 < I_{\text{geo}} < 2$ Class 2 – moderately polluted
SD2	0.0	-2.3	-2.4	-0.2	-1.9	0.4	-4.0	0.5	-3.1	$2 < I_{\text{geo}} < 3$ Class 3 – moderately to heavily polluted
SD3	0.0	-1.9	-1.3	-0.2	-0.9	0.4	-2.7	0.5	-0.3	$3 < I_{\text{geo}} < 4$ Class 4 – heavily polluted
SK1	-1.2	-2.9	-2.9	-2.2	-2.5	0.3	-4.0	0.5	-2.1	$4 < I_{\text{geo}} < 5$ Class 5 – heavily to extremely polluted
SK2	-0.9	-1.9	-1.7	-1.1	-0.8	0.4	-3.0	0.5	-2.1	$5 < I_{\text{geo}}$ Class 6 – extremely polluted
SK3	-1.2	-1.6	-1.3	-0.9	-1.1	0.4	-2.8	0.6	-1.1	
EF	Cu	Cd	Co	Cr	Ni	Zn	As	Pb	Hg	
SB1	3.2	2.3	3.5	3.6	5.3	6.1	0.7	5.1	4.5	EF interpretation values
SB2	4.5	2.0	3.0	3.6	4.7	7.4	0.8	6.9	4.7	$EF < 1$: no enrichment
SB3	2.7	2.0	3.2	3.2	4.9	5.5	0.6	4.3	4.0	$EF < 3$: minor enrichment
SD1	9.2	4.8	2.9	7.4	4.2	12.1	1.1	12.8	9.4	EF 3-5: moderate enrichment
SD2	12.9	2.7	2.5	11.6	3.6	16.7	0.8	18.6	1.5	EF 5-10: moderately severe enrichment
SD3	7.5	2.1	3.2	6.8	4.2	10.1	1.2	11.3	6.5	EF 10-25: severe enrichment
SK1	8.8	2.8	2.8	4.4	3.5	25.5	1.3	28.5	4.9	EF 25-50: very severe enrichment
SK2	4.4	2.3	2.6	3.9	4.7	11.4	1.1	12.4	2.0	$EF > 50$: extremely severe enrichment
SK3	3.2	2.5	3.0	3.9	3.5	10.0	1.0	11.5	3.5	

The downstream site (Kutumuke) showed the lowest I_{geo} values, generally negative for most metals (Cd, Co, Cr, Ni, As, Hg), placing them in Classes 0–1 (practically unpolluted to unpolluted–moderately polluted). Only Zn ($I_{\text{geo}} \approx 0.3$ –0.4) and Pb ($I_{\text{geo}} \approx 0.5$ –0.6) indicated slight enrichment, likely due to residual contamination from upstream transport or atmospheric deposition. The overall pattern (Bendela > Dima Lumbu > Kutumuke) thus confirmed a progressive decrease in contamination downstream, consistent with the dilution of organic and particulate matter and the self-purification capacity of the river system.

The Enrichment Factor (EF) values (Table 4) supported these findings. At Bendela, most metals exhibited moderate to moderately severe enrichment ($EF = 3$ –10), confirming anthropogenic contributions superimposed on natural background levels. At Dima Lumbu, Cu (7.5–12.9), Zn (10.1–16.7), and Pb (11.3–18.6) showed severe enrichment ($EF > 10$), suggesting localized inputs from human activities such as domestic effluents and agricultural discharges. In contrast, Kutumuke sediments displayed minor to moderate enrichment ($EF < 5$) for most

metals, except Zn and Pb ($EF = 10$ –25), which still indicated severe enrichment in some samples, likely due to residual particulate transport and adsorption processes. Mercury presented high EF values, especially at Bendela ($EF > 9.4$), reflecting its strong association with organic matter and its downstream persistence.

Both I_{geo} and EF results demonstrated that Zn, Pb, Cu, and Hg were the most enriched elements, revealing marked anthropogenic influence in the upstream and midstream zones. The observed enrichment trends closely followed the OM and CaCO_3 gradients (Bendela > Dima Lumbu > Kutumuke), highlighting the controlling role of sediment geochemistry in trace metal accumulation.

