



Physicochemical qualities and ecological risk assessment of soil and plants heavy metals contamination in a selected areas around Kipushi mining at the Congolese Copperbelt in DR Congo

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ABSTRACT

Mining activities in Kipushi, Democratic Republic of Congo, have generated extensive tailings and waste rock, leading to long-term accumulation of trace metals in soils and vegetation. Despite their ecological and public health significance, integrated assessments of contamination levels, metal speciation, and ecological risks remain scarce in this mining-impacted region. Soil ($n = 6$) and plant ($n = 6$) samples were collected from six sites during rainy and dry seasons. Total and bioavailable concentrations of Cd, Co, Cr, Cu, Pb, and Zn were determined using ICP-OES after acid digestion. Sequential extraction (BCR protocol) was applied to assess metal speciation. Contamination was quantified using enrichment factor (EF), contamination factor (CF), geo-accumulation index (Igeo), pollution index (PI), and potential ecological risk index (PERI). Statistical analyses included ANOVA and Pearson correlations. Soils displayed high variability in pH (4.4–7.5), organic matter (2.8–8.1 %), and cation exchange capacity (6–10 meq/100 g). Co, Cu, and Zn frequently exceeded FAO limits, with maximum values of 60.1, 424.1, and 560.7 mg/kg, respectively. CF and Igeo indicated considerable to very high contamination for Cu, Zn, and Co at multiple sites. Sequential extraction revealed that Cd, Cr, and Pb were mainly in reducible fractions, suggesting high remobilization potential, while Cu and Cr were largely residual. In plants, *Persea americana*, *Melissa officinalis*, and *Lanea discolor* accumulated Co, Cr, and Cu above WHO thresholds, with bioconcentration factors up to 0.29. PERI highlighted very high ecological risks, particularly for Pb and Zn in P1–P4. These findings confirm severe contamination of Kipushi

Abbreviations: BRC, Community Bureau of References; CEC, Cation exchange capacity; OC, Organic carbon; TME, Trace metal element; FAO, Food and Agriculture Organization; CF, Contamination factor; EF, Enrichment factor; PERI, Potential ecological risk factor; ICP-OES, Inductively coupled plasma optical emission spectroscopy; Igéo, Geo-accumulation index; PI, Pollution index; OM, Organic matter; PERI, Potential ecological risk index.

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soils and vegetation by mining residues, with metals present in labile forms prone to environmental transfer. Native species showed contrasting roles in phytoextraction (*P. americana*) and phytostabilization (*Bamboussa vulgaris*). The results underline the urgent need for phytoremediation-based strategies, stricter environmental controls, and systematic monitoring to protect ecosystems and human health in the Congolese Copperbelt.

Introduction

Soil contamination by heavy metals has emerged as a major environmental challenge due to the non-biodegradable nature of these elements, their toxicity to biota, and their strong tendency to accumulate in food chains (Alloway, 2013; Kumar et al., 2022). Anthropogenic activities, particularly mining and metallurgical processes, are recognized as dominant sources of cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn) in terrestrial ecosystems [1–5]. Once released into soils, these metals may persist for decades and interfere with ecosystem functioning, leading to soil degradation, reduced agricultural productivity, and risks to human health including carcinogenicity (Pb, Cr(VI)) and organ toxicity (Cd, Co, Cu) (Kabata-Pendias, 2011; Antoniadis et al., 2019). The mobility and bioavailability of heavy metals are controlled by key soil physicochemical properties such as pH, organic matter (OM), organic carbon (OC), and cation exchange capacity (CEC). Acidic conditions, low CEC, and limited OM content can promote the solubilization of trace metals, increasing their transfer into plants and water systems [6–12].

The Central African Copperbelt, shared between the Democratic Republic of the Congo (DRC) and Zambia, is one of the most metallogenically endowed provinces worldwide. Kipushi, in the southeastern DRC, hosts a polymetallic Cu–Zn–Pb–Co deposit with a long history of industrial and artisanal exploitation. Decades of mining have produced large volumes of tailings and waste rock, much of which was deposited without engineered containment, resulting in wind and water erosion of fine particles into surrounding soils, streams, and croplands [13–16]. Despite the recognized environmental hazards, systematic monitoring of soil contamination, metal speciation, and plant uptake in Kipushi remains limited [1,6,17–19].

Therefore, this study aimed to provide an integrated assessment of heavy metal contamination in soils and plants from the Kipushi mining area. Specifically, the objectives were to (i) quantify total and bioavailable concentrations of Cd, Co, Cr, Cu, Pb, and Zn; (ii) apply the BCR sequential extraction protocol to determine metal speciation and mobility; (iii) evaluate ecological risk using multiple contamination indices (EF, CF, Igeo, PI, PERI); and (iv) investigate the capacity of native plant species to accumulate or stabilize

