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TRACE ELEMENTS AND MERCURY IN FISH AND LEAFY VEGETABLES FROM THE ARUWIMI RIVER (BANALIA AND BASOKO TERRITORIES, DEMOCRATIC REPUBLIC OF THE CONGO): A BASELINE SURVEY WITH EXPLORATORY MULTIVARIATE ANALYSIS

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ABSTRACT

Fish and leafy vegetables supply most of the animal protein and greens eaten along the Aruwimi River, yet nothing is known about their trace-element content. We analysed the dorsal muscle of ten fish (nine species) and the leaves of cassava (Manihot esculenta) and sweet potato (Ipomoea batatas) collected in the Banalia and Basoko territories (Tshopo Province) during the 2025 dry season. Fourteen elements were determined by ICP-MS, and total mercury separately. Scandium, nickel, thorium and uranium were found only in the leaves. Most elements were strongly right-skewed; Hg was the only one whose raw distribution did not depart from normality (Shapiro–Wilk $p = 0.40$). The leaves contained more Cr, Mn and Co than the fish (exact Mann–Whitney $p = 0.030$, the smallest value attainable with two leaf samples), whereas As was higher in fish. Spearman correlations and an exploratory principal component analysis separated a Cr–Mn–Fe–Co–Zn group, which mostly distinguished leaves from fish (PC1, 44.6% of the variance), from a Hg–Cd–Pb axis (PC2, 18.3%). Mercury in fish ranged from 0.52 to 4.44 mg/kg dry weight, i.e. an estimated 0.10–1.11 mg/kg wet weight; three to four of the ten fish exceeded the 0.5 mg/kg guideline, depending on the moisture assumed. One Pollimyrus isidori specimen returned 1,250 mg/kg Pb, a biologically implausible value that must be re-analysed; Pb in every other sample was 0.55 mg/kg dry weight or less. With twelve samples and no replication within species, these data are a first baseline rather than a risk assessment, but they make a case for targeted monitoring of Hg in fish from this part of the Congo Basin, whose upper course drains artisanal gold-mining areas of Ituri.

KEYWORDS: Trace elements; mercury; freshwater fish; cassava leaves; Aruwimi River; Congo Basin; food safety; principal component analysis

1. INTRODUCTION

People fish the rivers of the central Congo Basin daily, and cassava and sweet-potato fields on their banks provide the leaves most households cook. When trace elements reach these foods, the people who depend on them are exposed with little alternative. Trace metals and metalloids enter freshwater systems through rock weathering and soil erosion, and through human activities such as mining, waste disposal, and agriculture (Alloway, 2013; Kabata-Pendias, 2011). Fish integrate exposure from water, sediment, and prey, whereas leafy crops mostly reflect what roots take up from the soil, with some foliar deposition (Förstner & Wittmann, 2012).

Mercury deserves particular attention. In Africa, freshwater fish usually contain modest Hg concentrations. Still, sites close to artisanal and small-scale gold mining stand out with mean values above the FAO/WHO guideline of 0.5 mg/kg wet weight (Hanna et al., 2015). Mercury amalgamation remains common at artisanal gold sites in north-eastern DR Congo, notably in Ituri (AEMAPRI & IPIS, 2018), and the Ituri River is the upper course of the Aruwimi. Further downstream, in Banalia and Basoko, no measurement of trace elements in fish or crops has been published to our knowledge (Hanna et al., 2015). Data from other DRC settings, such as soils and sediments around a legacy copper mine in Kongo-Central (Kutakimina et al., 2026), show how strongly local geology and mining history shape metal levels, and they cannot be transposed to the Aruwimi.

Environmental concentration data are rarely normally distributed: they are bounded at zero, often skewed by a few high values, and frequently include results below the detection limit (Reimann & de Caritat, 2005; Helsel, 2012). With small samples, these features weigh heavily on the choice of statistics. We therefore paired rank-based tests and correlations with an exploratory principal component analysis (PCA) on log-transformed data.

This study set out to (i) describe concentrations of 14 trace elements and Hg in fish and leafy vegetables from the Aruwimi River in Banalia and Basoko; (ii) compare the two types of food; (iii) identify groups of co-varying elements; and (iv) compare Hg, Pb and Cd with food-safety limits after estimating wet-weight concentrations. Four null hypotheses were

tested: concentrations follow a normal distribution (H01); fish and leaves do not differ (H02); elements are not correlated (H03); and no dominant multivariate gradient structures the data (H04).

2. MATERIALS AND METHODS

2.1. Study area

The Aruwimi River rises as the Ituri in north-eastern DR Congo and joins the Congo River on its right bank at Basoko, after draining about 116,000 km². The study covered two reaches of its lower course in Tshopo Province (Fig. 1): a reach in Basoko territory, around Yambomba and Likombe (about 1°22′N, 24°05′E), and a reach near the town of Banalia, around Longonu (about 1°30′N, 25°13′E). The climate is equatorial, with annual rainfall of 1,700–2,100 mm and mean temperatures of 24–26 °C. Lateritic soils overlie Precambrian basement rocks, with alluvium along the river. Households combine fishing with shifting cultivation of cassava, plantain and rice.