3.4.2 Contamination Factor (CF), Degree of Contamination (CD), and Ecological Risk Indices (Eri, RI)

The Contamination Factor (CF, Table 5) exhibited a distinct upstream-to-downstream decreasing

Table 5 Results for the ecological risk indices CF, CD, Eri, and RI calculated for trace elements in the sediment samples

CF											CD	Eri										RI
Sample ID	Sc	Cu	Cd	Co	Cr	Ni	Zn	As	Pb	Hg		Sample ID	Hg	Cd	As	Co	Cu	Pb	Cr	Zn		
SB1	0.6	2.0	1.4	2.2	2.3	3.3	3.9	0.4	3.2	2.9	18.3	SB1	114.3	42.9	4.5	11.1	9.9	16.2	4.5	3.9	207.3	
SB2	0.5	2.3	1.0	1.5	1.8	2.3	3.7	0.4	3.4	2.3	16.4	SB2	92.9	30.6	3.9	7.4	11.3	17.2	3.5	3.7	170.5	
SB3	0.7	1.9	1.4	2.3	2.3	3.5	3.9	0.4	3.1	2.9	18.3	SB3	114.3	42.9	4.3	11.5	9.7	15.4	4.6	3.9	206.6	
SD1	0.2	1.6	0.8	0.5	1.3	0.7	2.1	0.2	2.2	1.6	10.2	SD1	64.3	24.5	1.9	2.5	7.9	11.0	2.5	2.1	116.8	
SD2	0.1	1.5	0.3	0.3	1.3	0.4	1.9	0.1	2.1	0.2	7.8	SD2	7.1	9.2	0.9	1.4	7.4	10.7	2.7	1.9	41.4	
SD3	0.2	1.5	0.4	0.6	1.3	0.8	2.0	0.2	2.2	1.3	9.4	SD3	50.0	12.2	2.3	3.1	7.3	10.9	2.7	2.0	90.5	
SK1	0.1	0.6	0.2	0.2	0.3	0.3	1.9	0.1	2.1	0.4	5.8	SK1	14.3	6.1	0.9	1.0	3.2	10.5	0.7	1.9	38.6	
SK2	0.2	0.8	0.4	0.5	0.7	0.8	2.0	0.2	2.2	0.4	7.1	SK2	14.3	12.2	1.9	2.3	3.9	11.0	1.4	2.0	48.9	
SK3	0.2	0.7	0.5	0.6	0.8	0.7	2.0	0.2	2.3	0.7	7.9	SK3	28.6	15.3	2.1	3.0	3.3	11.7	1.6	2.0	67.7	

CF classification

CF<1	Low contamination
1<CF<3	Moderate contamination
3<CF<6	Considerable contamination
6<CF	Very high contamination

CD**Classification**

8☐CD<16	Moderate contamination
16☐CD<32	High contamination
32☐CD	Very high contamination

Eri classification

Eri <40	Low ecological risk
40 < Eri < 80	Moderate ecological risk
80 < Eri < 160	Considerable ecological risk
160 < Eri < 320	High ecological risk
Eri > 320	Very high ecological risk

RI Classification

RI<150	Low ecological risk or low ecological level
150<IR<300	Moderate ecological pollution level or moderate ecological risk
300<IR<600	Considerable ecological risk or severe ecological pollution level
IR>600	Very high ecological risk or serious ecological pollution level

trend, consistent with the river's flow from Bendela (upstream) to Kutumuke (downstream) via Dima Lumbu.

At the upstream site (Bendela), CF values were the highest for most metals, confirming strong contamination. Zinc (3.7–3.9), lead (3.1–3.4), and mercury (2.3–2.9) indicated considerable contamination levels, while Cd (1.0–1.4) and Cu (1.9–2.3) showed moderate enrichment. These elevated CF values reflected the combined influence of anthropogenic inputs—such as agricultural runoff, domestic discharges, and mining residues—and favorable geochemical conditions for metal retention due to the high organic matter (11.37%) and moderate CaCO₃ content (2.42%).

