



Accumulation of toxic metals in sediments and oligochaetes around urban uncontrolled landfills in Kinshasa, DR Congo

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Abstract Urban uncontrolled landfills in Kinshasa generate metal-rich leachates that contaminate surrounding freshwater streams, sediments, and biota. To assess the extent of this contamination, sediment from six freshwater streams in Kinshasa (N'djili, Limete, Lemba, Selembao, Mont-Ngafula, Makala) were analyzed to assess contamination by heavy metals—including Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn,

As, Mo, Cd, Sn, Sb, Pb and Hg—and bioaccumulation in terrestrial (*Lumbricus terrestris*) and aquatic (*Tubifex tubifex*, *Nais elinguis*, *Enchytraeus albidus*) oligochaetes. Sediments were digested following the Swiss Federal Soil Ordinance (OSol 814.12) and analyzed using ICP-MS for metals and a Direct Mercury Analyzer (CV-AAS) for total Hg. Oligochaete tissues were freeze-dried, acid-digested ($\text{HNO}_3\text{--HClO}_4$), and analyzed using the same instrumentation. Sediment pollution levels were assessed using the Geoaccumulation Index (Igeo), Enrichment Factor (EF), contamination factor (CF), and the overall Ecological Risk Index (RI), while ecological thresholds were compared to the Canadian Sediment Quality Guidelines. Bioaccumulation factors (BAF) were calculated to quantify metal transfer from sediments to organisms. Sediments showed strong contamination at landfill-impacted sites, with Hg reaching $3.8 \text{ mg}\cdot\text{kg}^{-1}$ dry weight—far exceeding Canadian SQGs (TEL: $0.17 \text{ mg}\cdot\text{kg}^{-1}$) and PELs ($0.486 \text{ mg}\cdot\text{kg}^{-1}$). Cu and Zn were also highly elevated (up to 687.9 and $995.3 \text{ mg}\cdot\text{kg}^{-1}$, respectively). RI values were highest at Limete (1014–3552.7), indicating very high ecological risk. Aquatic oligochaetes exhibited greater bioaccumulation than terrestrial species, with Hg up to $0.876 \text{ mg}\cdot\text{kg}^{-1}$ and Cu up to $93.1 \text{ mg}\cdot\text{kg}^{-1}$. High BAFs were observed, particularly for Cd (118.2 at Mont-Ngafula) and Sn (263.1 at Makala), confirming strong sediment-to-organism transfer. Fine, organic-rich sediments and proximity to landfill leachates

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were positively correlated with metal contamination and bioavailability.

Keywords Uncontrolled · Landfills · Heavy metals · Oligochaetes · Bioaccumulation · Ecological risk assessment · Kinshasa

Introduction

Uncontrolled open dumps and landfills constitute a major environmental challenge in urban areas worldwide, particularly in rapidly expanding cities of developing countries. Driven by accelerated urbanization, population growth, and inadequate waste management infrastructure, these unregulated disposal sites fail to effectively contain hazardous materials and leachates. During rainfall events, water percolates through waste piles and mobilizes leachates enriched with toxic substances, including heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As), as well as persistent organic pollutants. Owing to their toxicity, persistence, and bioaccumulative behavior, these contaminants pose serious ecological and public health risks by degrading soil and aquatic ecosystems and entering the food chain (Akonga et al., 2025; Grangxabe et al., 2024; Oros, 2025; Saidon et al., 2024). In parallel, the decomposition of organic waste generates greenhouse gases, notably methane, thereby contributing to climate change, while populations living in low-income urban neighborhoods experience disproportionate exposure to these environmental hazards (Gochfeld & Burger, 2011; Hajat et al., 2015; Magazzino et al., 2024).

Unlike organic contaminants, heavy metals are non-biodegradable and tend to persist in the environment. Their strong affinity for fine-grained particles and organic matter leads to their accumulation in soils and sediments, which act not only as long-term sinks but also as potential secondary sources of pollution under changing physicochemical conditions. Consequently, sediments play a critical role in the redistribution of contaminants within aquatic systems. Understanding the transfer of metals from sediments to living organisms is therefore essential for evaluating ecological risks and predicting human exposure through trophic pathways (Lundemi et al., 2022; Roberts, 2012).

Among sediment-dwelling organisms, oligochaete worms—both terrestrial and aquatic—are of particular ecological importance. Through burrowing, ingestion, and continuous interaction with sediments, they influence sediment structure, microbial activity, and contaminant bioavailability. Several species, including *Lumbricus terrestris*, *Tubifex tubifex*, *Nais elinguis*, and *Enchytraeus albidus*, exhibit a strong capacity to bioaccumulate heavy metals in their tissues, making them reliable bioindicators of environmental contamination (Frank et al., 2023; Gkika et al., 2024; Lourenço et al., 2011; Moreno-Ocio et al., 2024). Beyond their role in biomonitoring, oligochaetes are increasingly recognized for their potential contribution to bioremediation processes, as their biological activity can enhance contaminant transformation and reduce metal bioavailability in soils and sediments. While vermiremediation in terrestrial environments is relatively well documented, the application of oligochaetes to contaminated aquatic sediments remains insufficiently explored despite its promising potential (Shi et al., 2020; Zeb et al., 2020).

The Democratic Republic of the Congo (DRC), and particularly the city of Kinshasa, exemplifies the environmental pressures associated with uncontrolled landfills and deficient urban waste management. Rapid population growth, industrial development, and weak regulatory enforcement have intensified pollution of urban soils and waterways. Nevertheless, data on heavy metal contamination in sediments and aquatic biota—especially sediment-dwelling oligochaetes—remain scarce. Investigating these organisms is therefore crucial for improving knowledge of contamination levels, ecological risks, and possible monitoring and remediation strategies in this rapidly urbanizing context (Vivien et al., 2014).

Urban rivers in Kinshasa receive inputs from multiple anthropogenic sources, including industrial effluents (pharmaceuticals, paint manufacturing, breweries), artisanal activities (vehicle repair workshops, small-scale agriculture), and domestic waste originating from uncontrolled dumpsites. The convergence of these inputs, combined with hydrodynamic and sedimentary processes, leads to the formation of contamination hotspots where toxic metals accumulate in sediments and become bioavailable to benthic organisms. Assessing metal concentrations in riverbank soils, sediments, and oligochaete tissues thus provides an integrated view of contamination

patterns, ecological impacts, and the potential transfer of pollutants through aquatic food webs to higher trophic levels, including humans.

Against this background, the present study aimed to address existing knowledge gaps by: (1) assessing the concentrations of heavy metals in riverbank soils, river sediments, and the tissues of terrestrial and aquatic oligochaetes in areas influenced by uncontrolled urban landfills in Kinshasa; (2) evaluating the associated ecological and toxicological risks using indices such as the Geoaccumulation Index (Igeo), Enrichment Factor (EF), and Ecological Risk Index (RI); (3) investigating bioaccumulation patterns in oligochaetes in relation to sediment characteristics, species-specific traits, and proximity to contamination sources; and (4) exploring the potential of oligochaetes as sentinel species for environmental monitoring and as biological tools for sustainable bioremediation strategies.

By linking the global issue of uncontrolled urban waste disposal with the ecological role of oligochaetes and the specific environmental context of Kinshasa, this study provides a comprehensive framework for understanding and managing heavy metal contamination in urban aquatic systems. The findings

highlight both the severity of environmental risks associated with landfill-derived pollution and the promising utility of oligochaetes in monitoring and remediation programs.

Materials and methods

Description of study sites

Six areas crossed by freshwater streams, all located in the city of Kinshasa and within the catchment basin of the N'djili River, were selected as study sites: N'djili, Limete, Lemba, Selembao, Mont-Ngafula, and Makala (Fig. 1). These sites were chosen because they act as outlets for stormwater runoff and for both solid and liquid wastes originating from surrounding municipal areas. They are also impacted by various human activities: industrial operations, particularly in the pharmaceutical sector, paint production, and breweries in Limete; artisanal activities such as vehicle and motorcycle repair and maintenance, as well as small-scale agriculture involving pesticides and fertilizers in N'djili; and predominantly domestic activities in Lemba, Mont-Ngafula, Selembao, and Makala.



Fig. 1 Sampling site of: **A** Lemba, **B** Limete, **C** N'djili, **D** Mont-Ngafula, **E** Selembao, **F** Makala (Photos by M.M. Akonga)

Several uncontrolled landfills producing leachates that flow into rivers are present at all studied sites (Mavakala et al., 2016) (Fig. 2). Local populations consume fish from these rivers, potentially exposing themselves to bioaccumulated pollutants.

Sampling procedure

In May 2025, riverbed sediment samples approximately 3 m from the shoreline were collected using a plastic scoop and transferred into 0.5 L plastic containers. At each site, five subsamples were collected at intervals of approximately 3 m and combined to form a composite sample, representing the average conditions of the sampling area. Four composite samples (240–300 g each) were collected per site, except for Mont-Ngafula, where three samples were collected, yielding a total of 23 samples. Samples were labeled as follows: Selembao: SSe1, SSe2, SSe3, SSe4;

Lemba: SLe1, SLe2, SLe3, SLe4; N'djili: SN1, SN2, SN3, SN4; Limete: SLi1, SLi2, SLi3, SLi4; Mont-Ngafula: SMo1, SMo2, SMo4; Makala: SMak1, SMak2, SKak3, SKak4.