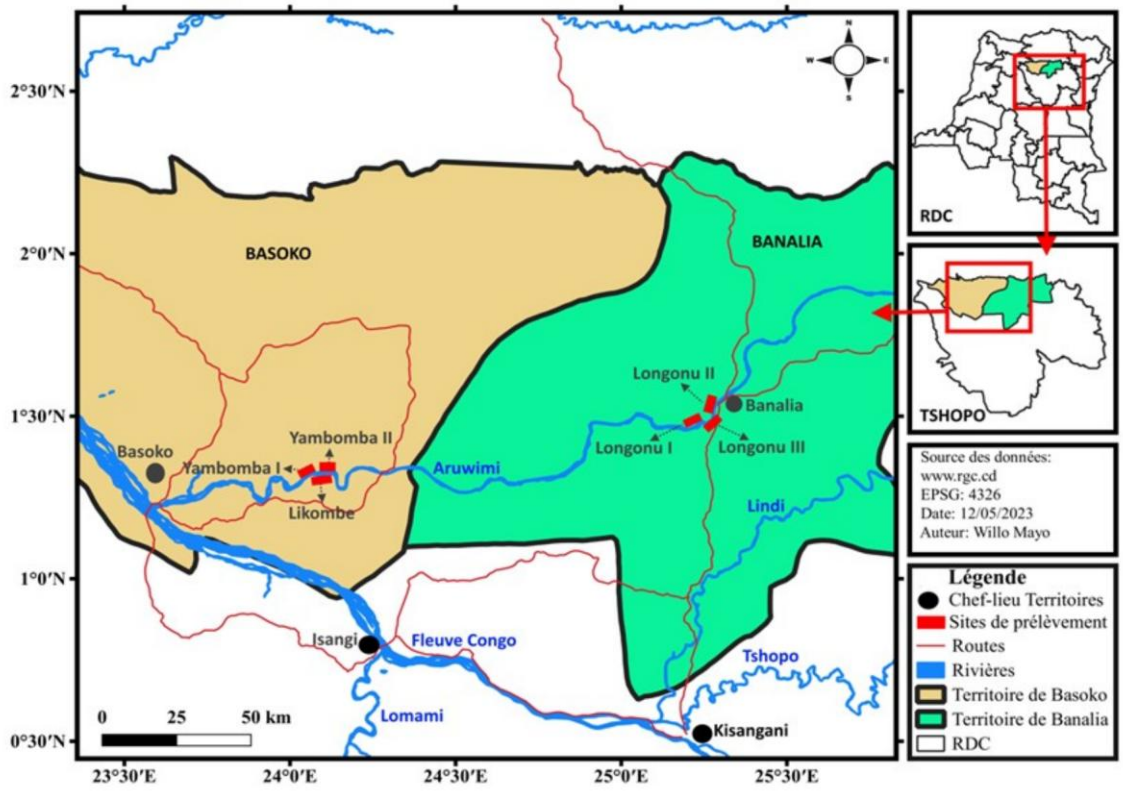


Figure 1. Sampling points along the Aruwimi River in Basoko territory (Yambomba I–II, Likombe) and Banalia territory (Longonu I–III), Tshopo Province, DR Congo.

2.2. Sampling

Twelve samples were collected between June and August 2025, during the dry season. Fishermen caught the fish with gillnets and traps; the ten specimens belonged to nine species: Clarias angolensis, Clarias gariepinus, Distichodus sexfasciatus, Distichodus fasciolatus, Pollimyrus isidori (two specimens), Clupeocharax schoutedeni, Synodontis decorus, Chrysichthys wagenaari and Gnathobagrus depressus. Leaves of sweet potato (Ipomoea batatas) and cassava (Manihot esculenta) were picked from riverside fields. Fish were kept on ice in clean polyethylene bags until dissection. Specimens were identified with standard keys. Positions were recorded by GPS, but the data sheet does not state which reach each sample came from.

2.3. Sample preparation and analysis

About 50 g of dorsal muscle was cut from each fish after removal of the viscera. Leaves were rinsed with deionised water, air-dried and ground in an agate mortar. All samples were then freeze-dried for 48 h and homogenised. Aliquots of about 0.5 g were digested in a 3:1 mixture of HNO3 (65%) and H2O2 (30%) in closed Teflon vessels in a microwave system (Mars 6, CEM) at 180 °C for 20 min, then diluted to 25 mL with ultrapure water (18.2 MΩ·cm). Sc, Cr, Mn, Fe, Cu, Ni, Co, Zn, As, Cd, Pb, Th and U were measured by ICP-MS (Agilent 7900). Total Hg was measured on the dried material with a direct mercury analyser (DMA). The previous draft cited cold-vapour atomic fluorescence (PSA Millennium Merlin), but the data sheet is labelled 'Hg DMA'; please state the instrument actually used. Results are expressed in mg/kg dry weight (dw).

Each batch included procedural blanks and certified reference materials (NIST SRM 2976 mussel tissue for fish; NIST SRM 1515 apple leaves for plants). Recoveries were between 85% and 112%, and all results were blank-corrected. Method detection limits ranged from 0.001 mg/kg (Cd, Hg) to 0.5 mg/kg (Fe). Moisture content was not determined.

2.4. Data treatment and statistics

Values reported as zero were treated as below the detection limit (non-detects). Sc, Ni, Th and U were detected only in the two leaf samples and Cu in three samples; these five elements are described but excluded from statistical tests. Nine elements detected in at least ten of the twelve samples (Cr, Mn, Fe, Co, Zn, As, Cd, Pb, Hg) were analysed further. The two Pb non-detects were replaced by half of the lowest detected Pb value (0.0135 mg/kg), a simple substitution whose limits are discussed by Helsel (2012); because rank-based methods treat the substituted values as tied lowest ranks, the choice of value does not affect the Spearman or Mann–Whitney results.