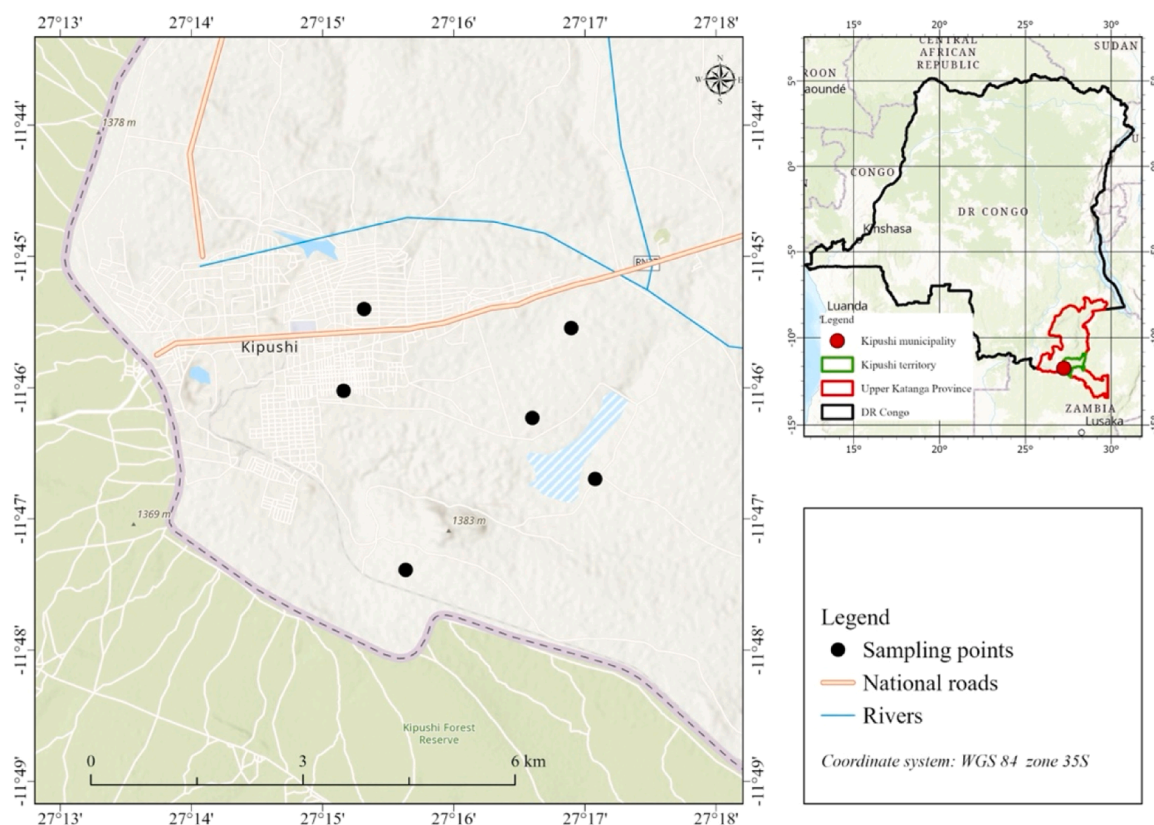


Fig. 1. Map of sampling sites.

metals, with a view toward identifying candidates for phytoremediation. This comprehensive approach is expected to provide essential insights into the environmental quality of the Congolese Copperbelt and to inform strategies for ecological restoration and public health protection.

Materials and methods

Reagents and standards

All reagents used for the preparation of extraction solutions were of analytical grade (Merck pro-analysis). All solutions and dilutions were prepared using doubly deionized water ($18.2 \text{ M}\Omega\cdot\text{cm}^{-1}$) from Thermo Scientific Barnstead Easy Pure II systems. Stock standard solutions of $1000 \text{ mg}\cdot\text{L}^{-1}$ for various elements were prepared from metal wires or salts of purity higher than 99.998 % (VWR International). Working standard solutions were freshly prepared daily from the stock solutions. All glassware and plastic laboratory equipment were rinsed three times with doubly deionized water after soaking in a 10 % HNO_3 (v/v) bath for 24 h.

Study area

The study was conducted in Kipushi, a mining town in the Haut-Katanga province of the Democratic Republic of Congo, located at $28^\circ 10' \text{E}$ and $12^\circ 30' \text{S}$ (Fig. 1). Six soil sampling sites (P1–P6) were selected to represent areas with different levels of mining impact:

- P1–P4: sites located in agricultural land and residential zones near tailings dams, directly exposed to mine dust and effluents;
- P5–P6: sites adjacent to artisanal mining activities and highly acidic soils influenced by acid mine drainage;
- Reference site: Miombo forest, considered the least anthropized area, used as the geochemical background for index calculations.

The miombo forest is a vast ecosystem of subtropical woodland savanna in southern and central Africa. In the context of Kipushi, the miombo forest is particularly important because it harbors plant species capable of accumulating or stabilizing heavy metals (species with phytoremediation potential). It is considered the least anthropized site in Katanga Province.

Soil sampling

At each site, three soil samples were collected at 0–25 cm depth using a hand auger and GPS positioning. Approximately 1 kg of soil per replicate was placed in sterile polyethylene bags, homogenized, and transported to the laboratory. In parallel, three plant samples per site (6 species in total) were collected to assess metal accumulation in edible or ecologically significant species. After homogenization and quartering, samples were air-dried and sieved through a 2 mm mesh to retain only the soil fraction. A total of six soil samples were collected, along with six plant samples taken at the same time. The plants used in this study are perennial species with life cycles lasting more than one year, unlike other studies that focused on seasonal plants. The soil was ground in a mortar to reduce it to a powder with particle size $<180 \mu\text{m}$ and then oven-dried at 105°C for 24 h prior to various analyses [20].