At the middle site (Dima Lumbu), CF values were generally lower than at Bendela but still reflected moderate contamination for some metals. Zn (2.0–2.1), Pb (2.2–2.3), and Hg (1.6) maintained relatively elevated levels, while Cd and Cu ranged from 0.8 to 1.6. This moderate contamination likely resulted from the combination of localized inputs (domestic and agricultural effluents) and partial dilution of upstream contaminants. The heterogeneous OM (1.26–6.05%) and CaCO₃ (0.37–8.19%) contents in this section also suggested spatially variable metal retention driven by sediment composition and depositional conditions.

At the downstream site (Kutumuke), CF values dropped markedly for all metals except Pb and Zn, which remained slightly elevated (Pb: 2.1–2.3; Zn ≈

2.0), indicating residual contamination from upstream transport. Most other metals exhibited $CF < 1$, corresponding to low contamination. The low organic matter (2.64%) and minimal $CaCO_3$ content (0.16%) limited the sediment's adsorption capacity, while the higher water flow and sediment dilution enhanced metal dispersion and self-purification processes.

The degree of contamination (CD) followed the same spatial gradient, decreasing from upstream to downstream. Bendela exhibited the highest CD values (16.4–18.3), indicating moderate overall contamination. Dima Lumbu showed intermediate CD levels (7.8–10.2), while Kutumuke displayed the lowest values (5.8–7.9), corresponding to low contamination. These results confirmed that sediment contamination progressively decreased along the river, consistent with the dilution of pollutants downstream.

The ecological risk factor (E_{ri}) identified Hg and Cd as the main contributors to ecological risk. At Bendela, E_{ri} values were the highest: Hg (92.9–114.3), Cd (30.6–42.9), and Pb (15.4–17.2), indicating considerable ecological risk. At Dima Lumbu, E_{ri} values for Hg (64.3) and Cd (up to 24.5) were lower but still signaled a moderate potential risk, while other metals contributed minimally ($E_{ri} < 10$). At Kutumuke, E_{ri} values dropped sharply (Hg: 14.3–28.6; Cd: 6.1–15.3), corresponding to low to moderate ecological risk levels.

The potential ecological risk index (RI), integrating all elements, confirmed this pattern. Bendela recorded the highest RI values (170.5–207.3), corresponding to moderate to considerable ecological risk. Dima Lumbu exhibited intermediate RI values (41.4–116.8), representing low to moderate risk, while Kutumuke showed the lowest RI (38.6–67.7), indicating low ecological risk.

Taken together, the combined indices (Igeo, EF, CF, CD, E_{ri} , and RI) enabled three key observations: 1. Spatial gradient: Contamination and ecological risk clearly decreased downstream, following the sequence Bendela > Dima Lumbu > Kutumuke, consistent with the progressive dilution and dispersion of metals along the river's flow. 2. Priority pollutants: Zn, Pb, Cu, Cd, and Hg are the contaminants of primary concern. Hg and Cd contribute most to ecological risk (E_{ri} , RI), while Zn and Pb exhibit strong enrichment (EF, Igeo). 3. Anthropogenic and geochemical influence: High contamination and risk levels at Bendela reflect the influence of human

activities combined with favorable geochemical conditions (high OM and $CaCO_3$). In contrast, the downstream decline at Kutumuke indicates natural attenuation and self-purification processes.

These observations demonstrated that sediment quality and ecological risks along the Kasai River are strongly controlled by both anthropogenic inputs and natural geochemical gradients, with significant pollution attenuation occurring downstream from Bendela to Kutumuke.

3.5 Concentrations of Trace Metals in Fish Muscle

The concentrations of trace metals in fish muscle tissues collected along the Kasai River—from the upstream site at Bendela, through Dima Lumbu, to the downstream site Kutumuke—are presented in Table 6. For the analytical quality assurance, the certified reference material DORM-4 (fish protein, NRCC, Canada) was analyzed, and the measured concentrations were in excellent agreement with the certified values, confirming the reliability and accuracy of the analytical procedure.