Normality was checked with the Shapiro–Wilk test on raw and log10-transformed values. Fish (n = 10) and leaves (n = 2) were compared with the exact two-sided Mann–Whitney U test. With these group sizes the smallest attainable p-value is 2/66 = 0.030, so the test can only detect complete separation of the two groups. Associations between elements were measured with Spearman's rank correlation (ρ), first on all twelve samples and then on the ten fish alone. PCA was run on the correlation matrix of log10-transformed, standardised data for the nine elements. Bartlett's test of sphericity and the Kaiser–Meyer–Olkin (KMO) index were computed, and components with eigenvalues above 1 were retained. Statistical significance was set at $\alpha = 0.05$, without correction for multiple comparisons given the exploratory aim. Analyses were run in Python 3.13 with NumPy 2.5, pandas 3.0 and SciPy 1.18; the script and data are provided as supplementary material.

To compare fish and leaves with food-safety limits, which are expressed on a fresh-weight basis, dry-weight results were multiplied by 0.20 and 0.25, corresponding to an assumed moisture content of 75–80%. The resulting range was compared with the Codex Alimentarius general standard for contaminants (FAO/WHO, CXS 193-1995, as amended) and with Commission Regulation (EU) 2023/915: 0.5 mg/kg for Hg in fish (1.0 mg/kg for predatory species), 0.30 mg/kg for Pb in fish muscle (EU) and in leafy vegetables (Codex and EU), 0.050 mg/kg for Cd in fish muscle (EU), and 0.2 mg/kg (Codex) or 0.10 mg/kg (EU) for Cd in leafy vegetables. The Codex values for Hg apply to methylmercury; comparing them with total Hg is conservative, since methylmercury usually makes up most, but not all, of the Hg in fish muscle.

3. RESULTS

3.1. Concentrations in fish and leaves

Raw results for each sample are listed in Table S1 and summarised in Table 1 and Fig. 2. Iron was the most abundant element in fish (median 129 mg/kg dw), followed by Zn and Mn; in the leaves, Mn (181 and 630 mg/kg dw) and Fe (213 and 372 mg/kg dw) dominated. Four elements were found only in the leaves: Ni (2.6 and 11.0 mg/kg), Sc, Th and U (all below 0.11 mg/kg). Copper was detected in both leaf samples (0.55 and 1.38 mg/kg) and in a single fish, Clupeocharax schoutedeni (14.8 mg/kg).

Mercury was present in every sample. In fish it ranged from 0.52 mg/kg dw in C. schoutedeni to 4.44 mg/kg dw in the second P. isidori specimen; the two leaf samples contained 1.34 and 2.17 mg/kg dw. Lead was below 0.55 mg/kg dw in all samples except that same P. isidori specimen, which returned 1,250 mg/kg dw. Because this single value dominates every summary of Pb (mean 104 mg/kg dw with it, 0.25 mg/kg dw without it), medians are used to describe Pb.

Table 1. Trace-element concentrations (mg/kg dry weight) in fish muscle and leaves from the Aruwimi River. Fish: median (minimum–maximum); <LOD: below detection limit.

Element	Detected in fish	Detected in leaves	Fish, n = 10	I. batatas	M. esculenta
Sc	0/10	2/2	<LOD	0.037	0.021
Cr	10/10	2/2	4.31 (1.80–13.5)	34.8	42.4
Mn	10/10	2/2	12.6 (3.66–124)	181	630
Fe	10/10	2/2	129 (70.1–678)	372	213
Cu	1/10	2/2	<LOD (<LOD–14.8)	0.551	1.38
Ni	0/10	2/2	<LOD	2.63	11.0
Co	10/10	2/2	0.420 (0.143–0.878)	17.0	6.49
Zn	10/10	2/2	34.3 (22.5–76.9)	52.7	213
As	10/10	2/2	0.106 (0.063–0.268)	0.056	0.037
Cd	10/10	2/2	0.182 (0.112–0.338)	0.063	0.532
Pb	8/10	2/2	0.303 (<LOD–1,250)	0.261	0.359
Th	0/10	2/2	<LOD	0.105	0.092
U	0/10	2/2	<LOD	0.018	0.008
Hg	10/10	2/2	1.75 (0.522–4.44)	1.34	2.17