Physicochemical properties of soil samples

Soil samples were air-dried, sieved ($<2 \text{ mm}$), and characterized for pH (1:10 soil–water suspension, YSI 556 HACH meter), organic carbon (ISO 1999 method), organic matter (loss on ignition, 450°C , 24 h), cation exchange capacity (CEC; ammonium acetate digestion), and texture (USDA triangle) [21–23]. Soil moisture was determined gravimetrically after oven drying at 105°C [24]. Moisture content was calculated using Equation 1:

$$\text{Humidité (\%)} = \frac{\text{masse du sol humide (g)} - \text{masse du solsec(g)}}{\text{masse du solsec(g)}} \times 100$$

Sample Preparation for ICP-OES Analysis

Reagents and standards: All reagents used for the preparation of extraction solutions were of analytical grade (Merck pro-analysis). All solutions and dilutions were prepared using doubly deionized water ($18.2 \text{ M}\Omega\cdot\text{cm}^{-1}$) from Thermo Scientific Barnstead Easy Pure II systems. Stock standard solutions of $1000 \text{ mg}\cdot\text{L}^{-1}$ for various elements were prepared from metal wires or salts of purity higher than 99.998 % (VWR International). Working standard solutions were freshly prepared daily from the stock solutions. All glassware and plastic laboratory equipment were rinsed three times with doubly deionized water after soaking in a 10 % HNO_3 (v/v) bath for 24 h.

Metal determination (total and bioavailable fractions)

Two digestion procedures were performed: the first using aqua regia for total metal content, and the second using ammonium acetate and EDTA at pH 4.65 for the bioavailable fraction.

For the first digestion, 25 mg of soil were mixed with 2 mL of HNO_3 (65 %), 1 mL of H_2O_2 , and 6 mL of HCl (37 %). The mixture was digested gently on a sand bath for about 2 h. The solution was then evaporated to dryness and re-dissolved in 3 mL of concentrated HCl. Forty milliliters of water and concentrated HCl were added to the mixture and brought to a boil for 10 min. For the second digestion, 20 g of air-dried soil were mixed with 100 mL of extraction solution (0.5 M ammonium acetate, 0.5 M acetic acid, and 0.02 M EDTA) at pH 4.65 in a 250 mL Erlenmeyer flask. The mixture was shaken for 30 min and then filtered [21,24–27]. The instrument used was a

Perkins-Elmer Optima 3000XL Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES).

Sequential extraction of trace metal element following the BCR scheme

Step 1: Exchangeable and acid-soluble fraction

The extraction procedure was applied to 2 g of dry soil sample (not ground and sieved to 2 mm). To 2 g of soil placed in a Teflon centrifuge tube, 80 mL of 0.11 M acetic acid (CH_3COOH) solution were added. The mixture was shaken for 16 h at room temperature. After shaking, the extract was separated from the solid residue by centrifugation at 10,000 rpm for 20 min and stored at 4 °C prior to ICP analysis. The residue was washed with 20 mL of distilled water, centrifuged, and transferred to a new tube.

Step 2: Reducible fraction (release under reducing conditions)

Eighty mL of 0.1 M hydroxylamine hydrochloride ($\text{NH}_2\text{OH}\cdot\text{HCl}$) solution were added to the residue from the previous step. The tube was shaken for 16 h at room temperature. The supernatant was isolated by centrifugation at 10,000 rpm for 20 min and stored at 4 °C before ICP analysis. The residue was washed again with 20 mL of distilled water, centrifuged, and transferred to a new tube.

Step 3: Oxidizable fraction (release under oxidizing conditions)

The residue from the previous step was treated with 20 mL of 8.8 M hydrogen peroxide (H_2O_2). The pH was adjusted to 2 using nitric acid (HNO_3). The mixture was left at room temperature with intermittent shaking for one hour. Digestion continued in a water bath at 90 °C for another hour to reduce the volume. This operation was repeated twice. The residue was then treated with 100 mL of 1 M ammonium acetate ($\text{CH}_3\text{COONH}_4$). The mixture was shaken for 16 h at room temperature, and the supernatant was separated as in steps 1 and 2. The residue was washed with 20 mL of distilled water, centrifuged, and recovered again.

Step 4: Residual fraction

The residue was digested with aqua regia. The same procedure used in total digestion was followed to recover the residual fraction. Heavy metal contents were determined in the four fractions by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) [22,28].

Estimation of TME Contamination Intensity in Soil

To estimate the observed potential pollution intensity, the enrichment factor (EF), contamination factor (CF), geo-accumulation index (Igeo), pollution index (PI), and potential ecological risk factor (PERI) were calculated. These indices are based on comparing measured values with reference values such as the average elemental concentrations in the Earth's crust.

Determination of the enrichment factor in soil samples (EF)

The enrichment factor (EF) Table 1 is a vital tool for determining the degree of anthropogenic heavy metal pollution in soils at specific sites. This factor is calculated using the following formula:

$$EF = \frac{[\text{Me}]_{\text{sample}} / [\text{Al}]_{\text{sample}}}{[\text{Me}]_{\text{reference}} / [\text{Al}]_{\text{reference}}}$$

With, $[\text{Me}]_{\text{samples}}$ = Concentration of the measured element in the soil sample from sites subject to anthropogenic activities.

$[\text{Al}]_{\text{sample}}$ = Concentration aluminum in the soil sample from anthropogenically influenced sites.

$[\text{Me}]_{\text{reference}}$ = Concentration of the measured element in the reference soil (natural or unaffected site), also known as the natural background concentration.

$[\text{Al}]_{\text{reference}}$ = Concentration of aluminum in the reference soil [24,29].

In this study, the reference site is in the south, near the Zambian border.

It is worth noting that aluminum was used for geochemical normalization because it is generally measured, poorly soluble, and not significantly affected by pollution.