In parallel, terrestrial and aquatic oligochaete worms were collected from the same sites. The terrestrial species included the earthworm (*Lumbricus terrestris* Linnaeus, 1758), and the aquatic species included the sludge worm (*Tubifex tubifex* Müller, 1774), the aquatic oligochaete (*Nais elinguis* Müller, 1774), and the white potworm (*Enchytraeus albidus* Henle, 1837). Sampling was conducted in late April (rainy season) and early May (onset of the dry season), when rivers were still experiencing residual flooding. These hydrological conditions promoted the transport of terrestrial organisms into river systems, leading to their accumulation in surface sediments. Consequently, *Lumbricus terrestris* was collected from surface sediments rather than from soil,

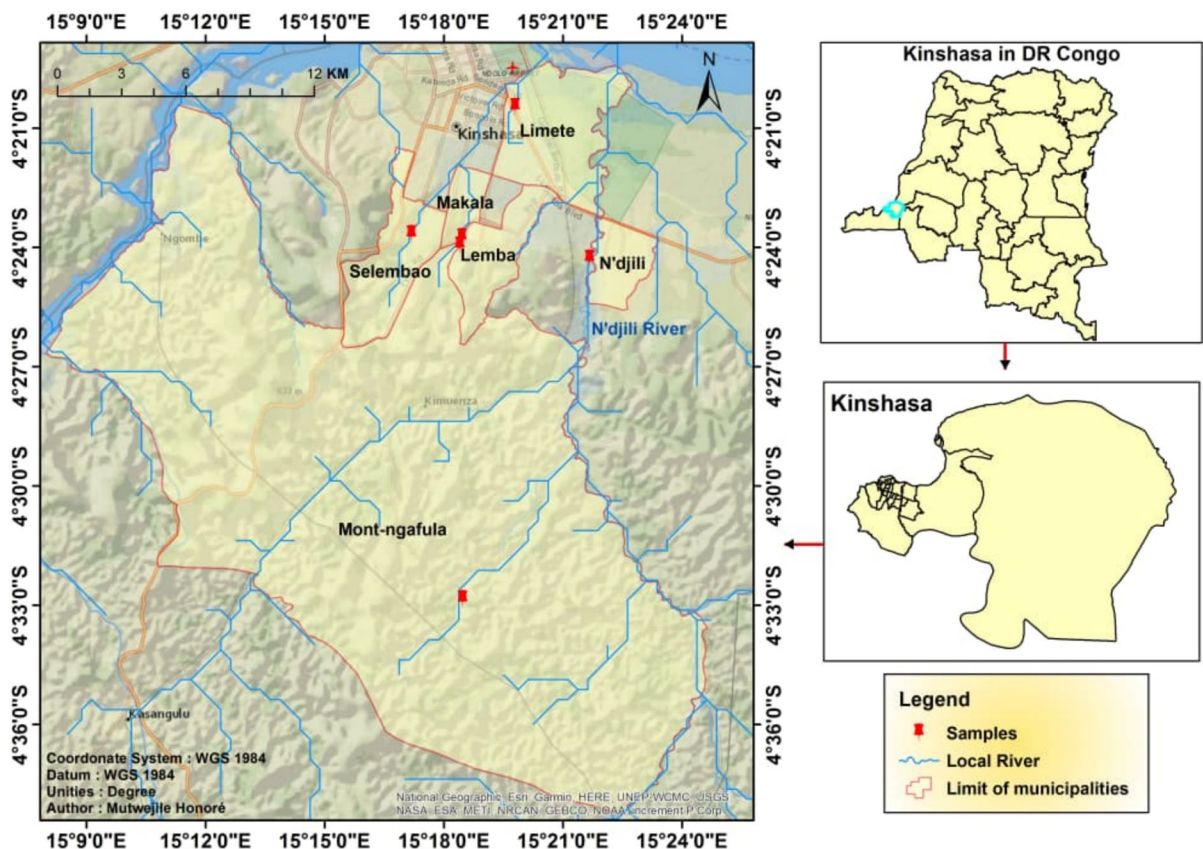


Fig. 2 Study areas with the location of sediment and worm sampling sites in the municipalities of Selembao, Lemba, N'djili, Limete, Mont-Ngafula et Makala

reflecting the hydrological context prevailing during the sampling period. On average, 118 individuals per site (mean weight 0.91 g each) were collected, placed in plastic containers, and labeled as follows: N'djili: ON1 (*Nais elinguis*), ON2 (*Tubifex tubifex*), ON3 (*Enchytraeus albidus*), ON4 (*Lumbricus terrestris*); Limete: OLi1 (*Nais elinguis*), OLi2 (*Tubifex tubifex*), OLi3 (*Enchytraeus albidus*), OLi4 (*Lumbricus terrestris*); Lemba: OLe1 (*Lumbricus terrestris*), OLe2 (*Enchytraeus albidus*), OLe3 (*Enchytraeus albidus*), OLe4 (*Nais elinguis*); Makala: OMak1 (*Nais elinguis*), OMak2 (*Lumbricus terrestris*), OMak3 (*Enchytraeus albidus*), OMak4 (*Tubifex tubifex*); Mont-Ngafula: OMo1 (*Nais elinguis*), OMo2 (*Tubifex tubifex*), OMo3 (*Enchytraeus albidus*), OMo4 (*Lumbricus terrestris*); Selembao: OSe1 (*Nais elinguis*), OSe2 (*Tubifex tubifex*), OSe3 (*Enchytraeus albidus*), OSe4 (*Lumbricus terrestris*).

All sediment, and worm samples were stored at 4 °C and transported under refrigeration to the analytical platform of the University of Geneva for analysis.

Physicochemical properties of sediment

The analysis of sediment samples included the assessment of several physicochemical parameters, such as water content (WC), organic matter (OM), carbonate (CaCO_3), and particle size distribution. WC was determined by measuring the weight loss of the samples after drying in an oven at 100 °C until constant weight. OM was quantified by incinerating dried samples at 550 °C for one hour in a muffle furnace (Salvis AG, Lucerne, Switzerland), and calculating the resulting weight reduction. The CaCO_3 fraction was evaluated by subjecting the incinerated samples to an additional combustion step at 1000 °C for one hour using the same furnace.

Particle size distribution was assessed using roughly 1 g of fresh sediment. After 5 min of ultrasonic treatment of the sediment in deionized water, the sediment particle size was determined with a Coulter LS-100 laser diffraction analyzer (Beckman Coulter, Fullerton, CA, USA) (Atibu et al., 2023; Mabidi et al., 2024).

Analysis of heavy metals in sediment samples

The preparation and digestion of sediment samples were conducted in accordance with the guidelines of

the Swiss Federal Soil Ordinance (Osol) 814.12 (RS 814.12, 1998). Sample aliquots were first oven-dried at 60 °C and then ground to a fine powder. Approximately 1 g of the processed sediment was subjected to acid digestion in 10 mL of 2 M nitric acid (HNO_3) using Teflon digestion vessels, followed by heating at 100 °C for 16 h. After cooling to ambient temperature, the mixtures were centrifuged (Centrifuge 3 K-1, Sigma, Switzerland) at 4000 rpm for 15 min to remove any insoluble residue. The supernatants were then diluted at a ratio of 1:200 with 1% suprapur-grade HNO_3 . Metal concentrations were subsequently measured using inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700× series, Santa Clara, CA, USA).

For method validation and to ensure the analytical accuracy, the certified reference material stream sediment STSD-1 (National Research Council, Ottawa, Ontario, Canada) was processed in parallel with the sediment samples. Results were reported in milligrams per kilogram (mg kg^{-1} dry weight).

Analysis of heavy metals in oligochaete samples

The analytical procedure used to determine heavy metal concentrations in oligochaete specimens was based on the approach developed by Suami et al. (2019)—originally intended for oysters and crayfish—with adjustments derived from methodologies proposed by Rashed (2001) and Sivaperumal et al. (2007). Worms were dissected, the sediment gut content carefully removed, and specimens washed with distilled water. The oligochaete tissues were freeze-dried using an Adolf Kühner freeze dryer (Birsfelden, Switzerland), and the bulk dry tissues finely ground to obtain a uniform powder. Accurately weighed aliquots of approximately one gram of each powdered sample were subjected to acid digestion in 10 mL of a 3:1 acid mixture composed of high-purity nitric acid (65%, Merck KGaA, Darmstadt, Germany) and perchloric acid (70%, Merck KGaA, Darmstadt, Germany). The digestion process was carried out overnight at 110 °C in Teflon vessels. Once cooled to ambient temperature, the digested solutions were centrifuged, diluted with 1% ultrapure nitric acid, and then analyzed via Inductively Coupled Plasma Mass Spectrometry (ICP-MS). All acid dilutions were performed using ultrapure water (Milli-Q, 18 M Ω -cm, Merck, Darmstadt, Germany).

As a quality control measure, the fish protein certified reference material for trace metals DORM-4 (National Research Council, Ottawa, Canada) was digested and analyzed alongside the samples. The concentrations of metals were reported in milligrams per kilogram (mg kg^{-1} dry weight).

Determination of mercury concentrations in sediment and oligochaete samples

Total mercury (Hg) concentrations in both sediment and oligochaete samples were determined using a Direct Mercury Analyzer (DMA 80-III, MWS GmbH), which operates via cold vapor atomic absorption spectroscopy (CV-AAS). This analytical technique involves thermal decomposition of the samples, followed by mercury amalgamation in a gold trap and subsequent quantification of the vaporized mercury.

For the analytical quality control of sediment analysis, the standard reference material for inorganics in marine sediment SRM 2702 (National Institute of Standards & Technology, USA) was processed alongside the samples, employing the Feststoffe Schnell protocol (in brief: no pre-drying, combustion at 750°C).

As a quality control procedure in the analyses of oligochaete tissues, the DORM-4 certified reference material was used, and the Kunstoff protocol applied (drying at 400°C and combustion at 750°C). Mercury concentrations were reported in milligrams per kilogram (mg kg^{-1} dry weight) (Mudinga et al., 2024).

Assessment of sediment pollution

Sediment contamination was evaluated using two principal indices: the Geoaccumulation Index (I_{geo}) and the Enrichment Factor (EF) (Banze wa Mutombo et al., 2022). The geoaccumulation index (I_{geo}) was used, and calculated as:

$$I_{\text{geo}} = \log_2 \left[\frac{M}{(1.5 \times B)} \right] \quad (1)$$

where M is the measured metal concentration in the sediment and B is the background level of the same metal. The constant 1.5 accounts for the

natural variability in background metal concentrations (Banze wa Mutombo et al., 2022).

The enrichment factor (EF) was used to further quantify the degree of contamination, as it allows differentiation between natural (geogenic) and anthropogenic metal sources. EF was calculated using the following formula:

$$EF = (M/Sc)_{\text{sample}} / (M/Sc)_{\text{background}} \quad (2)$$

where, M refers to the concentration of a given heavy metal, while Sc represents scandium concentration in the same sample or in the background. Scandium was selected as a conservative element for normalization purposes. The geochemical background values for the metals were taken from the Upper Continental Crust (UCC) reference data (Sun et al., 2022).

Estimation of ecological risk indices

To evaluate the degree of metal contamination in sediment, the contamination factor (CF) was determined as follows (Swain, 2024; Hånkanson Saleem et al., 2024):

$$CF = M/B \quad (3)$$

where M and B are, respectively, the metal concentrations in the sample and its geochemical baseline (UCC value).

The cumulative impact of multiple heavy metals in a sample was assessed using the contamination degree (CD), calculated as:

$$CD = \sum CF_m \quad (4)$$

where, CF_m is the contamination factor for each metal included in the assessment. The elements considered were Hg, Cd, As, Co, Cu, Pb, Cr, and Zn.