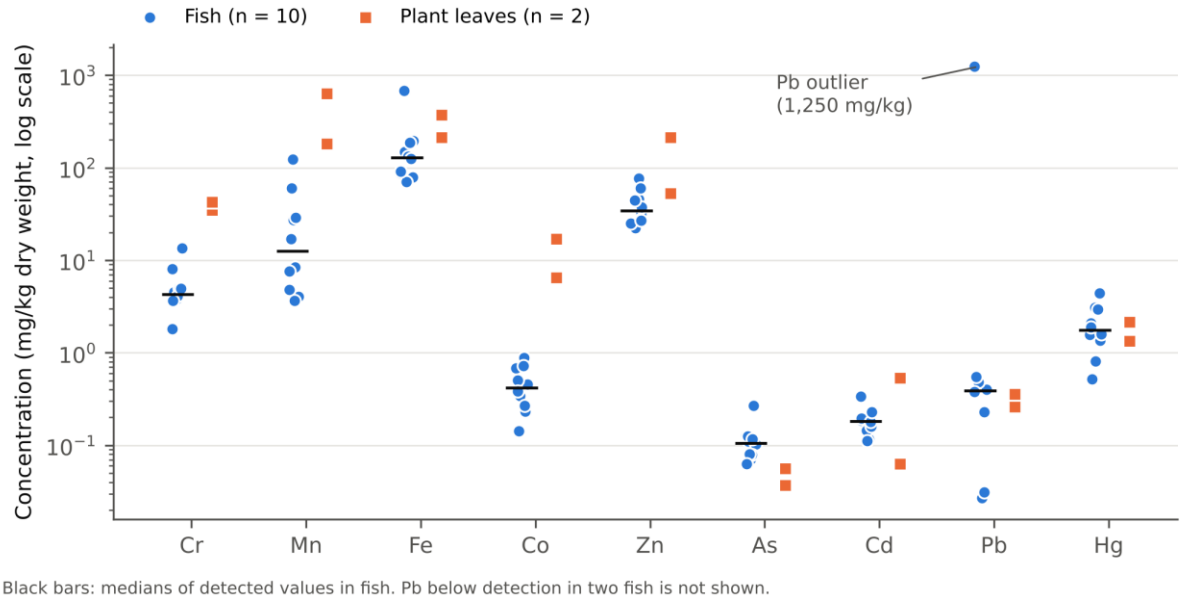


Figure 2. Concentrations of the nine elements detected in at least ten samples, in fish (circles) and leaves (squares). Logarithmic scale; horizontal bars are medians of detected values in fish.

3.2. Distributions

Of the nine elements tested, eight departed from normality on the raw scale (Shapiro–Wilk $p \leq 0.015$; Table 2). Hg was the exception ($W = 0.932$, $p = 0.403$). After log10 transformation, Mn, Fe, Zn, As, Cd and Hg no longer departed from normality, while Cr, Co and Pb still did, the latter because of the extreme Pb value. H01 is therefore rejected for all elements except Hg.

3.3. Fish versus leaves

The leaves contained more Cr (34.8–42.4 against a fish median of 4.3 mg/kg dw), Mn (181–630 against 12.6) and Co (6.5–17.0 against 0.42) than any fish ($U = 0$, $p = 0.030$). Arsenic followed the opposite pattern: both leaf samples (0.037 and 0.056 mg/kg) were below the lowest fish value (0.063 mg/kg; $U = 20$, $p = 0.030$). Fe and Zn tended to be higher in the leaves without complete separation ($p = 0.121$), and Cd, Pb and Hg did not differ ($p \geq 0.91$). H02 is rejected for Cr, Mn, Co and As only.

Table 2. Shapiro–Wilk normality tests (n = 12) and exact Mann–Whitney comparison of fish (n = 10) and leaves (n = 2). The smallest attainable Mann–Whitney p-value is 0.030.

Element	W (raw)	p (raw)	p (log10)	U	p	Higher in
Cr	0.644	<0.001	0.042	0	0.030	Leaves
Mn	0.553	<0.001	0.395	0	0.030	Leaves
Fe	0.711	0.001	0.330	2	0.121	–
Co	0.497	<0.001	0.021	0	0.030	Leaves
Zn	0.606	<0.001	0.068	2	0.121	–
As	0.794	0.008	0.849	20	0.030	Fish
Cd	0.817	0.015	0.882	10	1.000	–
Pb	0.327	<0.001	0.002	10	1.000	–
Hg	0.932	0.403	0.897	11	0.909	–

3.4. Correlations

Across the twelve samples, Cr, Mn, Fe, Co and Zn were all positively correlated (Fig. 3). The strongest pairs were Cr–Zn ($\rho = 0.87$, $p < 0.001$), Fe–Co ($\rho = 0.78$, $p = 0.003$), Cr–Fe and Fe–Zn (both $\rho = 0.78$, $p = 0.003$) and Mn–Co ($\rho = 0.75$, $p = 0.005$). Mercury was positively correlated with Cd ($\rho = 0.64$, $p = 0.024$) and negatively with Cr ($\rho = -0.62$, $p = 0.033$) and Zn ($\rho = -0.59$, $p = 0.042$). Arsenic and Pb showed no significant association with any element.

Part of this structure comes from the contrast between leaves and fish, so the analysis was repeated on the ten fish. Within fish, the negative links between Hg and Cr ($\rho = -0.83$, $p = 0.003$) and between Hg and Zn ($\rho = -0.82$, $p = 0.004$) became

stronger, Cr–Zn remained strong (ρ = 0.83, p = 0.003), and Fe–Zn (ρ = 0.70), Co–As (ρ = 0.70), Cr–Fe and Fe–Co (both ρ = 0.66) were significant at p < 0.05. The Hg–Cd correlation, in contrast, was not significant among fish alone. H03 is rejected for these pairs.