Table 1
Pollution intensity scale based on EF value ranges.

Class	EF value range	Pollution intensity
1	$FE \leq 2$	No or low anthropogenic enrichment
2	$2 < FE < 5$	Moderate enrichment
3	$5 < FE < 20$	Significant enrichment
4	$20 < FE < 40$	Very high enrichment
5	$FE \geq 40$	Extreme enrichment

Determination of contamination factor in soil samples (CF)

The contamination factor (CF) Table 2 is used to assess the level of metal contamination in sediments. It is calculated using the following equation:

$$CF = \frac{C_m}{C_b}$$

Where: C_m : Concentration of the metal in the soil sample and C_b : Geochemical background value of the metal [24,31,29,32]

Determination of the geoaccumulation index in soil samples (Igeo)

The geo-accumulation index (Igeo) Table 3 is an empirical parameter used to quantify the accumulation of a metal in contaminated soils. Developed by Müller in 1979, Igeo is expressed by the following formula [24,31,33,29] :

$$I_{geo} = \log_2 \left(\frac{[Me]_{sample}}{[Me]_{reference}} \times 1.5 \right)$$

The correction factor of 1.5 accounts for natural fluctuations in the metal content that may be attributed to mineralogical variations in the soil.

Pollution index (PI)

The pollution index (PI) of the soil is calculated based on the average of the ratios of metal concentrations in soil samples to their respective guideline limits. These limits represent assumed tolerable levels in soil as proposed by Kloke (1979), cited by: [24,34]. In this study, PI is calculated using the following equation:

$$PI = \left(\frac{Cd}{3} + \frac{Co}{30} + \frac{Cr}{150} + \frac{Cu}{100} + \frac{Pb}{100} + \frac{Zn}{300} \right) / 6$$

A PI greater than 1 indicates soil polluted by multiple metals.

Determination of the potential ecological risk factor and the ecological risk index for trace metal elements in the soils

The potential ecological risk factor (Er) Table 4 and the ecological risk index (RI or PERI) Table 5 are essential tools for assessing the degree of metal pollution in terrestrial and aquatic ecosystem compartments, such as soils and sediments [24].

The potential ecological risk factor (PERF) is calculated by multiplying the toxic response factor (Tr) by the contamination factor (CF) of a given metal: PERF = Tf x FC [15].

Avec TF = Toxic response factor of the given metal; FC = Contamination factor of the given metal.

Statistical analysis

Descriptive statistics, one-way analysis of variance (ANOVA), and Pearson correlation matrices were applied to test spatial and

Table 2
Contamination levels based on CF values.

CF value range	Contamination level
CF < 1	Low contamination
1 ≤ CF < 3	Moderate contamination
3 ≤ CF < 6	Considerable contamination
CF ≥ 6	Very high contamination

Table 3
Igeo classes according to Müller [24].

Class	Igeo value range	Contamination level
0	Igeo < 0	Uncontaminated soil
1	0 < Igeo < 1	From uncontaminated to moderately contaminated
2	1 < Igeo < 2	Moderately contaminated
3	2 < Igeo < 3	Moderately to heavily contaminated
4	3 < Igeo < 4	Heavily contaminated
5	4 < Igeo < 5	Heavily to extremely contaminated
6	5 > Igeo	Extremely contaminated soil

Table 4
Toxic response factor (Tr) values for selected heavy metals.

Heavy metal	Toxic Response Factor (TRF)
Cd	30
As	10
Pb	5
Cu	5
Co	5
Cr	2
Zn	1
Mn	1

[15].

Table 5
Criteria for the degree of ecological risk based on the ecological risk factor (ERF).

Ecological Risk Factor (ERF) Value Scale	Ecological Risk level
FRPE < 40	Low ecological risk
40 ≤ FRPE < 80	Moderate potential risk
80 ≤ FRPE < 160	Considerable potential risk
160 ≤ FRPE < 320	High potential ecological risk
FRPE > 320	Very high ecological risk

[30,24].

seasonal differences in soil and plant metal concentrations. Statistical significance was set at $p \leq 0.05$. Analyses were performed using STATISTICA 10 and OriginPro 10.8 for graphical outputs. Principal component analysis (PCA) was applied to identify patterns of co-contamination and to link soil properties with metal distributions.

Quality control

All analyses were conducted in triplicate. Reagents were of analytical grade (Merck), and blanks were included for each digestion batch. Method accuracy was verified using matrix spiking with 1 ppm mixed standards (Cd, Co, Cr, Cu, Pb, Zn; VWR International). Recoveries ranged between 95 % and 110 %, and detection limits (LOD) were ≤ 0.01 mg/kg for Cd, Pb, and Cr, and ≤ 0.05 mg/kg for Cu, Co, and Zn. Relative standard deviations (RSD) were consistently ≤ 10 %.

Reference standards

Due to the absence of comprehensive national guidelines in the DRC, international FAO/WHO values were used as reference limits for agricultural soils and edible plants. This ensures comparability with global studies and provides a robust basis for ecological and human health risk assessment.

Results and discussion

Physicochemical properties of the studied soils

The distribution of trace metals in Kipushi soils was strongly controlled by soil physicochemical properties, notably pH, organic matter (OM), and cation exchange capacity (CEC) (Table 6). The level of soil contamination by trace metal elements (TMEs) is strongly influenced by physicochemical properties such as texture, organic carbon (OC), pH, cation exchange capacity (CEC), and organic matter (OM), in addition to the concentration and type of metals present. The main soil properties of the study sites are summarized in

Table 6
Physicochemical properties of the studied soils.