Chromium, Nickel, and Cobalt exhibited generally low concentrations in fish muscle from the Kasai River (Cr: 1.0–1.9 mg kg⁻¹; Ni and Co < 0.4 mg kg⁻¹) (Table 6). This indicates limited bioaccumulation potential and predominantly lithogenic origins for these metals. Manganese and iron showed wider variability, with Mn ranging from 3.1 to 19.1 mg kg⁻¹ and Fe from 23.4 to 88.9 mg kg⁻¹. As essential micronutrients, their variations likely reflect differences in species metabolism, feeding habits, and local geochemical background. Copper and Zinc displayed notable spatial and interspecies variability. Cu concentrations (0.8–3.3 mg kg⁻¹) were moderate and below nutritional concern thresholds. However, Zn reached elevated values—up to 59 mg kg⁻¹ in *S. congicus* from Kutumuke. Such enrichment suggests possible bioaccumulation and may reflect increased exposure to Zn-enriched sediments or suspended particulates downstream. Arsenic and selenium occurred at low levels (As < 0.1–0.3 mg kg⁻¹; Se 0.4–1.9 mg kg⁻¹), remaining below reference values and indicating minimal risk from toxic inorganic arsenic species. Cadmium, lead, and mercury require closer attention due to their toxicity and regulatory importance. Cd concentrations ranged from 0.2 to 0.7 mg kg⁻¹ d.w., with the highest values observed in *S. congicus* from Kutumuke.

Table 6 Concentrations of trace elements in fish muscle samples (mg kg⁻¹ dry weight)

Sample site	Fish Sample ID	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Ag	Cd	Sn	Ba	Pb	Hg
DORM4	Ref. Value	1.87	3.17	343	ND	1.34	15.7	51.6	6.87	3.45	0.0252	0.299	ND	ND	0.404	0.4
	Det. Value	1.9	3.1	318.4	0.3	1.4	15.8	51.9	6.2	3.7	0.03	0.3	0.2	4.9	0.4	0.4
BENDELA	<i>D.fasciolatus</i>	1.9	6.5	88.9	0.1	0.3	3.3	35.1	0	1.6	0.5	0.5	0.3	4.8	0.3	0.4
DIMA LUMBU		1.5	3.1	23.4	0.1	0.2	1.3	21.9	0	1.2	0.3	0	0.2	2.5	0.6	0
KUTUMUKE		1.8	11.5	62.1	0.2	0.3	1.3	32	0.1	1.9	0.5	0.7	0.2	8.8	0.8	0.1
BENDELA	<i>S.congicus</i>	1.3	5.7	46.5	0.1	0.2	0.9	39	0	0.7	0.3	0	0.2	11.5	0.5	0.7
DIMA LUMBU		1.4	7.8	36.6	0.1	0.3	1.6	53.2	0.1	1.2	0.4	0	0.2	8.5	0.3	0.8
KUTUMUKE		1.3	9.6	63.3	0.2	0.3	0.8	59.2	0.1	0.4	0.3	0.6	0.2	25.1	1.6	0.9
BENDELA	<i>M. angolensis</i>	1.2	19.1	50.1	0.1	0.3	1.4	51.9	0.1	1.6	0.4	0	0.2	18.6	0.1	1
DIMA LUMBU		1.3	12.4	45	0	0.4	1	52.2	0	0.8	0.5	0	0.2	14.8	0.1	0.6
KUTUMUKE		1	7.3	57.6	0	0	1.5	54	0.1	1.1	0.4	0	0	13	0	0.9

(0.6–0.7 mg kg⁻¹). Lead concentrations varied between 0.2 and 1.6 mg kg⁻¹ d.w.. Mercury levels ranged from 0.04 to 0.97 mg kg⁻¹. Other elements such as Ag, Sn, and Ba were sporadically detected, with Ba reaching 25.1 mg kg⁻¹ in *S. congicus* at Kutumuke and 18.6 mg kg⁻¹ in *M. angolensis* at Bendela, possibly reflecting localized industrial or geogenic influences.