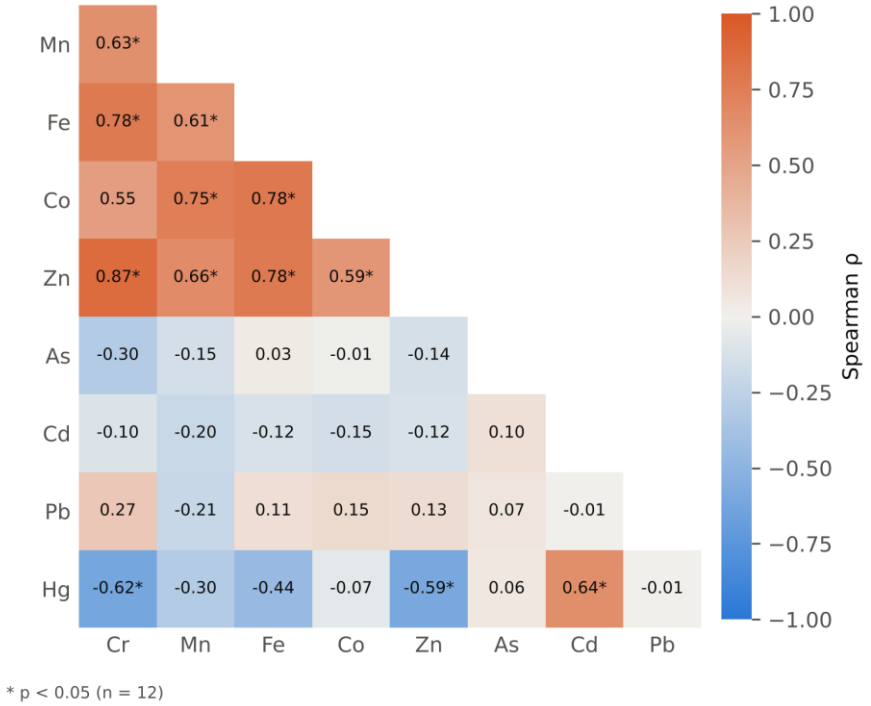


Figure 3. Spearman correlation matrix of the nine elements detected in at least ten samples (n = 12). Asterisks mark p < 0.05.

3.5. Principal component analysis

Three components had eigenvalues above 1 and together explained 78.2% of the variance (Table 3). PC1 (44.6%) carried high positive loadings for Cr (0.94), Mn, Co and Zn (0.88 each) and Fe (0.75). PC2 (18.3%) was defined by Hg (0.80), Cd (0.74) and, to a lesser extent, Pb (0.49). PC3 (15.4%) combined Pb (0.70), As (0.67) and Fe (0.50). On the PC1–PC2 plane (Fig. 4), the two leaf samples lie at the positive end of PC1, far from the fish; the second P. isidori specimen and the cassava sample have the highest PC2 scores.

Bartlett's test was significant (χ^2 = 75.9, df = 36, p < 0.001), but the KMO index was only 0.33, well below the usual threshold of 0.5. With twelve samples for nine variables, the PCA is a descriptive summary of the correlation structure and should not be read as a source apportionment. Within that limit, H04 is rejected: PC1 is a clear gradient that largely reflects the difference between leaves and fish.

Table 3. Loadings of the nine elements on the three retained principal components (log10-transformed, standardised data; n = 12). Loadings above 0.6 in absolute value are in bold.

	PC1	**PC2**	**PC3**
Cr	0.94	0.14	0.03
Mn	0.88	0.00	-0.08
Fe	0.75	-0.20	0.50
Co	0.88	0.17	0.17
Zn	0.88	0.14	-0.14
As	-0.33	-0.32	0.67
Cd	-0.06	0.74	-0.31
Pb	-0.10	0.49	0.70
Hg	-0.34	0.80	0.23
Eigenvalue	4.01	1.64	1.39
Variance (%)	44.6	18.3	15.4