Sample	pH H ₂ O	Texture (%)			%			
		Sand	Silt	Clay	Humidity	OC	OM	CEC
P1	6,42	50	22	28	7,24	2,0	3,5	6
P2	5,19	30	27	43	9,16	2,7	4,6	7
P3	6,3	22	35	43	13,06	2,0	3,5	6
P4	7,5	27	35	38	6,95	4,7	8,1	6
P5	4,84	50	0	50	9,94	4,3	7,4	10
P6	4,42	28	30	42	11,55	1,6	2,8	8
Norme [24]	5–6					12–25	3.6–6.5	10–20

Table 7

Total trace metal element contents in Kipushi soils.

Sample	Concentration of soil trace metal element (mg/kg)					
	Cd	Co	Cr	Cu	Pb	Zn
P1	1,13 ± 0,04	29,80 ± 1,11	15,80 ± 0,83	424,11 ± 13,12	29,40 ± 2,21	560,70 ± 32,12
P2	0,89 ± 0,01	30,00 ± 1,23	4,61 ± 0,01	160,40 ± 6,74	16,78 ± 1,01	121,51 ± 5,23
P3	0,35 ± 0,01	48,30 ± 3,12	10,90 ± 0,12	127,51 ± 8,32	12,91 ± 0,45	238,78 ± 19,18
P4	0,39 ± 0,01	60,11 ± 2,17	8,82 ± 0,15	163,30 ± 9,90	21,90 ± 0,97	363,33 ± 23,42
P5	0,64 ± 0,02	24,50 ± 1,82	8,67 ± 0,43	40,70 ± 2,98	8,50 ± 0,24	66,89 ± 4,32
P6	0,33 ± 0,01	13,52 ± 0,12	10,91 ± 0,82	25,7 ± 1,01	5,20 ± 0,20	17,50 ± 0,86
Norme [24]	2	30	150	100	100	300

Table 6. Soil pH varied considerably between sites, ranging from extremely acidic at P6 (4.42) and P5 (4.84) to slightly acidic at P1 (6.30), P2 (5.19), and P3 (6.42), while P4 was alkaline (7.50). The acidic conditions, likely related to acid mine drainage, increase metal solubility and mobility, as observed in other polluted soils [3,35]. This suggests favorable conditions for metal mobility at most sites except P4. Soil texture was generally clay-rich, exceeding 40 % clay across all sites. P5 contained no silt (50 % sand, 50 % clay), while P3, P4, and P6 were clay-silt soils. Moisture content ranged from 6.95 % (P4) to 13.06 % (P3), with finer textures retaining more water. These characteristics are consistent with previous observations in the Copperbelt [36,37,33,38]].

Organic matter played a key role in metal retention. OM content was highest at P4 (8.1 %) and P5 (7.4 %), with corresponding OC values of 3–4.7 %, exceeding the 3 % threshold favorable for metal binding. Sites P1, P2, P3, and P6 had moderate OC levels (1.7–2.7 %). Elevated OM levels are likely linked to plant litter and organic residues, enhancing complexation of TMEs [39,40]. These values were higher than those reported in Moroccan agricultural soils [41]. Cation exchange capacity (CEC) was highest at P5 (10 meq/100 g), reflecting the combined influence of high clay and OM contents, and ranged from 6 to 9 meq/100 g at other sites. Elevated CEC enhances the retention of cationic metals and reduces their immediate mobility [36,40].

Trace metal element concentrations across the different soil samples

Metal concentrations varied considerably between sites, with Zn, Cu, and Co frequently exceeding FAO guideline values, while Cd, Pb, and Cr generally remained within acceptable limits (Table 7). Cd concentrations were consistently below 2 ppm, Cr below 150 ppm, and Pb below 100 ppm dry weight. Although Pb was overall low, slightly elevated values were recorded at P4. Cobalt concentrations reached concerning levels: P1 (29.8 ppm) and P2 (30.0 ppm) were near the critical threshold, while P3 (48.3 ppm) and P4 (60.1 ppm) exceeded recommended limits, indicating potential ecological risk. Copper contamination was more pronounced, with P1–P4 all surpassing the 100 ppm threshold (424.1, 160.4, 127.5, and 163.3 ppm, respectively). Zinc also exceeded the 300 ppm limit at P1 (560.7 ppm) and P4 (363.3 ppm). These findings highlight localized hotspots of Cu, Zn, and Co contamination, consistent with other mining-impacted soils worldwide [40,39,42,36,37,43,44,35,45].

Pearson correlation matrix

We used Pearson correlation matrix to assess the correlation between different parameters measured in this study. The values of this different correlations are shown in Fig. 2 below.