Considering the mining discharges into the river as the main source of trace metals, one could expect higher concentrations in fish at Bendela and the lowest at Kutumuke. It should be noted that in this study it was not possible to analyse river water samples, which would allow to correlate trace metal concentrations in fish with metal concentrations in water.

However, fish are also mobile and the metal concentrations in fish filet do not forcibly reflect the contamination of water at the local of their capture.

To evaluate potential health implications, observed concentrations were compared with the maximum permissible levels established by the European Union Regulation (EU 2023/915) and by the Codex Alimentarius (FAO/WHO). Since regulatory limits are expressed on a wet-weight (w.w.) basis, values were converted to dry-weight (d.w.) equivalents assuming 75% moisture content. The results are presented in Table 7. Most metals in fish tissues remained within international safety limits. However, Pb and Cd occasionally exceeded EU thresholds, particularly in

Table 7 Comparison of trace element concentrations in fish muscle from Kasi River (mg kg⁻¹ d.w.) with EU and FAO Codex recommended limits

Metal	Fish from Kasai River (mg kg ⁻¹)	Limit EU/Codex	Compliance status
Cd	0.2–0.7	0.20 (≈0.05 mg kg ⁻¹ w.w.)	Some samples exceed (e.g., <i>S. congicus</i> Kutumuke=0,6)
Pb	0.2–1.6	1.20 (≈ 0.30 mg kg ⁻¹ w.w.)	Exceedance is <i>S. congicus</i> Kutumuke (1,6)
Hg (total)	0.04–0.97	2.0 (non-predators, ≈ 0.5 mg kg ⁻¹ w.w.); 4.0 (predators, ≈1.0 mg kg ⁻¹ w.w.)	All within limits, but <i>M. angolensis</i> Bendela (0,97) approaches predator threshold
As (total)	<0.1–0.3	3.2 (≈ 0.8 mg kg ⁻¹ w.w.)	Far below regulatory limits
Zn	18–59	No official Codex/EU limit (nutritional guideline < 100 mg kg ⁻¹ d.w.)	High in <i>S. congicus</i> (59) and possible bioaccumulation
Cu	0.8–3.3	No Codex/EU limit (<30 mg kg ⁻¹ d.w. recommended)	All within safe levels
Fe	23–89	No Codex/EU limit	Conform
Mn	3–19	No Codex/EU limit	Conform

Table 8 Estimated Daily Intake (EDI), Non-carcinogenic risk (THQI, HI) and Carcinogenic risk (CR) of inorganic arsenic and hexavalent chromium (Cr (VI)) in fish