	PC1	PC2	PC3
Cumulative (%)	44.6	62.9	78.2

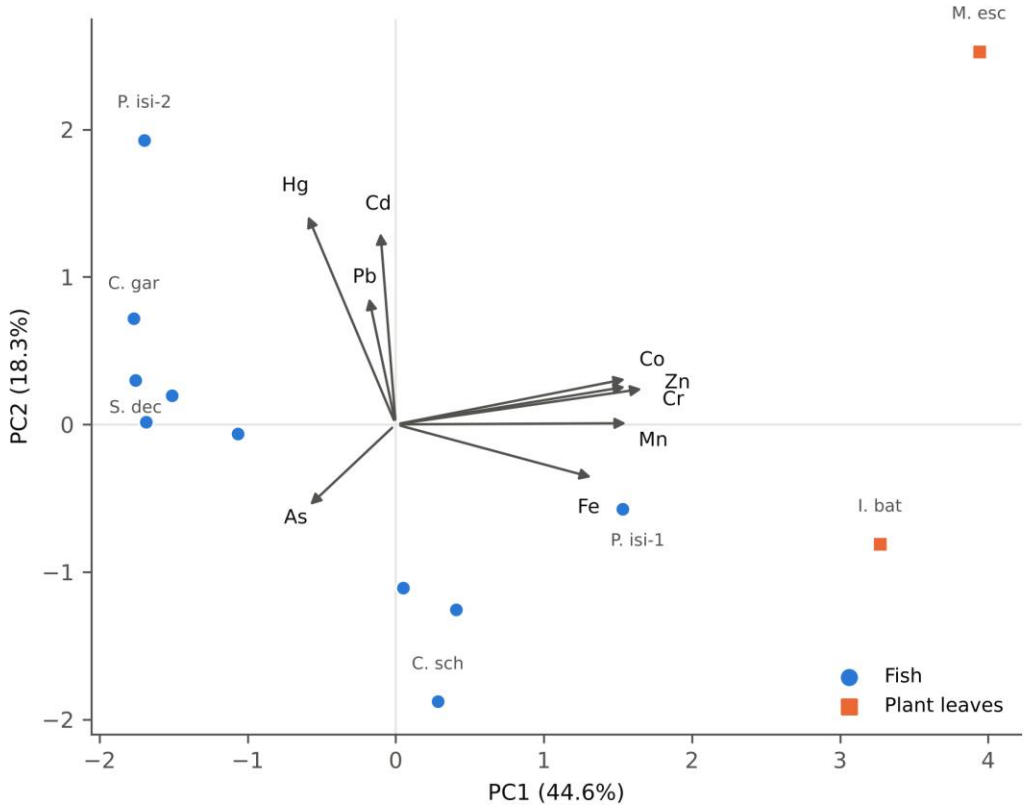


Figure 4. PCA biplot (PC1 and PC2) of log10-transformed, standardised concentrations. Arrows show element loadings (scaled ×1.8); labels identify the samples discussed in the text (P. isi-1 and P. isi-2: the two Pollimyrus isidori specimens; M. esc: Manihot esculenta; I. bat: Ipomoea batatas).

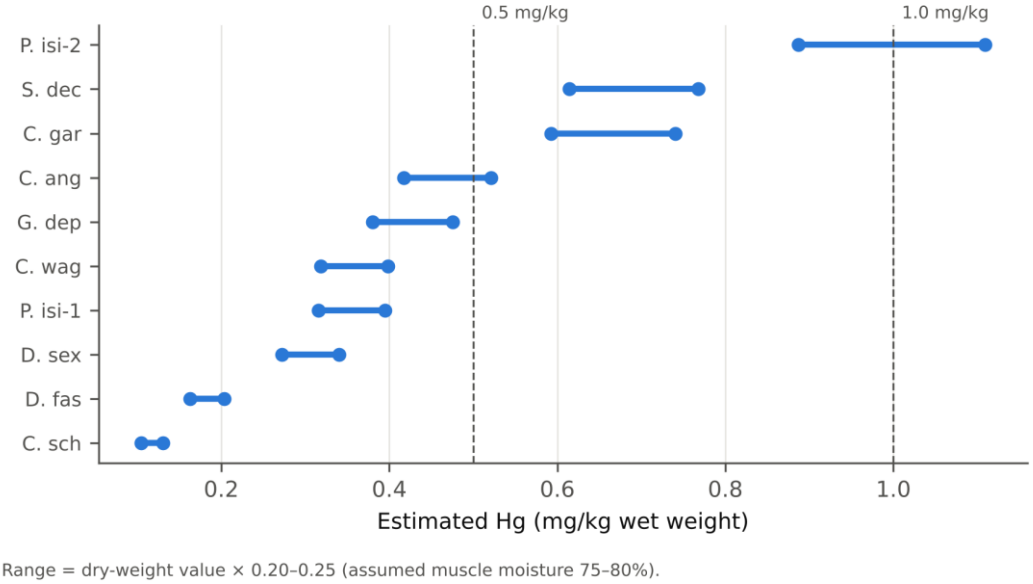
3.6. Comparison with food-safety limits

On an estimated wet-weight basis, Hg in fish ranged from 0.10–0.13 mg/kg (C. schoutedeni) to 0.89–1.11 mg/kg (second P. isidori) (Table 4; Fig. 5). Three fish exceeded 0.5 mg/kg with the 0.20 factor (P. isidori, Synodontis decorus, C. gariepinus) and a fourth (C. angolensis, 0.52 mg/kg) with the 0.25 factor; only the second P. isidori approached or exceeded 1.0 mg/kg. Excluding the extreme value, Pb in fish did not exceed 0.14 mg/kg wet weight. Cadmium in fish was estimated at 0.022–0.085 mg/kg, so one to three fish exceeded the EU limit of 0.050 mg/kg depending on the factor. In the leaves, Pb (0.05–0.09 mg/kg) remained below the 0.3 mg/kg limit, whereas Cd in cassava (0.11–0.13 mg/kg) exceeded the EU limit of 0.10 mg/kg but not the Codex level of 0.2 mg/kg.

Table 4. Estimated wet-weight concentrations (mg/kg) of Hg, Pb and Cd, obtained by multiplying dry-weight values by 0.20 and 0.25, compared with food-safety limits. *1.0 mg/kg for predatory species. †Value to be verified (see Section 4.2).

Sample	Hg	Pb	Cd
Clarias angolensis	0.42–0.52	<LOD	0.037–0.046
Distichodus sexfasciatus	0.27–0.34	0.005–0.007	0.023–0.029
Pollimyrus isidori (1)	0.32–0.39	0.08–0.10	0.041–0.051
Clupeocharax schoutedeni	0.10–0.13	0.006–0.008	0.029–0.036
Synodontis decorus	0.61–0.77	0.046–0.057	0.032–0.040
Pollimyrus isidori (2)	0.89–1.11	250–312†	0.039–0.049
Chrysichthys wagenaari	0.32–0.40	0.10–0.12	0.036–0.045
Clarias gariepinus	0.59–0.74	<LOD	0.068–0.085

Sample	Hg	Pb	Cd
Gnathobagrus depressus	0.38–0.48	0.076–0.095	0.046–0.057
Distichodus fasciolatus	0.16–0.20	0.11–0.14	0.022–0.028
Ipomoea batatas	0.27–0.34	0.052–0.065	0.013–0.016
Manihot esculenta	0.43–0.54	0.072–0.090	0.106–0.133
Limit, fish	0.5 (1.0)*	0.30	0.050
Limit, leafy vegetables	–	0.30	0.10 (EU) / 0.2 (Codex)



Range = dry-weight value × 0.20–0.25 (assumed muscle moisture 75–80%).