The results (Fig. 2) confirm significant contamination of Kipushi soils with several trace metals, particularly copper (Cu), zinc (Zn), cobalt (Co), lead (Pb), and cadmium (Cd). Maximum concentrations reached 424.1 mg/kg for Cu and 560.7 mg/kg for Zn at site P1, far above international thresholds [24]. These elevated levels reflect a clear anthropogenic origin, most likely related to historical and ongoing mining activities exploiting polymetallic ore deposits rich in Cu, Zn, and Pb. The mobility of these metals is strongly influenced by soil properties such as pH, organic matter (OM), cation exchange capacity (CEC), and texture. Acidic conditions ($\text{pH} \leq 5$ at P5 and P6) promote metal solubility and bioavailability, enhancing plant uptake and leaching risks. This trend is supported by correlations between pH and Cu ($r = 0.544$), Pb ($r = 0.744$), and Zn ($r = 0.799$) (Table 8), although the Zn relationship may indicate saturation from chronic contamination. Low CEC values (6–8 meq/100 g) in several samples further reduce the soils' retention capacity, increasing metal availability [36,41,3]. From a public health perspective, the detection of Cd and Pb above tolerable thresholds is particularly concerning. Cd is nephrotoxic even at low doses, while Pb is a potent neurotoxin with severe effects on children. Ecologically, excessive Cu and Zn threaten microbial activity, soil fauna, and plant productivity. These findings emphasize the urgent need for remediation measures in Kipushi to reduce human exposure and safeguard ecosystem integrity.

Contamination factor (CF) and pollution index

Fig. 3 below presents the contamination factor (CF) for trace metal elements in the different soil samples analyzed in this study.

The Fig. 4 below shows the pollution index (PI) of trace metal elements in the different soil samples studied.

The results presented in Figs. 3 and 4 show the contamination factor (CF) and the pollution index (PI) for the analyzed trace metal elements. Samples P1 and P2 exhibited considerable contamination in cadmium, with CF values ranging between 3 and 6. Sample P1 also showed high contamination in copper, while all samples displayed elevated contamination in lead and zinc, with CF values well

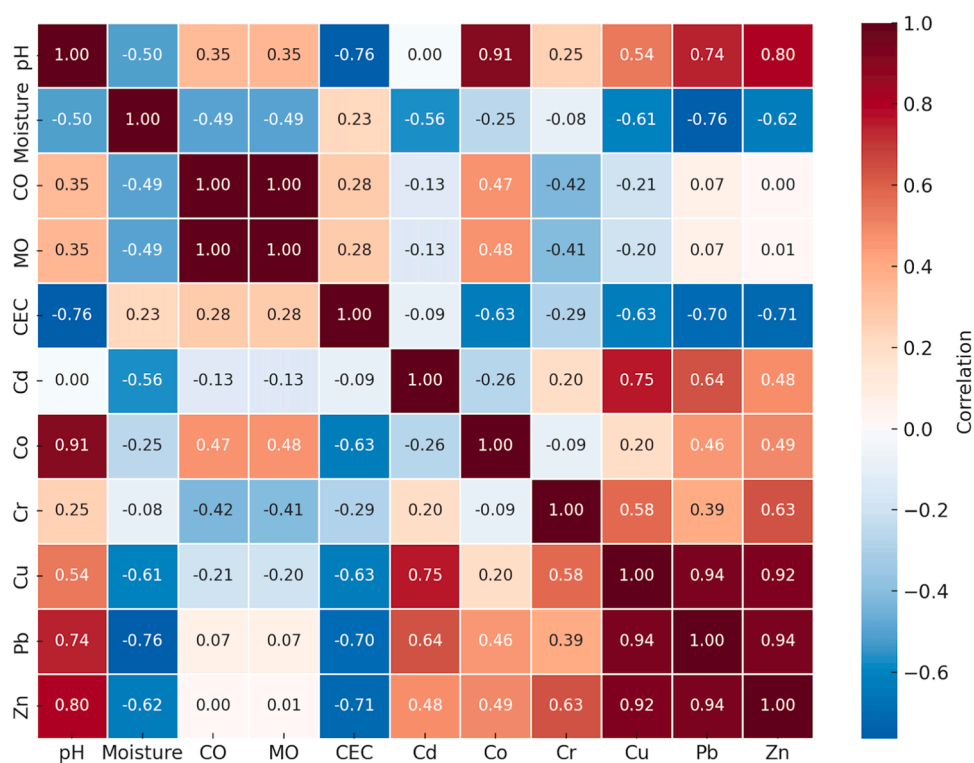


Fig. 2. Correlation matrix of soil parameters and metal.

Table 8
Potential Ecological Risk Index.

Sample	Cd	Co	Cr	Cu	Pb	Zn
P1	169,5	4,1	5,6	64,6	519	661
P2	134,1	4,15	1,6	24,4	296	160
P3	52,5	6,7	3,9	19,4	228	315
P4	59,7	8,3	3,1	24,9	388	480
P5	55,2	3,4	3,1	6,2	150	87,5
P6	55,2	1,85	3,9	3,9	92,6	23,1

above 6.

Regarding the pollution index, only sample P1 showed multi-element pollution, with a PI value greater than 1, specifically 1.31.

Enrichment factor (EF)

Fig. 5 below shows the enrichment factor (EF) for trace metal elements in the various soil samples analyzed.

The Fig. 5 illustrates the enrichment factor (EF) levels for each trace metal element (TME) in the soils from point 1 (P1) to point 6 (P6). For the following elements—cadmium, cobalt, chromium, and copper—there is no anthropogenic enrichment, as their EF values are below 1. Samples P5 and P6 also show no anthropogenic enrichment in lead, with EF values below 2, specifically 1.97 and 1.15, respectively. Sample P6, with an EF value of 1.15, is therefore considered non-anthropogenically enriched in lead. Samples P2, P3, and P4 show moderate anthropogenic enrichment in lead, whereas sample P1 exhibits significant anthropogenic enrichment in lead with an EF value of 6.48. As for zinc, sample P5 displays significant anthropogenic enrichment. Samples P2 and P3 also exhibit significant enrichment with respective EF values of 10.0 and 19.7. Sample P4 is categorized as having very strong enrichment in zinc with a value of 29.91. Only sample P1 reaches the category of extreme enrichment, with a zinc EF value of 41.22.