EDI																	
Sample site	Sample ID	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Ag	Cd	Sn	Ba	Pb	Hg	
BEND-ELA DIMA LUMBU KUTU-MUKE	<i>D.fasciolatus</i>	0.00035	0.0012	0.01646	0.00002	0.00006	0.00061	0.0065	0	0.0003	0.00009	0.00009	0.00006	0.00089	0.00006	0.00007	
		0.00028	0.00057	0.00433	0.00002	0.00004	0.00024	0.00405	0	0.00022	0.00006	0	0.00004	0.00046	0.00011	0.00001	
		0.00033	0.00213	0.0115	0.00004	0.00006	0.00024	0.00592	0.00002	0.00035	0.00009	0.00013	0.00004	0.00163	0.00015	0.00001	
		0.00024	0.00106	0.00861	0.00002	0.00004	0.00017	0.00722	0	0.00013	0.00006	0	0.00004	0.00213	0.00009	0.00012	
BEND-ELA DIMA LUMBU KUTU-MUKE	<i>S.congius</i>	0.00026	0.00144	0.00678	0.00002	0.00006	0.0003	0.00985	0.00002	0.00022	0.00007	0	0.00004	0.00157	0.00006	0.00015	
		0.00024	0.00178	0.01172	0.00004	0.00006	0.00015	0.01096	0.00002	0.00007	0.00006	0.00011	0.00004	0.00465	0.0003	0.00016	
		0.00022	0.00354	0.00927	0.00002	0.00006	0.00026	0.00961	0.00002	0.0003	0.00007	0	0.00004	0.00344	0.00002	0.00018	
		0.00024	0.0023	0.00833	0	0.00007	0.00019	0.00966	0	0.00015	0.00009	0	0.00004	0.00274	0.00002	0.0001	
BEND-ELA DIMA LUMBU KUTU-MUKE		0.00019	0.00135	0.01066	0	0	0.00028	0.01	0.00002	0.0002	0.00007	0	0	0.00241	0	0.00016	
		THQI															
		Sample site	Sample ID	Cr	Fe	Ni	Zn	As	Cd	Pb	Hg	HI	CR As	CR Cr (VI)	Se/Hg		
		BEND-ELA DIMA LUMBU KUTU-MUKE	<i>D.fasciolatus</i>	0.0002	0.024	0.003	0.02	0.00	0.09	0.02	0.7	0.9	0	2.67×10^{-10}	4		
BEND-ELA DIMA LUMBU KUTU-MUKE	<i>S.congius</i>	0.0002	0.006	0.002	0.01	0.00	0	0.03	0.1	0.2	0	2.14×10^{-10}	30				
		0.0002	0.016	0.003	0.02	0.07	0.13	0.04	0.1	0.4	4.58×10^{-10}	2.52×10^{-10}	31.7				
		0.0002	0.012	0.002	0.02	0.00	0	0.03	1.2	1.3	0	1.83×10^{-10}	1.1				
		0.0002	0.010	0.003	0.03	0.07	0	0.02	1.5	1.6	4.58×10^{-10}	1.98×10^{-10}	1.5				
BEND-ELA DIMA LUMBU KUTU-MUKE	<i>M.angolensis</i>	0.0002	0.017	0.003	0.04	0.07	0.11	0.09	1.6	1.9	4.58×10^{-10}	1.83×10^{-10}	0.5				
		0.0001	0.013	0.003	0.03	0.07	0	0.01	1.8	1.9	4.58×10^{-10}	1.68×10^{-10}	1.6				
		0.0002	0.012	0.004	0.03	0.00	0	0.01	1	1.1	0	1.83×10^{-10}	1.4				
		0.0001	0.015	0.000	0.03	0.07	0	0	1.6	1.7	4.58×10^{-10}	1.45×10^{-10}	1.3				

benthic species such as *S. congicus* from Kutumuke, thus representing a potential health concern for frequent consumers. Hg concentrations remained below limits but approached the critical levels in predatory species (*M. angolensis* from Bendela). The elevated Zn concentrations ($> 50 \text{ mg kg}^{-1} \text{ d.w.}$) observed in some samples suggested also notable bioaccumulation, although Zn is not directly regulated in fish tissues.

A clear spatial gradient was observed along the river, with metal concentrations decreasing downstream following the pattern Bendela > Dima Lumbu > Kutumuke. This trend mirrors the sediment geochemical composition, particularly the downstream decline in organic matter and CaCO_3 contents that influence metal bioavailability.

Species-specific differences were also evident: benthic feeders such as *S. congicus* accumulated higher Pb and Zn, likely reflecting sediment contact and feeding behavior, whereas predatory species like *M. angolensis* exhibited higher Hg, consistent with biomagnification along the food web.

3.6 Assessment of Human Health Hazards from Consumption of Fish

The health hazards associated with the consumption of three fish species—*Distichodus fasciolatus*, *Synodontis congicus*, and *Marcusenius angolensis*—collected along the Kasai River were evaluated using the Estimated Daily Intake (EDI), non-carcinogenic risk indices (THQI and Hazard Index, HI), carcinogenic risk (CR), and the selenium-to-mercury molar ratio (Se/Hg) (Table 8).

EDI values for toxic metals (As, Cr (VI), Hg, Cd, Pb) were consistently low across all species and sites, and well below international safety thresholds. Essential elements (Fe, Zn) displayed higher but non-toxic intakes, and Se levels were sufficient to mitigate potential mercury toxicity. Spatially, EDI values decreased downstream, following the sediment contamination gradient (Bendela > Dima Lumbu > Kutumuke), consistent with observed reductions in organic matter and carbonate content.