Figure 5. Estimated wet-weight Hg in each fish. Each bar spans the values obtained with conversion factors of 0.20 and 0.25; dashed lines mark the 0.5 and 1.0 mg/kg guideline levels.

4. DISCUSSION

4.1. Mercury is the main concern

Mercury is the element most likely to matter for health here. Hanna et al. (2015), who compiled 407 measurements from 12 African countries, found a mean of 0.16 mg/kg wet weight across locations, with only sites near artisanal gold mining exceeding 0.5 mg/kg on average. The estimated median of our fish, about 0.35–0.44 mg/kg wet weight, sits well above that continental mean, and three or four of ten fish exceeded 0.5 mg/kg. The Ituri, which becomes the Aruwimi, drains areas where gold is still amalgamated with mercury (AEMAPRI & IPIS, 2018), which makes upstream mining a plausible source. Our data cannot test this: there are no water, sediment or upstream samples, and two reaches do not make a gradient.

The distribution of Hg among species is also unexpected. The highest value came from a small mormyrid, P. isidori, while the second specimen of the same species had less than half as much (4.44 against 1.58 mg/kg dw). Mercury in fish generally rises with body mass and trophic level (Hanna et al., 2015), and the size and weight of our specimens were not recorded, so we cannot tell whether size explains this difference. The strong negative correlations of Hg with Cr and Zn among fish may point in the same direction, if smaller individuals have higher Cr and Zn and lower Hg, but this remains to be tested.

The leaves contained 1.3–2.2 mg/kg dw Hg, much more than the levels usually reported for crop plants, which are commonly below 0.1 mg/kg (Kabata-Pendias, 2011). Plants take up little Hg from soil, so if these values are confirmed they would rather suggest foliar deposition of gaseous or particulate Hg. Because this is also the pattern expected from contamination during sample handling, the leaf results need to be checked against a second digestion and a plant reference material certified for Hg before they are interpreted.

4.2. Lead: one value to verify

The 1,250 mg/kg dw Pb measured in the second P. isidori is more than 2,000 times the next highest fish value (0.55 mg/kg) and several orders of magnitude above concentrations reported in fish muscle. A live fish with such a muscle burden is hard to reconcile with Pb toxicity, and the specimen shows no other anomaly apart from its high Hg. The most likely explanations are a transcription or unit error (a value of 1.250 mg/kg would fall within the range of the other samples), contamination of the aliquot, or a fragment of metallic lead such as a fishing sinker. Re-analysing the stored material should settle the matter. Leaving this value aside, Pb in fish and leaves was low and below food limits.

4.3. Differences between fish and leaves

Cassava and sweet-potato leaves held more Cr, Mn and Co than fish muscle, and only the leaves contained detectable Ni, Sc, Th and U. This pattern fits uptake from lateritic soils rich in Fe and Mn oxides, which retain and release these elements (Alloway, 2013; Kabata-Pendias, 2011), together with some adhering soil particles despite washing. Cassava is known to accumulate Mn in its leaves, so the high value in this sample (630 mg/kg dw) is not, by itself, evidence of contamination. Arsenic showed the opposite pattern, with higher values in fish, which is consistent with the accumulation of arsenic compounds through aquatic food webs. Cadmium in cassava leaves deserves follow-up: the estimated 0.11–0.13 mg/kg fresh weight slightly exceeds the EU limit, and cassava leaves are a daily food in the region.

The Cr–Mn–Fe–Co–Zn group on PC1 should not be over-interpreted as a geochemical source. Because the leaves carry high values of all five elements, the group mainly reflects the difference between two food types, and with only two leaf samples it rests on very few points. Similarly, PC2 brings together Hg, Cd and Pb, but Pb loads on it largely because of the same specimen that carries both the highest Hg and the extreme Pb. These axes are useful to describe the data set, not to identify sources.

4.4. Iron in fish muscle

Iron in fish muscle (70–678 mg/kg dw) is higher than is commonly reported for this tissue. The highest value, in the first P. isidori specimen, may reflect blood or small particles left in a small fish, or contamination during grinding. It does not raise a health concern, but it suggests that preparation of the smallest specimens should be checked.

4.5. LIMITATIONS

Several features of the data limit what can be concluded. There are twelve samples, one specimen per species except P. isidori, and only two leaf samples, so between-group tests have very little power. The reach of origin of each sample is not available, so spatial differences could not be tested. Sampling covered one dry season. Moisture content was not measured, which makes the wet-weight comparison approximate, and fish length and weight were not recorded. No water or sediment was analysed, and no exposure calculation (estimated daily intake, target hazard quotient) was attempted, as it would require local consumption data. Finally, two values, the extreme Pb and the leaf Hg, need analytical confirmation.