Geo-accumulation index (I_{geo})

Fig. 6 below shows the geo-accumulation index (I_{geo}) values for the analyzed samples.

Fig. 6 presents the geo-accumulation index (I_{geo}) values for the studied trace metal elements—namely cadmium, cobalt, chromium, copper, lead, and zinc. Soil samples from P1 to P6 were identified as uncontaminated with respect to cadmium, chromium, and

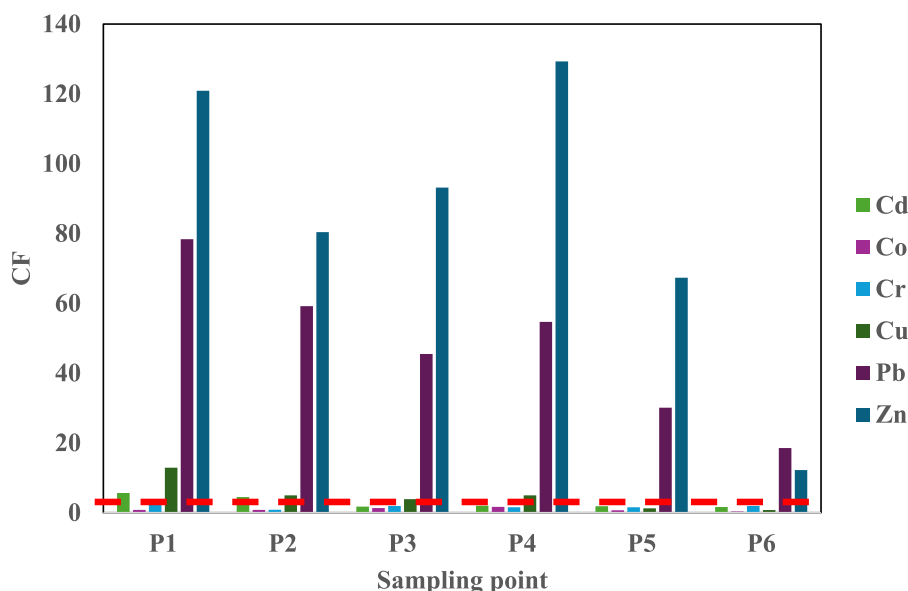


Fig. 3. Contamination factor (CF) of trace metal elements at the sampling points.

Legend: P1–P4: sites located in agricultural land and residential zones near tailings dams, P5–P6: sites adjacent to artisanal mining activities.

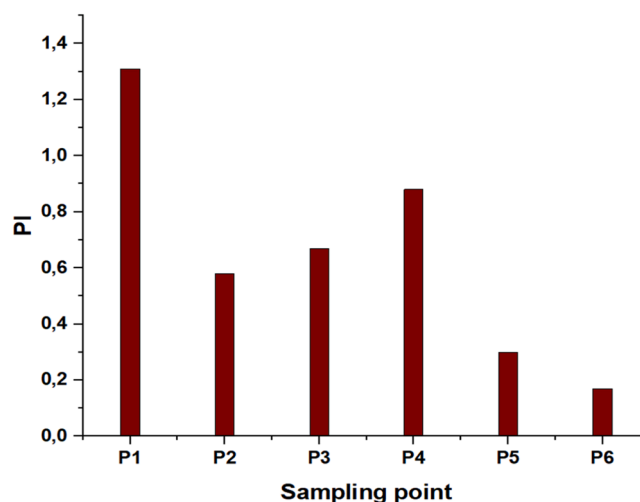


Fig. 4. Pollution Index (PI) of trace metal element in the sampling points.

Legend: P1–P4: sites located in agricultural land and residential zones near tailings dams, P5–P6: sites adjacent to artisanal mining activities.

lead, as all exhibited Igeo values ≤ 0 , placing them in Class 0. However, sample P4 was found to be extremely contaminated with cobalt, with an Igeo value of 6.49, thus falling into Class 6. Meanwhile, soil samples P1, P2, P4, and P6 were classified in Class 3, indicating moderate pollution with copper, with Igeo values above 1.2. In terms of zinc, samples P1 and P4 were identified as heavily polluted, with Igeo values greater than 3, while sample P5 showed moderate pollution levels for zinc.

Potential ecological risk index (PERI)

Table 8 below provides the calculated values of the Potential Ecological Risk Factor (Er) for each of our soil samples.

The Potential Ecological Risk Index (PERI) accurately quantifies and summarizes the risk level associated with each individual factor [46,44]. As shown in Table 8 above, the PERI values for the studied trace metal elements ranged from 1.85 to 661. A low ecological risk was observed for cobalt and chromium, with values below 9 across all samples. The same applies to copper, except for sample P1, which exhibited a high potential ecological risk associated with copper. A very high ecological risk was recorded for lead and zinc in samples P1 to P4, while sample P6 showed a moderate ecological risk from zinc. Overall, the soils from the Kipushi study area are contaminated with certain elements and present a significant ecological risk [33]. The work of Wang et al. 2020 on a