THQI values for individual metals were < 1 , indicating that they are of minimal health concern. Cumulative HI ranged from 0.1 to 1.9, with the highest value observed in *M. angolensis* at Bendela. While frequent consumption of this species may approach precautionary thresholds, the overall non-carcinogenic risk is low.

The lifetime cancer risk due to As and Cr (VI) was negligible ($\leq 4.6 \times 10^{-10}$), suggesting no significant carcinogenic hazard to humans from fish consumption.

The Se/Hg ratios varied among species and sites. *D. fasciolatus* exhibited high ratios (4.0–31.7), indicating strong selenium-mediated protection. *S. congicus* showed low ratios (0.5–1.5), particularly at Kutumuke, signaling limited protection and potential concern for sensitive populations. *M. angolensis* had moderate ratios (1.3–1.6), implying partial protection. These patterns reflect both species-specific accumulation and the upstream-to-downstream decline in sediment mercury content.

EDI, THQI/HI, CR, and Se/Hg results confirmed a low risk of non-carcinogenic and carcinogenic effects, with spatial patterns consistent with sediment geochemistry and metal bioavailability. The overall results indicated that fish from the Kasai River are generally safe for human consumption. Notwithstanding, the highest HI values and lowest Se/Hg ratios were observed in *M. angolensis* at Bendela and *S. congicus* at Kutumuke, suggesting the need for continued monitoring.

4 Conclusions

This study provided the first comprehensive assessment on the contamination by inorganic micropollutants of sediments and edible fish from the Kasai River near Bandundu city, DRC. Sediment analyses revealed a distinct upstream-to-downstream gradient in trace metal concentrations, with the highest levels observed at Bendela: Cu ($16\text{--}57 \text{ mg kg}^{-1}$), Zn ($134\text{--}279 \text{ mg kg}^{-1}$), Pb ($42\text{--}69 \text{ mg kg}^{-1}$), and Hg ($0.04\text{--}0.97 \text{ mg kg}^{-1}$). Organic matter (2.6–11.4%) and calcium carbonate (0.16–2.72%) were identified as key factors influencing metal retention, highlighting the interplay between sediment geochemistry and metal accumulation. Ecological risk indices indicated moderate to considerable risk, with Hg (Eri = 93–114), Cd (Eri = 31–43), and Pb (Eri = 15–17) as the primary contributors.

In fish, toxic metal concentrations were generally low: Cr ($1.0\text{--}1.9 \text{ mg kg}^{-1}$), Ni and Co ($< 0.4 \text{ mg kg}^{-1}$), As ($< 0.1\text{--}0.3 \text{ mg kg}^{-1}$), and Se ($0.4\text{--}1.9 \text{ mg kg}^{-1}$). However, Pb ($0.2\text{--}1.6 \text{ mg kg}^{-1}$) and Cd ($0.2\text{--}0.7 \text{ mg kg}^{-1}$) occasionally exceeded EU limits, particularly in benthic species such as *Synodontis congicus* at Kutumuke. Hg levels remained below regulatory thresholds, though *Marcusenius*

angolensis at Bendela approached 0.97 mg kg^{-1} . Integrated risk assessments—namely Estimated Daily Intake (EDI), Target Hazard Quotients ($\text{THQ} < 1$), Hazard Index ($\text{HI} = 0.1\text{--}1.9$), and carcinogenic risk ($\text{CR} \leq 4.58 \times 10^{-10}$)—indicated overall low health risk, with site and species-specific variations. Selenium-to-mercury molar ratios ($\text{Se/Hg} = 0.5\text{--}31.7$) further revealed differential protective effects against mercury toxicity, particularly limited in some benthic feeders.

This study demonstrated also that while sediments were moderately to considerably contaminated by heavy metals, the analyzed fish species generally remained safe for human consumption. Furthermore, the findings underscored the importance of periodic monitoring of the contamination of Kasai River as well as the need for improved management of anthropogenic discharges from mining, agriculture, and urban activities in order to safeguard both the aquatic ecosystems and the health of local fish consumers.

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Declarations

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