5. CONCLUSIONS

This first survey of trace elements in fish and leafy vegetables from the lower Aruwimi River shows that most elements occur at levels expected for these foods, but that Hg is a concern. Three to four of the ten fish analysed probably exceed the 0.5 mg/kg wet-weight guideline, and their median is more than twice the African average reported in the literature. Leaves of cassava and sweet potato contain more Cr, Mn and Co than fish, and cassava leaves may slightly exceed the EU limit for Cd. One extreme Pb value and the high Hg in leaves must be verified before publication of any risk estimate. We recommend (i) re-analysing the samples with the extreme Pb and the leaf Hg values; (ii) sampling several individuals of the most consumed species, with length, weight, and moisture; (iii) adding water and sediment and extending sampling upstream towards the Ituri gold-mining areas and into the rainy season; and (iv) collecting fish and cassava-leaf consumption data so that exposure and hazard quotients can be calculated for local consumers.

DECLARATIONS

Data availability. The raw data are given in Table S1; the analysis script is available as supplementary material.

Competing interests. The authors declare no competing interests.

REFERENCES

1. AEMAPRI & IPIS (2018). Voix du Congo: Étude sur l'orpaillage et l'utilisation du mercure dans l'exploitation minière artisanale en Ituri. International Peace Information Service, Antwerp.
2. Alloway, B. J. (Ed.) (2013). Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability (3rd ed.). Springer, Dordrecht.
3. European Commission (2023). Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food. Official Journal of the European Union, L 119, 103–157.
4. FAO/WHO (1995, as amended). General Standard for Contaminants and Toxins in Food and Feed (CXS 193-1995). Codex Alimentarius Commission, Rome.
5. Förstner, U., & Wittmann, G. T. W. (2012). Metal Pollution in the Aquatic Environment (2nd ed.). Springer, Berlin.
6. Hanna, D. E. L., Solomon, C. T., Poste, A. E., Buck, D. G., & Chapman, L. J. (2015). A review of mercury concentrations in freshwater fishes of Africa: patterns and predictors. Environmental Toxicology and Chemistry, 34(2), 215–223. https://doi.org/10.1002/etc.2818
7. Helsel, D. R. (2012). Statistics for Censored Environmental Data Using Minitab and R (2nd ed.). Wiley, Hoboken.
8. Kabata-Pendias, A. (2011). Trace Elements in Soils and Plants (4th ed.). CRC Press, Boca Raton.
9. Kutakimina, P. B., et al. (2026). Geochemical evaluation of trace metals and rare-earth elements in soils and sediments from a legacy copper mining site in Kongo-Central, Democratic Republic of the Congo. Discover Geoscience (accepted).
10. Reimann, C., & de Caritat, P. (2005). Distinguishing between natural and anthropogenic sources for elements in the environment: regional geochemical surveys versus enrichment factors. Science of the Total Environment, 337(1–3), 91–107.

Supplementary material

Table S1. Raw concentrations (mg/kg dry weight) in the twelve samples. <LOD: below detection limit (reported as 0 in the original data sheet).

Sample	Sc	Cr	Mn	Fe	Cu	Ni	Co	Zn	As	Cd	Pb	Th	U	Hg
Clarias angolensis	<LOD	3.955	16.935	86.982	<LOD	<LOD	0.343	31.473	0.071	0.185	<LOD	<LOD	<LOD	2.085
Distichodus sexfasciatus	<LOD	4.523	124.058	196.314	<LOD	<LOD	0.687	45.52	0.127	0.116	0.027	<LOD	<LOD	1.36
Pollimyrus isidori (1)	<LOD	13.537	60.442	678.236	<LOD	<LOD	0.878	76.868	0.268	0.204	0.402	<LOD	<LOD	1.579
Clupeocharax schoutedeni	<LOD	5.018	27.491	149.095	14.789	<LOD	0.457	60.47	0.11	0.144	0.031	<LOD	<LOD	0.522
Synodontis decorus	<LOD	1.805	28.926	78.876	<LOD	<LOD	0.503	22.451	0.102	0.161	0.228	<LOD	<LOD	3.071
Pollimyrus isidori (2)	<LOD	3.825	4.035	132.87	<LOD	<LOD	0.718	27.405	0.126	0.197	1250	<LOD	<LOD	4.436
Chrysichthys wagenaari	<LOD	4.091	4.81	70.145	<LOD	<LOD	0.143	37.2	0.079	0.18	0.481	<LOD	<LOD	1.594
Clarias gariepinus	<LOD	3.654	3.656	124.3	<LOD	<LOD	0.232	25.084	0.08	0.338	<LOD	<LOD	<LOD	2.963
Gnathobagrus depressus	<LOD	4.966	8.354	91.6	<LOD	<LOD	0.269	26.783	0.117	0.228	0.378	<LOD	<LOD	1.901
Distichodus fasciolatus	<LOD	8.054	7.597	185.996	<LOD	<LOD	0.383	44.522	0.063	0.112	0.548	<LOD	<LOD	0.813
Ipomoea batatas	0.037	34.759	181.035	371.751	0.551	2.627	17.033	52.651	0.056	0.063	0.261	0.105	0.018	1.342
Manihot esculenta	0.021	42.364	629.597	212.892	1.376	11.002	6.485	212.982	0.037	0.532	0.359	0.092	0.008	2.166