To assess ecological threats posed by these contaminants, the individual ecological risk index (Er_m) was determined using the formula (Suresh et al., 2012):

$$Er_m = Tr_m \times CF_m \quad (5)$$

where Tr_m represents the toxic response factor specific to each metal: Hg (40), Cd (30), As (10), Co (5), Cu (5), Pb (5), Cr (2), and Zn (1) (Islam et al., 2015).

Finally, the overall potential Ecological Risk Index (RI) was obtained by summing the risk indices for all metals:

$$RI = \sum Er_m \quad (6)$$

This cumulative index takes into account both the toxicity and the ecological sensitivity associated with multiple metal pollutants.

In addition, ecotoxicological assessments were carried out by comparing the measured concentrations of metals in sediments to the thresholds defined in Sediment Quality Guidelines (SQGs) and Probable Effect Levels (PELs) for protection of aquatic organisms, as adopted in Canada (CCME, 1999).

Bioaccumulation factor (BAF)

To estimate the transfer of metals from contaminated sediments to benthic organisms, the bioaccumulation factor (BAF) was calculated. The BAF represents the ratio between the concentration of metals in earthworms and in the surrounding sediment, using the following formula (Dedeke et al., 2016; Wang et al., 2018):

$$BAF = C_{ew}/C_s \quad (7)$$

where C_{ew} is the metal concentration in the earthworm tissue ($\text{mg}\cdot\text{kg}^{-1}$ dry weight) and C_s is the average concentration of the corresponding metal in sediment ($\text{mg}\cdot\text{kg}^{-1}$ dry weight). This evaluation was performed on samples collected from the municipalities of N'djili, Limete, and Lemba, which are the areas affected by uncontrolled landfill sites.

Analytical quality control statement and statistical treatment of data

All heavy-metal determinations were performed under strict analytical quality-control procedures. Each batch of samples included calibration standards, procedural blanks, duplicate samples, and certified reference materials (CRMs) to ensure the accuracy and precision of the measurements. Analytical determinations were carried out in triplicate, and the coefficients of variation measurements remained below 5%, indicating excellent instrument stability and reproducibility throughout the analysis. Triplicate

analytical results were averaged prior to statistical processing.

Statistical analyses focused on assessing relationships among measured variables and evaluating patterns in metal contamination. Spearman's rank correlation coefficients were computed using XLSTAT version 2021.1 (Addinsoft, New York, USA, accessed July 2025), a non-parametric method appropriate for datasets that may not satisfy normality assumptions. Data normality was verified using the Shapiro–Wilk test, and homogeneity of variance was assessed with Levene's test to ensure the robustness of the correlation analysis. Statistical significance was evaluated at the 95% confidence level ($p < 0.05$). All statistical analyses were conducted using the averaged triplicate values for each sample.

This approach ensures that the dataset is treated with rigorous quality control and that statistical relationships are reliably quantified, providing a solid methodological foundation for subsequent interpretation of sediment metal contamination.

Results and discussion

Physicochemical characteristics of sediment samples

The physico-chemical parameters of the sediment samples revealed significant spatial variation across the six municipalities of Kinshasa (Table 1). Water content (WC) ranged from 11.04% at N'djili (SN2) to 48.37% at Limete (SLi3), with the highest values observed in Limete and Makala, indicating a higher water retention capacity associated with fine-grained sediments. Organic matter (OM) contents varied widely, from $<1\%$ in Mont-Ngafula and Makala to $>20\%$ in SLi4 (Limete) indicating contrasting depositional environments. Fine sediments in Limete and Selembao act as sinks for OM, whereas sandy sediments in Mont-Ngafula and Makala show limited accumulation, consistent with previous studies (Yu et al., 2019; Zhang et al., 2014).

Calcium carbonate (CaCO_3) contents ranged from 0.08% (SMo4, Mont-Ngafula) to 9.59% (SLi4, Limete), reflecting both differences in local lithology and diagenetic processes that may affect the metal mobility. Sediments texture confirmed these patterns: Mont-Ngafula and Makala were predominantly

Table 1 Physico-chemical parameters of sediment samples

Sampling site	Sample ID	WC %	OM %	CaCO ₃ %	Sand %	Silt %	Clay %	Mean (μm)
Selembao municipality	SSe1	40.05	11.24	3.43	10.3	82.82	6.88	11.26
	SSe2	26.75	5.57	1.73	32.18	65.22	2.6	24.16
	SSe3	26.73	6.86	2.21	36.64	59.57	3.79	26.19
	SSe4	29.33	7.5	2.35	24.59	72.13	3.28	19.18
Lemba municipality	SLe1	17.98	2.41	1.26	78.97	19.61	1.42	120.7
	SLe2	33.59	9.42	3.17	54.12	43.75	2.13	57.27
	SLe3	30.41	7.42	3.28	23.93	72.64	3.43	19.18
	SLe4	30.47	8.11	3.92	5.06	84.33	10.61	8.03
N'djili municipality	SN1	17.95	1.56	0.42	83.08	16.05	0.88	103.7
	SN2	11.04	2.96	1.37	67.6	31.24	1.16	103.6
	SN3	24.02	3.82	1.59	66.78	31.52	1.7	60.33
	SN4	16	1.17	1.3	89.27	9.69	1.04	244
Limete municipality	SLi1	40.54	13.37	4.01	23.76	75.22	1.02	23.4
	SLi2	30.47	7.08	2.7	47.08	52.45	0.47	48.24
	SLi3	48.37	12.89	4.37	35.05	63.97	0.98	33.38
	SLi4	31.3	21.06	9.59	23.76	74.82	1.42	23.31
Mont-Ngafula municipality	SMo1	12.84	0.75	0.2	93.06	5.92	1.02	235.6
	SMo2	16.15	0.39	0.15	98.29	1.56	0.15	304.8
	SMo4	13.5	0.24	0.08	98.63	1.37	0	250.4
Makala municipality	SMak1	13.25	0.36	0.31	96.98	2.62	0.4	284
	SMak2	14.58	0.53	0.35	92.35	6.68	0.97	221.3
	SMak3	16.34	0.31	0.35	98.02	1.66	0.32	312.6
	SMak4	41.65	0.39	0.5	97.86	1.78	0.36	301.7

sandy (>92%), whereas Selembao and Lemba contained >65% silt. Clay fractions were generally low (<5%), except for SSe1 (6.88%) and SLe4 (10.61%). Mean particle size ranged from 8.03 μm (Lemba) to 312.6 μm (Makala), reflecting the influence of hydrodynamic sorting and local sediment sources.

Site with fine, organic-rich sediments (Limete, Selembao, Lemba) are likely to retain more contaminants, particularly heavy metals, due to higher adsorption capacity (Pal & Hogland, 2022; Soriano et al., 2024). Conversely, sandy, organic-poor sediments from Mont-Ngafula and Makala show lower retention and may facilitate contaminant transport.

Concentrations of heavy metals in sediment samples

Trace metal concentrations are presented in Table 2. Accuracy was confirmed using certified reference materials STSD 1 and SRM 2702. For STSD 1, the measured values for V (45.7 mg·kg⁻¹), Cr (27.3 mg·kg⁻¹), Co (13.5 mg·kg⁻¹), Ni

(17.3 mg·kg⁻¹), Cu (35.4 mg·kg⁻¹), Zn (163.9 mg·kg⁻¹), As (15.7 mg·kg⁻¹), Cd (0.7 mg·kg⁻¹), and Pb (32.8 mg·kg⁻¹) closely matched the certified reference values (47, 28, 14, 18, 36, 165, 17, 0.8, and 34 mg·kg⁻¹, respectively), with deviations within acceptable analytical uncertainty. Similarly, for the certified reference material SRM 2702, the detected Hg concentration (0.4434 mg·kg⁻¹) was almost identical to the certified value (0.4474 mg·kg⁻¹) (Table 2). These results, combined with coefficients of variation below 5% for triplicate analyses, demonstrate the accuracy and reproducibility of the ICP-MS and DMA measurements and provide confidence in the interpretation of sediment contamination levels.

Mercury (Hg) concentrations ranged from 0.2 mg·kg⁻¹ (Lemba, Mont-Ngafula and Makala) to 3.8 mg·kg⁻¹ (Limete), with several samples exceeding both the Sediment Quality Guideline (SQG=0.17 mg·kg⁻¹) and the Probable Effect Level (PEL=0.486 mg·kg⁻¹) (CCME, 1999). The high

Table 2 Concentrations of trace metals in sediment samples (mg kg^{-1} dry weight) and results of trace metal analyses in certified reference materials

Sample ID	Hg (DMA)	Metal values (ICP-MS)										Cd	Sn	Sb	Pb
		Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Mo		
STSD 1	Ref. value	–	–	47	28	–	–	14	18	36	165	17	–	–	34
	Det. Value	–	–	45.7	27.3	3716.4	–	13.5	17.3	35.4	163.9	15.7	1.9	1.8	32.8
SRM 2702	Ref. value	0.4474	–	–	–	–	–	–	–	–	–	–	–	–	–
	Det. Value	0.4434	–	–	–	–	–	–	–	–	–	–	–	–	–
SSe1	0.7	2.0	187.6	26.3	16.1	82.0	16,385.6	1.6	5.1	58.2	174.1	1.1	≤LD	0.4	54.1
SSe2	0.4	1.0	165.7	14.2	8.0	47.3	8891.1	0.8	4.6	52.9	75.3	0.7	≤LD	0.1	55.3
SSe3	0.5	1.3	170.2	18.6	11.1	51.1	10,947.0	1.1	3.9	42.3	107.1	0.9	≤LD	1.2	25.3
SSe4	0.5	1.4	177.5	20.8	12.1	63.0	12,628.1	1.3	4.4	54.3	119.7	0.9	≤LD	0.2	91.0
SLe1	1.0	0.4	138.9	6.0	5.1	36.6	3915.4	0.6	2.1	37.7	64.4	0.4	≤LD	0.1	50.3
SLe2	0.6	0.8	160.3	10.0	44.0	83.6	7380.5	1.5	4.5	42.6	188.1	0.8	≤LD	0.5	70.1
SLe3	0.2	0.8	59.6	11.0	40.1	72.4	7691.1	1.0	3.5	67.9	156.5	0.7	≤LD	0.4	87.6
SLe4	0.4	1.3	180.8	18.7	65.3	113.8	11,943.2	1.5	5.3	64.7	198.4	1.0	≤LD	0.5	34.2
SN1	0.6	0.2	22.8	4.1	2.7	10.8	2558.2	0.2	0.5	42.2	23.0	0.2	≤LD	0.0	63.3
SN2	0.5	0.1	17.1	1.3	5.0	75.8	2066.5	0.3	1.6	76.6	87.8	0.2	≤LD	0.4	10.5
SN3	0.6	1.1	141.4	13.6	8.9	39.4	8494.9	0.8	2.5	14.5	36.7	0.5	≤LD	0.1	7.9
SN4	0.5	0.1	126.4	1.0	4.7	56.8	7319.1	0.7	2.5	687.9	98.9	0.6	≤LD	0.4	404.3
SLi1	0.6	0.6	178.5	7.7	58.2	160.4	8047.4	3.4	8.9	171.1	619.1	1.0	0.1	1.6	164.6
SLi2	3.2	0.4	58.2	5.1	60.6	85.0	4955.6	2.1	5.2	151.5	356.0	0.6	≤LD	0.7	28.5
SLi3	2.3	0.6	177.1	7.1	74.7	105.5	7284.0	4.1	7.9	153.5	544.1	0.9	0.1	1.3	176.7
SLi4	3.8	1.1	137.5	12.0	88.9	268.8	12,610.0	5.5	14.8	113.0	995.3	1.5	0.2	2.4	197.0
SMo1	0.2	0.1	62.4	2.5	31.3	4.3	1239.4	0.1	1.2	7.9	8.1	0.1	≤LD	0.0	0.8
SMo2	0.2	0.2	69.1	3.2	61.7	5.2	1500.2	0.1	2.3	7.0	4.6	0.1	≤LD	0.0	2.5
SMo4	0.2	0.1	69.8	2.8	51.5	6.2	1331.2	0.2	0.2	0.9	6.9	0.1	≤LD	≤LD	0.8
SMak1	0.3	0.2	43.7	3.2	43.1	13.7	2372.3	0.3	0.4	3.0	31.3	0.2	≤LD	0.0	4.9
SMak2	0.2	0.1	54.4	3.4	41.8	8.4	1872.1	0.2	0.9	3.1	20.1	0.2	≤LD	0.0	2.3
SMak3	0.3	0.1	63.5	2.8	82.5	12.6	2107.8	0.2	0.6	2.2	32.1	0.2	≤LD	0.0	3.9
SMak4	0.2	0.2	26.1	3.3	42.2	13.6	2962.9	0.2	0.6	2.2	23.5	0.2	≤LD	0.0	3.2
SQG	0.17	–	–	–	37.3	–	–	–	–	35.7	123.0	5.9	–	0.6	35.0
PEL	0.486	–	–	–	90.0	–	–	–	–	197.0	315.0	17.0	–	3.5	91.3

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). The symbol ≤LD means below the limit of detection and the symbol « – » means not analysed

levels observed in Limete are consistent with industrial discharges identified at this site (pharmaceuticals, paints, breweries) (Bernard et al., 2021; Gezahegn et al., 2025; Wada & Olawade, 2025).

Copper (Cu) and zinc (Zn) concentrations also were particularly high at N'djili (Cu = 687.9 mg·kg⁻¹; Zn = 98.9 mg·kg⁻¹) and Limete (Zn = 356–995.3 mg·kg⁻¹; Cu = 113–171.5 mg·kg⁻¹), exceeding PEL thresholds (197 mg·kg⁻¹ for Cu and 315 mg·kg⁻¹ for Zn). These results reflect artisanal automobile repair urban agriculture at N'djili (Duru et al., 2024; El-Sharkawy et al., 2025) and industrial activities at Limete.

Selembao and Lemba exhibited intermediate pollution, with Pb concentrations reaching 91.0 mg·kg⁻¹ and 87.6 mg·kg⁻¹, respectively, close to or exceeding the PEL threshold (91.3 mg·kg⁻¹). These values reflect the influence of domestic effluents and leachates from uncontrolled landfills, which are abundant in these areas. The presence of such landfills, as described in the site characterization, therefore appears to be a major factor contributing to the transfer of heavy metals into sediments (Igwegbe et al., 2024).

Conversely, Mont-Ngafula and Makala showed generally lower metal concentrations often below the SQG thresholds. For instance, Cu concentrations ranged from 0.9 to 7.9 mg·kg⁻¹, and Zn from 4.6 to 8.1 mg·kg⁻¹. This lower contamination may be explained by the predominance of domestic activities and a greater dilution of discharges in these peripheral zones of the city (Campos et al., 2022). However, the recurrent detection of Hg, even at low concentrations, suggests that diffuse pollution remains present and cannot be neglected (Dragun et al., 2025).

From an ecotoxicological perspective, several samples collected in Limete, N'djili, Lemba, and Selembao exceeded PEL values for Hg, Pb, Cu, and Zn, indicating a probable risk of toxic effects on benthic organisms, as outlined in CCME (1999).

Evaluation of environmental pollution parameters

The assessment of sediment contamination using the Geoaccumulation Index (Igeo) and the Enrichment Factor (EF) revealed clear spatial variations among the studied sites (Table 3). Globally, Igeo values for most metals such as Ti, V, Cr, Mn, Fe, Co, and Ni were negative, indicating that sediments remain

largely unpolluted with respect to these elements, reflecting natural background levels. In contrast, some potentially toxic metals such as Cu, Zn, Cd, Pb, and Hg displayed positive Igeo values ranging from slightly to strongly polluted categories (Banze wa Mutombo et al., 2022). Notably, Cd (Igeo up to 4.0 at Limete and Lemba) and Hg (Igeo between 2.3 and 5.5 at Selembao, Lemba, Limete, and Makala) emerged as the contaminants of most concern. These results revealed localized but significant anthropogenic inputs.

The EF analysis provided complementary insights. Elements such as Ti, Mn, Fe, and Co generally showed EF values < 3, indicating no enrichment or minor enrichment, confirming their natural origin. However, high EF values were recorded for Cd, Cu, Pb, and Hg. In particular, sediments from Limete (SLi1–SLi4) and Lemba (SLe1–SLe4) exhibited very severe to extremely severe enrichment for Cd (EF up to 299), Cu (up to 166), Pb (up to 162), and Hg (up to 753). N'djili (SN2, SN4) and Selembao (SSe2–SSe4) also showed remarkable enrichment in Cu, Zn, Pb, and Hg. Similarly, sediments from Makala and Mont-Ngafula, though less impacted overall, sporadically displayed very high EF values for Cr (up to 259 at Makala) and Hg (up to 393 at both sites).

These findings strongly suggest multiple anthropogenic sources: industrial effluents (pharmaceuticals, paint production, breweries) in Limete, artisanal activities involving metal use and oil residues in N'djili and Selembao, and domestic waste coupled with landfill leachates in Lemba, Mont-Ngafula, and Makala (Szulc et al., 2024). The elevated Cd, Pb, and Hg contamination is consistent with emissions from batteries, pigments, and other industrial by-products, while high Cu and Zn levels may result from vehicle maintenance and metal workshops (Lawal et al., 2015).

The combined use of Igeo and EF indices demonstrated that while concentrations of some metals remained at background levels, others, namely Cd, Pb, Cu, Zn, and especially Hg were present in concentrations far exceeding natural background and, thus, indicating significant anthropogenic discharges into the aquatic ecosystems of Kinshasa. The municipalities of Limete, Lemba, and N'djili stand out as the most contaminated sites, highlighting the urgent need for mitigation measures.

Table 3 Results of Igeo and FE calculated indices for metals in sediment samples

Igeo	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Sn	Pb	Hg	Igeo classification
SSe1	-4.6	-1.8	-1.7	-3.5	-1.7	-3.2	-2.6	0.6	0.7	-1.0	1.4	-4.8	0.9	3.1	Igeo ≤ 0 Class 0 – practically unpolluted
SSe2	-4.8	-2.7	-2.7	-4.3	-2.6	-4.2	-2.7	0.5	-0.5	-1.7	-0.6	-6.4	0.9	2.3	0 < Igeo < 1 Class 1 – unpolluted to moderately polluted
SSe3	-4.7	-2.3	-2.2	-4.1	-2.3	-3.8	-2.9	0.2	0.0	-1.3	3.0	-5.4	-0.2	2.6	1 < Igeo < 2 Class 2 – moderately polluted
SSe4	-4.7	-2.1	-2.1	-3.8	-2.1	-3.5	-2.8	0.5	0.2	-1.3	0.4	-5.4	1.6	2.6	2 < Igeo < 3 Class 3 – moderately to heavily polluted
SLe1	-5.0	-3.9	-3.4	-4.6	-3.7	-4.6	-3.8	0.0	-0.7	-2.5	-0.6	-5.4	0.7	3.6	3 < Igeo < 4 Class 4 – heavily polluted
SLe2	-4.8	-3.2	-0.3	-3.4	-2.8	-3.3	-2.7	0.2	0.8	-1.5	1.8	-4.8	1.2	2.8	4 < Igeo < 5 Class 5 – heavily to extremely polluted
SLe3	-6.2	-3.0	-0.4	-3.6	-2.8	-3.9	-3.1	0.9	0.6	-1.7	1.4	-5.4	1.5	1.3	5 < Igeo Class 6 – extremely polluted
SLe4	-4.6	-2.3	0.3	-3.0	-2.1	-3.3	-2.5	0.8	0.9	-1.2	1.8	-4.8	0.2	2.3	
SN1	-7.6	-4.5	-4.3	-6.4	-4.4	-6.2	-5.9	0.2	-2.2	-3.5	-	-6.4	1.1	2.8	
SN2	-8.0	-6.1	-3.4	-3.6	-4.7	-5.6	-4.2	1.0	-0.3	-3.5	1.4	-4.8	-1.5	2.6	
SN3	-5.0	-2.7	-2.6	-4.5	-2.6	-4.2	-3.6	-1.4	-1.5	-2.2	-0.6	-	-1.9	2.8	
SN4	-5.2	-6.5	-3.5	-4.0	-2.8	-4.4	-3.6	4.2	-0.1	-1.9	1.4	-0.6	3.8	2.6	
SLi1	-4.7	-3.5	0.1	-2.5	-2.7	-2.1	-1.8	2.2	2.5	-1.2	3.4	-4.0	2.5	2.8	
SLi2	-6.3	-4.1	0.2	-3.4	-3.4	-2.8	-2.5	2.0	1.7	-1.9	2.3	-5.4	-0.1	3.3	
SLi3	-4.7	-3.7	0.5	-3.1	-2.8	-1.9	-1.9	2.0	2.4	-1.3	3.1	-4.0	2.6	4.8	
SLi4	-5.0	-2.9	0.8	-1.7	-2.1	-1.4	-1.0	1.6	3.2	-0.6	4.0	-1.8	2.7	5.5	
SMo1	-6.2	-5.2	-0.7	-7.7	-5.4	-7.2	-4.6	-2.2	-3.7	-4.5	-	-	-5.2	1.3	
SMo2	-6.0	-4.8	0.2	-7.4	-5.1	-7.2	-3.7	-2.4	-4.5	-4.5	-	-	-3.6	1.3	
SMo4	-6.0	-5.0	0.0	-7.2	-5.3	-6.2	-7.2	-5.4	-3.9	-4.5	-	-	-5.2	1.3	
SMak1	-6.7	-4.8	-0.3	-6.0	-4.5	-5.6	-6.2	-3.6	-1.8	-3.5	-	-6.4	-2.6	1.8	
SMak2	-6.4	-4.7	-0.3	-6.7	-4.8	-6.2	-5.1	-3.6	-2.4	-3.5	-	-	-3.7	1.3	
SMak3	-6.1	-5.0	0.7	-6.2	-4.6	-6.2	-5.6	-4.1	-1.7	-3.5	-	-6.4	-2.9	1.8	
SMak4	-7.4	-4.8	-0.3	-6.0	-4.1	-6.2	-5.6	-4.1	-2.2	-3.5	-	-	-3.2	1.3	
EF	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Sn	Pb	Hg	EF interpretation values
SSe1	0.3	2.4	2.5	0.8	2.6	0.9	1.4	12.8	13.5	4.0	22.4	0.3	14.9	68.8	EF < 1 : no enrichment
SSe2	0.6	2.6	2.5	0.9	2.8	0.9	2.5	23.3	11.7	5.1	11.2	0.2	30.4	78.6	EF < 3 : minor enrichment
SSe3	0.5	2.6	2.7	0.7	2.6	0.9	1.7	14.3	12.8	5.1	103.6	0.3	10.7	75.5	EF 3-5 : moderate enrichment
SSe4	0.5	2.7	2.7	0.8	2.8	1.0	1.7	17.1	13.2	4.7	16.0	0.3	35.8	70.2	EF 5-10 : moderately severe enrichment
SLe1	1.3	2.8	4.0	1.7	3.1	1.7	2.9	41.5	24.9	7.3	28.1	1.0	69.2	491.1	EF 10-25 : severe enrichment
SLe2	0.7	2.3	17.3	1.9	2.9	2.1	3.1	23.4	36.4	7.3	70.2	0.8	48.2	147.3	EF 25-50 : very severe enrichment
SLe3	0.3	2.5	15.8	1.7	3.0	1.4	2.4	37.3	30.3	6.4	56.1	0.5	60.2	49.1	EF > 50 : extremely severe enrichment
SLe4	0.5	2.6	15.8	1.6	2.9	1.3	2.2	21.9	23.6	5.6	43.2	0.5	14.5	60.4	
SN1	0.4	3.8	4.2	1.0	4.0	1.1	1.4	92.8	17.8	7.3	0.0	1.0	174.1	589.3	
SN2	0.6	2.4	15.7	13.9	6.5	3.3	8.8	337.0	136.0	14.7	449.0	6.0	57.8	982.1	
SN3	0.5	2.3	2.5	0.7	2.4	0.8	1.3	5.8	5.2	3.3	10.2	0.0	4.0	107.1	
SN4	4.6	1.8	14.8	10.4	23.0	7.7	13.8	-	153.2	44.0	449.0	112.0	-	982.1	
SLi1	1.1	2.4	30.5	4.9	4.2	6.2	8.2	125.5	159.9	12.2	299.3	1.7	150.9	196.4	
SLi2	0.5	2.3	47.6	3.9	3.9	5.8	7.2	166.7	137.9	11.0	196.4	1.0	39.2	-	
SLi3	1.1	2.2	39.1	3.2	3.8	7.5	7.2	112.6	140.5	11.0	243.2	1.7	162.0	753.0	
SLi4	0.5	2.0	25.4	4.5	3.6	5.5	7.4	45.2	140.2	10.0	244.9	4.2	98.5	678.6	
SMo1	2.3	4.6	98.4	0.8	3.9	1.1	6.6	34.8	12.5	7.3	0.0	0.0	4.4	392.9	
SMo2	1.3	2.9	97.0	0.5	2.4	0.6	6.3	15.4	3.6	3.7	0.0	0.0	6.9	196.4	
SMo4	2.6	5.1	161.9	1.1	4.2	2.2	1.1	4.0	10.7	7.3	0.0	0.0	4.4	392.9	
SMak1	0.8	2.9	67.7	1.3	3.7	1.7	1.1	6.6	24.2	7.3	0.0	1.0	13.5	294.6	
SMak2	2.0	6.2	131.4	1.5	5.9	2.2	5.0	13.6	31.1	14.7	0.0	0.0	12.7	392.9	
SMak3	2.3	5.1	259.3	2.3	6.6	2.2	3.3	9.7	49.7	14.7	0.0	2.0	21.5	589.3	
SMak4	0.5	3.0	66.3	1.2	4.7	1.1	1.7	4.8	18.2	7.3	0.0	0.0	8.8	196.4	

Table 4 Results for the ecological risk indices CF, CD, Eri, and RI calculated for heavy metals in the sediment samples.

CF																		CD
Sample ID	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Mo	Cd	Sn	Sb	Pb	Hg	CD
SSe1	0.2	0.1	0.4	0.5	0.1	0.5	0.2	0.3	2.3	2.5	0.7	0.0	4.1	0.1	0.0	2.7	12.5	23.4
SSe2	0.1	0.1	0.2	0.2	0.1	0.3	0.1	0.2	2.1	1.1	0.5	0.0	1.0	0.0	0.0	2.8	7.1	14.9
SSe3	0.1	0.1	0.3	0.3	0.1	0.3	0.1	0.2	1.7	1.5	0.6	0.0	12.2	0.0	0.0	1.3	8.9	26.7
SSe4	0.1	0.1	0.3	0.3	0.1	0.4	0.1	0.2	2.2	1.7	0.6	0.0	2.0	0.0	0.0	4.6	8.9	20.5
SLe1	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	1.5	0.9	0.3	0.0	1.0	0.0	0.0	2.5	17.9	24.3
SLe2	0.1	0.1	0.2	1.3	0.1	0.2	0.2	0.2	1.7	2.6	0.5	0.0	5.1	0.1	0.0	3.5	10.7	25.6
SLe3	0.1	0.0	0.2	1.1	0.1	0.2	0.1	0.2	2.7	2.2	0.5	0.0	4.1	0.0	0.0	4.4	3.6	18.7
SLe4	0.1	0.1	0.3	1.9	0.2	0.3	0.2	0.3	2.6	2.8	0.7	0.0	5.1	0.1	0.0	1.7	7.1	22.0
SN1	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	1.7	0.3	0.1	0.0	0.0	0.0	0.0	3.2	10.7	16.1
SN2	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1	3.1	1.2	0.1	0.0	4.1	0.1	0.0	0.5	8.9	18.1
SN3	0.1	0.0	0.2	0.3	0.1	0.2	0.1	0.1	0.6	0.5	0.3	0.0	1.0	0.0	0.0	0.4	10.7	13.9
SN4	0.0	0.0	0.0	0.1	0.1	0.2	0.1	0.1	27.5	1.4	0.4	0.0	4.1	1.0	28.5	20.2	8.9	62.7
SLi1	0.1	0.1	0.1	1.7	0.3	0.2	0.3	0.4	6.8	8.7	0.7	0.1	16.3	0.1	1.0	8.2	10.7	53.5
SLi2	0.0	0.0	0.1	1.7	0.1	0.1	0.2	0.3	6.1	5.0	0.4	0.0	7.1	0.0	0.5	1.4	57.1	79.1
SLi3	0.1	0.1	0.1	2.1	0.2	0.2	0.4	0.4	6.1	7.7	0.6	0.1	13.3	0.1	1.0	8.8	41.1	80.1
SLi4	0.1	0.0	0.2	2.5	0.4	0.4	0.6	0.7	4.5	14.0	1.0	0.1	24.5	0.4	0.5	9.9	67.9	124.8
SMo1	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.1	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0	3.6	5.0
SMo2	0.0	0.0	0.1	1.8	0.0	0.0	0.0	0.1	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.1	3.6	5.9
SMo4	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	3.6	5.3
SMak1	0.0	0.0	0.1	1.2	0.0	0.1	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.0	0.0	0.2	5.4	7.6
SMak2	0.0	0.0	0.1	1.2	0.0	0.1	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.0	0.0	0.1	3.6	5.4
SMak3	0.0	0.0	0.0	2.4	0.0	0.1	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.0	0.0	0.2	5.4	8.6
SMak4	0.0	0.0	0.1	1.2	0.0	0.1	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.0	0.0	0.2	3.6	5.5

Eri									RI
Sample ID	Hg	Cd	As	Co	Cu	Pb	Cr	Zn	
SSe1	500.0	122.4	7.3	0.8	11.6	13.5	0.9	2.5	659.1
SSe2	285.7	30.6	4.7	0.4	10.6	13.8	0.5	1.1	347.3
SSe3	357.1	367.3	6.0	0.6	8.5	6.3	0.6	1.5	748.0
SSe4	357.1	61.2	6.0	0.7	10.9	22.8	0.7	1.7	461.0
SLe1	714.3	30.6	2.7	0.3	7.5	12.6	0.3	0.9	769.2
SLe2	428.6	153.1	5.3	0.8	8.5	17.5	2.5	2.6	618.9
SLe3	142.9	122.4	4.7	0.5	13.6	21.9	2.3	2.2	310.4
SLe4	285.7	153.1	6.7	0.8	12.9	8.6	3.7	2.8	474.2
SN1	428.6	0.0	1.3	0.1	8.4	15.8	0.2	0.3	454.7
SN2	357.1	122.4	1.3	0.2	15.3	2.6	0.3	1.2	500.5
SN3	428.6	30.6	3.3	0.4	2.9	2.0	0.5	0.5	468.8
SN4	357.1	122.4	4.0	0.4	137.6	101.1	0.3	1.4	724.3
SLi1	428.6	489.8	6.7	1.7	34.2	41.2	3.3	8.7	1014.1
SLi2	2285.7	214.3	4.0	1.1	30.3	7.1	3.5	5.0	2551.0
SLi3	1642.9	398.0	6.0	2.1	30.7	44.2	4.3	7.7	2135.7
SLi4	2714.3	734.7	10.0	2.8	22.6	49.3	5.1	14.0	3552.7
SMo1	142.9	0.0	0.7	0.1	1.6	0.2	1.8	0.1	147.3
SMo2	142.9	0.0	0.7	0.1	1.4	0.6	3.5	0.1	149.2
SMo4	142.9	0.0	0.7	0.1	0.2	0.2	2.9	0.1	147.0
SMak1	214.3	0.0	1.3	0.2	0.6	1.2	2.5	0.4	220.5
SMak2	142.9	0.0	1.3	0.1	0.6	0.6	2.4	0.3	148.2
SMak3	214.3	0.0	1.3	0.1	0.4	1.0	4.7	0.5	222.3
SMak4	142.9	0.0	1.3	0.1	0.5	0.8	2.4	0.3	148.3

CF classification

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

CD

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

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

Evaluation of environmental ecological risk parameters

The ecological risk indices revealed strong variability among the six studied sites (Table 4). Mercury (Hg) and cadmium (Cd) dominated the ecological risk profile, due to their elevated contamination factors and high toxic response factors. The Limete site showed the highest ecological threat, with RI values ranging from 1014.1 to 3552.7, driven mainly by extreme Hg (up to 2714.3) and Cd (up to 734.7) values. This reflects the impact of the abundant industrial activities (pharmaceuticals, paint factories, breweries) in this area.

Intermediate ecological risks were observed in Selembao (347.3–769.2), Lemba (310.4–769.2), and N'djili (454.7–724.3). In these sites, Hg remained the major contributor, but Cd, Pb, and Cu also had significant impacts, especially in N'djili (SN4) where Cu (137.6) and Pb (101.1) produced a sharp increase in RI (724.3). These results indicate mixed sources of contamination, including informal artisanal activities, small-scale agriculture, and domestic effluents (Suh et al., 2025).

By contrast, sediments from Mont-Ngafula (147.0–149.2) and Makala (148.2–222.3) showed low to moderate ecological risk, consistent with the predominance of domestic activities and fewer industrial inputs. However, the systematic detection of Hg in all samples highlights the persistence of diffuse contamination sources such as leachates from uncontrolled dumpsites and atmospheric depositions (Sánchez-Castro et al., 2023).

Overall, the ranking of ecological risk followed the order: Limete $\gg$ Selembao $\approx$ N'djili $\approx$ Lemba $>$ Makala $\approx$ Mont-Ngafula, confirming that leachates from uncontrolled landfills and industrial discharges are the primary sources of sediment contamination, while domestic and artisanal sources contribute to lower and more localized contamination.

Spearman correlations between trace metal concentrations and sediment physicochemical properties

The Spearman correlation analysis highlighted strong associations between trace metals and sediment

physicochemical properties (Table 5). In most sites, organic matter (OM) and CaCO_3 were positively correlated with the concentrations of a wide range of metals ($r=0.80$ – 1.00), while grain size exhibited strong negative correlations with metal concentrations in sediments ($r=-0.40$ to -1.00). This pattern indicates that metals preferentially bind to fine-grained sediments enriched in OM and carbonates, which provide a high surface area and reactive functional groups for adsorption (Boguta et al., 2022). Furthermore, the strong correlations observed for Cr, Mn, Fe, Co, Ni, Cu, and Zn suggest that these metals share common sources and exhibit similar geochemical behaviors.

The variability between sites reflects differences in anthropogenic pressures. Selembao, Lemba, and Limete showed the highest correlation intensities, consistent with the influence of uncontrolled landfills, industrial effluents, and domestic discharges. In contrast, N'djili and Makala displayed mixed correlation patterns, with some metals (e.g., Zn, As, Cd) negatively associated with OM and CaCO_3 likely due to inputs from agricultural runoff, artisanal mechanical activities, and heterogeneous waste leachates. Mont-Ngafula presented weaker and less consistent correlations, reflecting lower industrial impact and mainly domestic contributions.

The strong inter-metal correlations, particularly within the Cr–Mn–Fe–Co–Ni group ($r>0.90$ in several sites), further point to common anthropogenic sources. These findings are consistent with previous observations in urban river systems, where fine sediments act as major sinks for pollutants (Rügner et al., 2019).

Concentrations of heavy metals in oligochaete worms

The concentrations of trace metals determined in oligochaetes reflected both the spatial variability of sediment contamination and the bioaccumulation potential of benthic invertebrates investigated (Table 6). Mercury (Hg) levels in worms ranged from $0.059 \text{ mg}\cdot\text{kg}^{-1}$ in Limete (OLi2, *Tubifex tubifex*) to $0.876 \text{ mg}\cdot\text{kg}^{-1}$ in N'djili (ON3, *Enchytraeus albidus*), with several values exceeding the sediment PEL threshold of $0.486 \text{ mg}\cdot\text{kg}^{-1}$. These results are consistent with sediment analyses, where Limete and N'djili

Table 5 Spearman's rank correlation matrix between trace metals and physicochemical parameters in sediment samples

Selam- bao site	OM	CaCO ₃	Grain size	Hg	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Sn	Pb
WC	0.800	0.800	-1.000	0.632	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	1.000	0.800	0.632	-0.200	0.632	0.400
OM		1.000	-0.800	0.949	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.400	0.800	1.000	0.949	0.400	0.949	0.000
CaCO ₃			-0.800	0.949	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.400	0.800	1.000	0.949	0.400	0.949	0.000
Grain size				-0.632	-0.800	-0.800	-0.800	-0.800	-0.800	-0.800	-0.800	-0.800	-1.000	-0.800	-0.632	0.200	-0.632	-0.400
Hg					0.949	0.949	0.949	0.949	0.949	0.949	0.949	0.316	0.632	0.949	1.000	0.632	1.000	-0.316
Sc						1.000	1.000	1.000	1.000	1.000	1.000	0.400	0.800	1.000	0.949	0.400	0.949	0.000
Ti							1.000	1.000	1.000	1.000	1.000	0.400	0.800	1.000	0.949	0.400	0.949	0.000
V								1.000	1.000	1.000	1.000	0.400	0.800	1.000	0.949	0.400	0.949	0.000
Cr									1.000	1.000	1.000	0.400	0.800	1.000	0.949	0.400	0.949	0.000
Mn										1.000	1.000	0.400	0.800	1.000	0.949	0.400	0.949	0.000
Fe											1.000	0.400	0.800	1.000	0.949	0.400	0.949	0.000
Co												0.400	0.800	1.000	0.949	0.400	0.949	0.000
Ni													0.800	0.400	0.316	-0.400	0.316	0.200
Cu														0.800	0.632	-0.200	0.632	0.400
Zn															0.949	0.400	0.949	0.000
As																0.632	1.000	-0.316
Cd																	0.632	-0.800
Sn																		-0.316
Lemba site	OM	CaCO ₃	Grain size	Hg	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Sn	Pb
WC	1.000	0.400	-0.400	-0.200	0.632	0.600	0.400	0.800	0.800	0.400	0.949	0.800	0.200	0.800	0.800	0.949	0.894	0.000
OM		0.400	-0.400	-0.200	0.632	0.600	0.400	0.800	0.800	0.400	0.949	0.800	0.200	0.800	0.800	0.949	0.894	0.000
CaCO ₃			-1.000	-0.800	0.949	0.400	1.000	0.800	0.800	1.000	0.632	0.800	0.800	0.800	0.800	0.632	0.447	-0.200
Grain size				0.800	-0.949	-0.400	-1.000	-0.800	-0.800	-1.000	-0.632	-0.800	-0.800	-0.800	-0.800	-0.632	-0.447	0.200
Hg					-0.632	0.200	-0.800	-0.400	-0.400	-0.800	-0.316	-0.400	-1.000	-0.400	-0.400	-0.316	0.000	-0.400
Sc						0.632	0.949	0.949	0.949	0.949	0.833	0.949	0.632	0.949	0.949	0.833	0.707	-0.316
Ti							0.400	0.800	0.800	0.400	0.738	0.800	-0.200	0.800	0.800	0.738	0.894	-0.800
V								0.800	0.800	1.000	0.632	0.800	0.800	0.800	0.800	0.632	0.447	-0.200
Cr									1.000	0.800	0.949	1.000	0.400	1.000	1.000	0.949	0.894	-0.400
Mn										0.800	0.949	1.000	0.400	1.000	1.000	0.949	0.894	-0.400
Fe											0.632	0.800	0.800	0.800	0.800	0.632	0.447	-0.200
Co												0.949	0.316	0.949	0.949	1.000	0.943	-0.211
Ni													0.400	1.000	1.000	0.949	0.894	-0.400
Cu														0.400	0.400	0.316	0.000	0.400

Table 5 (continued)

Lemba site	OM	CaCO ₃	Grain size	Hg	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Sn	Pb
Zn															1.000	0.949	0.894	−0.400
As																0.949	0.894	−0.400
Cd																	0.943	−0.211
Sn																		−0.447
N'djili site	OM	CaCO ₃	Grain size	Hg	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Sn	Pb
WC	0.400	0.200	−0.400	0.894	0.949	0.800	0.800	0.200	−0.800	0.800	0.400	0.211	−0.800	−0.600	0.211	−0.738	−0.800	−0.400
OM		0.800	−1.000	0.447	0.632	0.200	0.800	0.800	0.000	0.200	0.400	0.105	−0.800	−0.400	−0.316	−0.211	−0.800	−1.000
CaCO ₃			−0.800	0.000	0.316	0.400	0.400	1.000	0.400	0.400	0.800	0.632	−0.400	0.200	0.211	0.316	−0.400	−0.800
Grain size			−0.447	−0.632	−0.200	−0.800	−0.800	−0.800	0.000	−0.200	−0.400	−0.105	0.800	0.400	0.316	0.211	0.800	1.000
Hg					0.943	0.447	0.894	0.000	−0.894	0.447	0.000	−0.236	−0.894	−0.894	−0.236	−0.943	−0.894	−0.447
Sc						0.632	0.949	0.316	−0.738	0.632	0.316	0.056	−0.949	−0.738	−0.056	−0.778	−0.949	−0.632
Ti							0.400	0.400	−0.400	1.000	0.800	0.738	−0.400	0.000	0.738	−0.211	−0.400	−0.200
V								0.400	−0.600	0.400	0.200	−0.105	−1.000	−0.800	−0.316	−0.738	−1.000	−0.800
Cr									0.400	0.400	0.800	0.632	−0.400	0.200	0.211	0.316	−0.400	−0.800
Mn									−0.400	0.200	0.200	0.316	0.600	0.800	0.105	0.949	0.600	0.000
Fe										−0.400	0.800	0.738	−0.400	0.000	0.738	−0.211	−0.400	−0.200
Co										−0.200	0.400	0.738	−0.200	0.400	0.738	0.316	−0.200	−0.400
Ni											0.105	0.632	0.889	0.500	0.316	0.500	0.105	−0.105
Cu													0.800	0.632	0.738	0.738	1.000	0.800
Zn															0.632	0.949	0.800	0.400
As																0.389	0.316	0.316
Cd																	0.738	0.211
Sn																		0.800
Limete site	OM	CaCO ₃	Grain size	Hg	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Sn	Pb
WC	0.200	0.400	−0.200	−0.600	0.316	0.800	0.200	0.000	0.200	0.200	0.400	0.200	0.600	0.200	0.200	0.200	0.316	0.400
OM		0.800	−1.000	0.200	0.949	0.400	1.000	0.400	1.000	1.000	0.800	1.000	−0.200	1.000	1.000	1.000	0.949	0.800
CaCO ₃			−0.800	0.400	0.949	0.200	0.800	0.800	0.800	0.800	1.000	0.800	−0.400	0.800	0.800	0.800	0.949	1.000
Grain size			−0.200	−0.949	−0.400	−1.000	−1.000	−0.400	−1.000	−1.000	−0.800	−1.000	0.200	−1.000	−1.000	−1.000	−0.949	−0.800

Table 5 (continued)

Makala site	OM	CaCO ₃	Grain size	Hg	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Sn	Pb
WC	0.000	0.949	0.600	-0.447	0.000	-0.200	0.000	0.000	-0.200	0.400	-0.775	0.316	-0.738	0.000	-0.447	-0.400
OM		0.316	-0.800	-0.894	0.000	-0.400	1.000	-1.000	-0.400	-0.200	-0.258	0.632	0.632	-1.000	-0.894	-0.800
CaCO ₃			0.316	-0.707	0.000	-0.316	0.316	-0.316	-0.316	0.316	-0.816	0.500	-0.500	-0.316	-0.707	-0.632
Grain size			0.447	0.000	0.000	0.200	-0.800	0.800	0.200	0.400	-0.258	-0.316	-0.949	0.800	0.447	0.400
Hg					0.000	0.447	-0.894	0.894	0.447	0.000	0.577	-0.707	-0.236	0.894	1.000	0.894
Sc						-0.894	0.000	0.000	0.894	0.894	0.577	-0.707	-0.236	0.000	0.000	0.447
Ti							-0.400	0.400	-0.600	-0.800	-0.258	0.316	0.105	0.400	0.447	0.000
V								-1.000	-0.400	-0.200	-0.258	0.632	0.632	-1.000	-0.894	-0.800
Cr									0.400	0.200	0.258	-0.632	-0.632	1.000	0.894	0.800
Mn										0.800	0.775	-0.949	-0.316	0.400	0.447	0.800
Fe											0.258	-0.632	-0.632	0.200	0.000	0.400
Co												-0.816	0.272	0.258	0.577	0.775
Ni													0.333	-0.632	-0.707	-0.949
Cu														-0.632	-0.236	-0.316
Zn															0.894	0.800
Sn																0.894

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

Table 6 Concentrations of trace metals in oligochaete worms (mg/kg—¹ dry weight)

Sample ID	Hg DMA	Metal values (ICP-MS)										Cd	Sn	Sb	Pb
		Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As				
DORM-4	0,412	—	—	1,87	3,17	343	—	1,34	15,7	51,6	6,87	ND	ND	ND	0,404
	0,423	10,9	1,5	1,8	3,2	320	0,5	1,4	16,3	51,0	8,7	0,6	0,3	1,5	0,5
OSe1	0,611	123,9	32,2	26,8	209,5	21,712	3,6	9,2	47,9	855,0	5,4	1,6	3,5	0,2	75,8
OSe2	0,794	202,9	26,2	27,0	68,9	24,878	7,3	9,0	58,9	665,6	6,6	2,2	1,6	0,8	45,8
OSe3	0,846	207,3	23,8	37,3	204,1	25,522	6,6	6,9	48,5	794,7	6,2	1,4	3,7	0,4	69,0
OLe1	0,186	68,6	10,6	10,3	72,4	8863	2,9	4,3	18,3	458,2	3,4	0,1	1,2	0,2	23,7
OLe2	0,361	85,6	19,9	20,9	96,6	13,722	2,9	6,4	29,3	383,7	3,4	0,7	1,7	≤LD	35,3
OLe3	0,318	91,9	22,3	15,7	91,1	14,147	2,3	6,0	19,2	416,1	3,7	0,2	1,5	0,0	25,9
OLe4	0,332	54,7	21,2	16,5	92,3	14,199	2,2	5,5	20,4	402,0	3,4	0,2	1,7	≤LD	30,8
ON1	0,184	99,1	15,9	13,1	87,3	10,686	3,8	4,8	20,8	680,7	5,0	0,3	1,7	0,9	49,8
ON2	0,281	90,0	20,6	15,3	72,9	12,979	2,2	5,0	17,0	396,7	3,7	0,3	1,4	0,2	46,6
ON3	0,876	223,9	32,3	20,9	209,9	22,702	7,6	8,6	97,8	873,7	5,9	0,6	3,5	0,6	68,5
ON4	0,235	108,9	11,8	12,9	74,4	8986	2,1	5,0	16,7	404,5	3,8	0,2	1,0	≤LD	25,1
OLi1	0,093	34,4	2,2	6,0	52,8	3091	5,4	5,8	31,0	570,9	3,3	0,2	2,2	1,0	23,2
OLi2	0,059	13,8	0,8	2,4	39,0	1586	3,8	6,1	16,9	353,4	3,2	≤LD	0,3	0,4	15,5
OLi3	0,335	68,7	9,8	28,1	216,7	11,093	7,9	16,2	93,1	892,6	3,3	1,1	3,0	11,8	99,0
OLi4	0,756	227,7	25,5	28,8	78,1	26,927	5,7	9,8	35,7	985,6	6,6	0,6	0,7	1,7	0,6
OMo1	0,340	102,9	16,1	11,0	68,9	10,470	2,2	3,9	18,6	541,4	4,7	0,2	0,3	1,2	0,5
OMo2	0,331	107,1	23,8	17,2	100,1	15,511	2,7	5,7	24,7	498,6	4,2	0,2	0,4	1,6	0,0
OMo3	0,441	95,8	23,8	16,1	93,0	14,998	2,6	5,2	25,0	505,3	4,7	0,3	0,4	1,7	0,2
OMo4	0,363	117,6	25,5	18,7	75,1	15,911	2,1	5,5	15,3	487,9	4,4	0,2	0,6	1,2	≤LD
OMak1	0,457	131,0	26,4	21,9	170,6	18,470	3,0	7,4	37,9	765,8	4,8	0,4	0,9	2,6	0,4
OMak2	0,494	249,6	40,6	33,6	283,6	28,224	4,3	11,5	60,9	1218,0	7,2	0,9	1,4	4,3	0,6
OMak3	0,507	99,5	17,5	12,9	64,1	10,907	2,4	4,2	21,9	439,6	4,1	0,2	0,3	1,1	0,0
OMak4	0,776	95,9	23,8	36,2	91,0	28,998	7,7	7,3	48,6	634,5	6,6	0,5	0,4	2,8	0,6

The aquatic oligochaete were labeled as follows: N'djili: ON1 (*Nais elinguis*), ON2 (*Tubifex tubifex*), ON3 (*Enchytraeus albidus*), ON4 (*Lumbricus terrestris*); Limete: OLi1 (*Nais elinguis*), OLi2 (*Tubifex tubifex*), OLi3 (*Enchytraeus albidus*), OLi4 (*Lumbricus terrestris*); Lemba: OLe1 (*Lumbricus terrestris*), OLe2 (*Enchytraeus albidus*), OLe3 (*Enchytraeus albidus*), OLe4 (*Nais elinguis*); Makala: OMak1 (*Nais elinguis*), OMak2 (*Lumbricus terrestris*), OMak3 (*Enchytraeus albidus*), OMak4 (*Tubifex tubifex*); Mont-Ngafula: OMo1 (*Nais elinguis*), OMo2 (*Tubifex tubifex*), OMo3 (*Enchytraeus albidus*), OMo4 (*Lumbricus terrestris*); Selembao: OSe1 (*Nais elinguis*), OSe2 (*Tubifex tubifex*), OSe3 (*Enchytraeus albidus*), OSe4 (*Lumbricus terrestris*)

exhibited the highest Hg contamination, suggesting efficient transfer of this toxic element from sediments to those worm species (Table 2). Elevated Hg bioaccumulation in *Enchytraeus* and *Tubifex*, known for their role as sentinel species in polluted environments (Irawati et al., 2019; Méndez-Fernández et al., 2014).

Copper (Cu) and zinc (Zn) showed also marked enrichment in oligochaetes, particularly at Limete (OLi3, *Enchytraeus albidus*: 93.1 mg·kg⁻¹ Cu; 892.6 mg·kg⁻¹ Zn) and Makala (OMak2, *Lumbricus terrestris*: 60.9 mg·kg⁻¹ Cu; 1218.0 mg·kg⁻¹ Zn). These values corroborated the high sediment loads previously observed at these sites (Akonga et al., 2025), and indicated that the worms actively accumulate bioavailable metal fractions. In contrast, Mont-Ngafula and Selembao presented moderate to high levels of Pb (up to 75.8 mg·kg⁻¹ at OSe1, *Nais elinguis*) despite relatively lower sediment concentrations, suggesting species-specific uptake dynamics and the influence of feeding strategies on metal assimilation (Shuhaimi-Othman et al., 2012).

Sites with predominantly sandy and organic-poor sediments (Mont-Ngafula, Makala) displayed lower metal accumulation in most worm species, except for localized peaks in Pb and Zn, in line with the lower retention capacity of coarse-grained substrates described in Table 1. Conversely, Limete, Selembao, and N'djili—characterized by finer sediments rich in organic matter and carbonates—showed the highest accumulation of trace metals in benthic fauna, confirming the role of sediment geochemistry in enhancing contaminant bioavailability.

From an ecotoxicological perspective, the exceedance of critical thresholds in both sediments and worms at Limete, N'djili, Selembao, and Lemba indicates a higher likelihood for trophic chain transfer of metals such as Hg, Cu, Zn, and Pb. Considering that oligochaetes are key prey items for fish, the bioaccumulation observed in these organisms highlights the potential for biomagnification of metals such as Hg, Cd, As, Sn through the aquatic food web, ultimately raising concerns for human health given the consumption of fish from these rivers (Nyarko et al., 2023). These findings reinforce the conclusion that urban effluents and industrial discharges in Kinshasa not only contaminate sediments but also threaten aquatic biota and food safety through metal bioavailability and bioaccumulation.

Bioaccumulation of heavy metals in oligochaetes

The bioaccumulation factor (BAF) of metals in the four oligochaete species (*Lumbricus terrestris*, *Tubifex tubifex*, *Nais elinguis* and *Enchytraeus albidus*) showed significant spatial and interspecific variability (Table 7, Fig. 3). The highest BAF values were observed for toxic metals such as Cd, Sn, Pb, Zn, and As, with localized peaks exceeding 100 (e.g., Cd=118.2 at Mont-Ngafula [OMo2]; Sn=263.1 at Makala [OMak2]), indicating substantial bioaccumulation even where sediment concentrations were moderate. Metals of lithogenic origin (Fe, Ti, Mn) generally displayed low BAF (<10), reflecting limited bioavailability or low bioaccumulation potential.

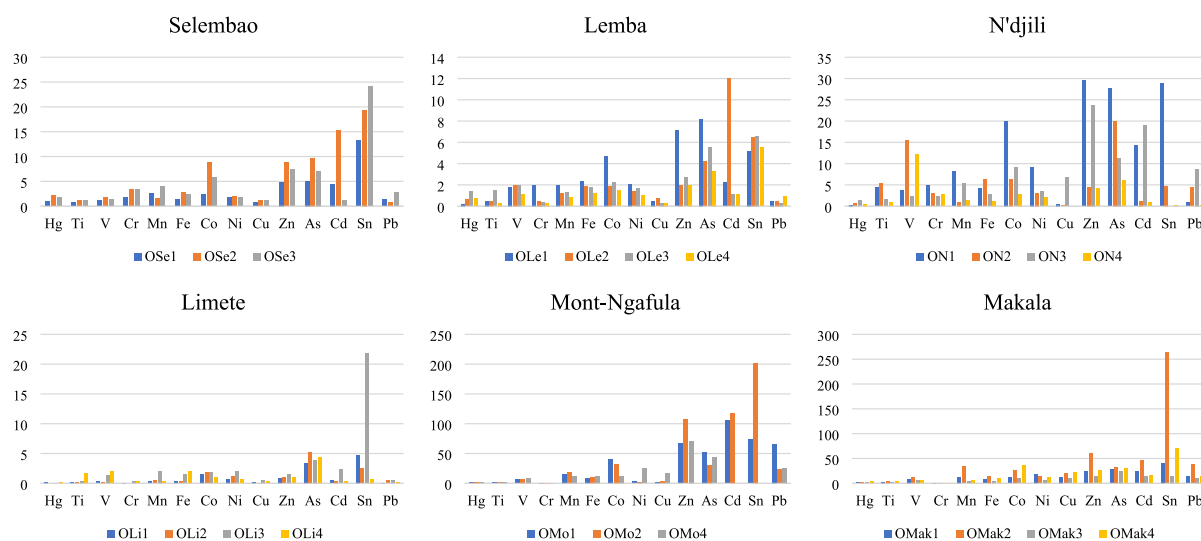
Spatial patterns revealed that Limete and N'djili, characterized by fine, organic-rich sediments, exhibited high BAF for Cu, Zn, and Hg, consistent with elevated sediment contamination. Selembao and Lemba showed intermediate BAF, particularly for Pb and Zn, likely influenced by domestic effluents and landfill leachates. Interestingly, Mont-Ngafula and Makala displayed disproportionately high BAF for some metals despite low sediment concentrations, suggesting enhanced mobility (bioavailability) of dissolved metal fractions in sandy sediments.

Interspecific differences were clear: sediment-ingesting species (*Tubifex* and *Enchytraeus*) accumulated metals more efficiently than *Nais* and *Lumbricus*, confirming their role as bioindicators (Moreno-Ocio et al., 2024). Aquatic oligochaetes are exposed to metals through both porewater (dissolved metals absorbed across the body surface) and ingestion of fine contaminated particles, which generally leads to higher bioaccumulation. Terrestrial oligochaetes, by contrast, are mainly exposed through ingestion of bulk soil or sediment, where metals are more strongly bound, resulting in lower uptake from dissolved fractions and typically lower BAF values (Méndez-Fernández et al., 2014).

Metal bioaccumulation in oligochaetes closely reflects sediment geochemistry and species-specific traits. Limete, N'djili, Selembao, and Lemba represent critical hotspots for contaminant transfer, while peripheral sandy sites show unexpected bioaccumulation, highlighting the importance of integrating biotic monitoring into sediment quality assessments (Méndez-Fernández et al., 2014).

Table 7 Calculated bioaccumulation factors (BAF) for trace metals in oligochaete worms

Sampling site	Sample ID	Hg	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Sn	Pb
Selembao municipality	OSe1	0.9	0.7	1.2	1.7	2.6	1.3	2.3	1.8	0.8	4.9	5.1	4.5	13.2	1.4
	OSe2	2.1	1.2	1.8	3.4	1.5	2.8	8.8	2	1.1	8.8	9.7	15.2	19.4	0.8
	OSe3	1.8	1.2	1.3	3.3	4	2.3	5.8	1.8	1.1	7.4	7.1	1.2	24.1	2.7
	OLe1	0.2	0.5	1.8	2	2	2.3	4.7	2.1	0.5	7.1	8.2	2.2	5.2	0.5
Lemba Municipality	OLe2	0.6	0.5	2	0.5	1.2	1.9	1.9	1.4	0.7	2	4.2	12	6.5	0.5
	OLe3	1.4	1.5	2	0.4	1.3	1.8	2.2	1.7	0.3	2.7	5.5	1.1	6.6	0.3
	OLe4	0.7	0.3	1.1	0.3	0.8	1.2	1.5	1	0.3	2	3.3	1.1	5.5	0.9
	ON1	0.3	4.4	3.8	4.8	8.1	4.2	20	9.2	0.5	29.6	27.6	14.3	28.9	0.8
N'djili Municipality	ON2	0.6	5.3	15.4	3	1	6.3	6.4	3.1	0.2	4.5	20	1.2	4.7	4.4
	ON3	1.4	1.6	2.4	2.3	5.3	2.7	9.1	3.4	6.7	23.8	11.3	18.9		8.7
	ON4	0.5	0.9	12.3	2.7	1.3	1.2	2.9	2	0	4.1	6	0.8	0.2	0.1
	OLi1	0.2	0.2	0.3	0.1	0.3	0.4	1.6	0.7	0.2	0.9	3.4	0.5	4.7	0.1
Limete Municipality	OLi2	0	0.2	0.2	0	0.5	0.3	1.8	1.2	0.1	1	5.3	0.4	2.5	0.5
	OLi3	0.1	0.4	1.4	0.4	2.1	1.5	1.9	2.1	0.6	1.6	3.9	2.3	21.8	0.6
	OLi4	0.2	1.7	2.1	0.3	0.3	2.1	1	0.7	0.3	1	4.4	0.3	0.7	0.2
	OMo1	1.4	1.6	6.6	0.4	16	8.4	40.3	3.2	2.3	66.6	53	105.4	73.5	66.2
Mont-Ngafula Municipality	OMo2	1.7	1.5	7.4	0.3	19.4	10.3	32.9	2.5	3.5	107.4	31.2	118.2	202.1	23.4
	OMo4	2.4	1.7	9	0.4	12	12	12.7	25.1	16.9	70.9	43.6			25.9
	OMak1	1.4	3	8.2	0.5	12.5	7.8	11.9	18.5	12.7	24.4	28	23.4	41.2	13.4
	OMak2	2.1	4.6	12.1	0.8	33.9	15.1	27.1	13.4	19.9	60.6	33.4	45.8	263.1	38.1
Makala municipality	OMak3	1.9	1.6	6.3	0.2	5.1	5.2	10	6.7	9.8	13.7	24.8	13.5	15.2	11
	OMak4	4.1	3.7	7.2	0.9	6.7	9.8	35.7	11.6	22.2	27	30.6	16.3	71.3	14.6

**Fig. 3** Histograms illustrating the bioaccumulation factor values of trace metals in the whole body of oligochaete worms from the study areas (X-axis: trace metals; Yaxis: metal concentrations (mg.kg^{-1} d.w.))

Given that local populations consume fish from these rivers, the bioaccumulation and biomagnification of these heavy metals represent a major public health concern. The potential for bioaccumulation of Cd, Pb, and Hg in aquatic organisms represents a pathway for human exposure, with possible health risks such as neurotoxicity (Hg, Pb), renal dysfunction (Cd), and chronic diseases (Dey et al., 2024; Ramish et al., 2024).

While these findings underline the natural ability of certain oligochaetes to absorb metals, any assertion regarding their use in active bioremediation should remain cautious. Our results demonstrate bioaccumulation capacity under current environmental conditions but do not provide experimental evidence on detoxification efficiency, metal excretion, or long-term population stability under remediation scenarios. Therefore, the present study supports their role primarily as bioindicators rather than as bioremediation agents.

Conclusions

This study highlighted that sediments from streams traversing urban areas in Kinshasa, particularly near uncontrolled landfills and industrial zones, are significantly contaminated with heavy metals such as Hg, Cd, Pb, Cu, and Zn. The highest concentrations were observed at Limete (Hg), N'djili (Cu), and Lemba (Pb), frequently exceeding sediment quality guidelines and indicating serious ecological risks for benthic organisms, with potential transfer of these pollutants through the aquatic food web to humans.

Bioaccumulation in earthworms (*Lumbricus terrestris*) and aquatic oligochaetes (*Tubifex tubifex*, *Nais elinguis*, *Enchytraeus albidus*) demonstrated that fine-grained, organic-rich sediments and proximity to waste sites strongly influence metal uptake. Observed bioaccumulation factors (e.g., Cd=118, Sn=263) revealed that these organisms can efficiently concentrate metals, underscoring their value both as bioindicators and as potential agents in bioremediation strategies targeting contaminated sediments.

The spatial distribution of contamination reflected the combined impacts of industrial discharges, domestic effluents, and landfill leachates, with Limete, N'djili, Lemba, and Selembao emerging as critical pollution hotspots. Even in peripheral areas such

as Mont-Ngafula and Makala, sandy sediments exhibited unexpected metal accumulation, highlighting the persistence and mobility of these contaminants in urban waterways.

Overall, the findings emphasize the urgent need for integrated management of industrial effluents, domestic wastewater, and solid urban waste to mitigate environmental and human health risks. The study also demonstrated the effectiveness of oligochaetes as sentinel species for monitoring heavy metal contamination and exploring sustainable bioremediation approaches in urban river ecosystems.

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Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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