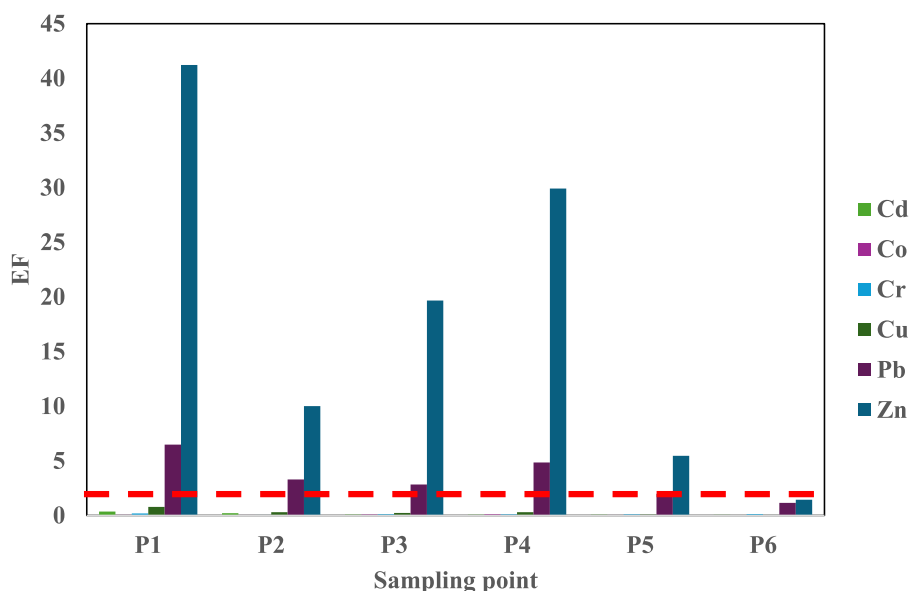


Fig. 5. Enrichment factor (EF) of trace metal element in sampling points.

Legend: P1–P4: sites located in agricultural land and residential zones near tailings dams, P5–P6: sites adjacent to artisanal mining activities.

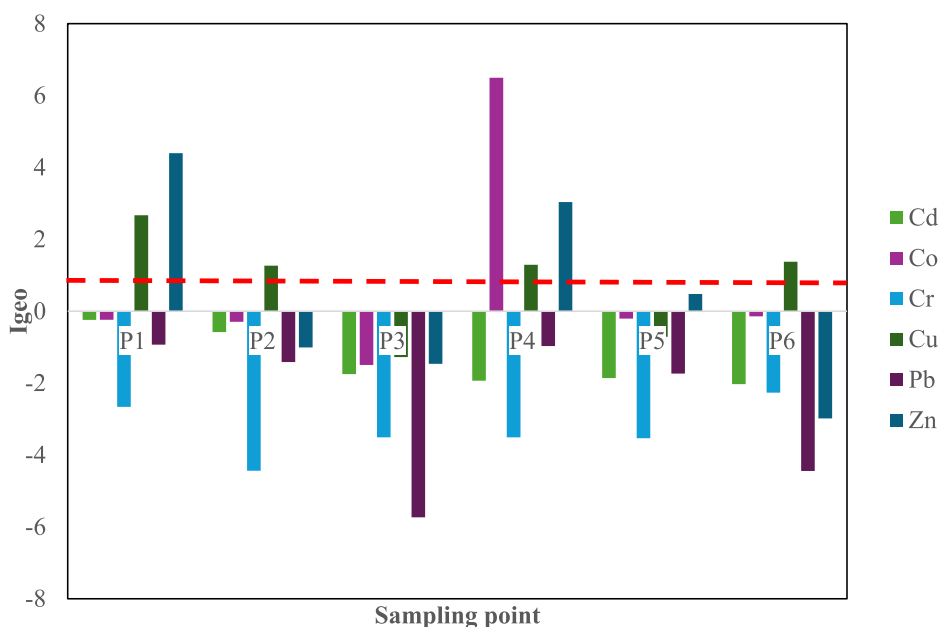


Fig. 6. Geo-accumulation Index (Igeo) of trace metal element in the sampling points.

Legend: P1–P4: sites located in agricultural land and residential zones near tailings dams, P5–P6: sites adjacent to artisanal mining activities.

geothermal site in Tibet showed high PERI values for Hg around 50 % and Cd around 30 %. Similar work was carried out in Malaysia by Boudia et al. 2024, who by adding the different elements per site found PERI values greater than 2000.

The concentrations of Cu (up to 424 mg/kg) and Zn (561 mg/kg) exceeded FAO guidelines and are comparable to, or higher than, values reported in other mining-impacted regions. For instance, Cu levels in Kipushi are greater than those reported in Lubumbashi agricultural soils (Bamba Muhaya et al., 2016) and approach those in Chinese mining zones [3]. Similarly, Pb concentrations in some sites (29 mg/kg) remain below thresholds but still pose chronic risk given their mobility. When assessed through pollution indices, EF and Igeo classified Zn and Cu as exhibiting significant to extreme enrichment at P1 and P4, confirming strong anthropogenic influence. PERI values revealed very high ecological risk for Pb and Zn, particularly at P1–P3, echoing findings from comparable sites in Ghana [30] and Tibet (Wang et al., 2020). These results highlight Kipushi as a hotspot of persistent ecological risk within the Central African

Copperbelt. From an ecotoxicological perspective, the excess of Zn and Cu threatens soil microbial activity, nutrient cycling, and plant productivity, while Pb and Cd represent long-term hazards to both ecosystems and human populations. Acidic soils further amplify these risks by promoting bioavailability and leaching potential.

Soil fractionation according to the BCR scheme

The results of soil fractionation conducted at the various sampling points using the BCR sequential extraction scheme are presented

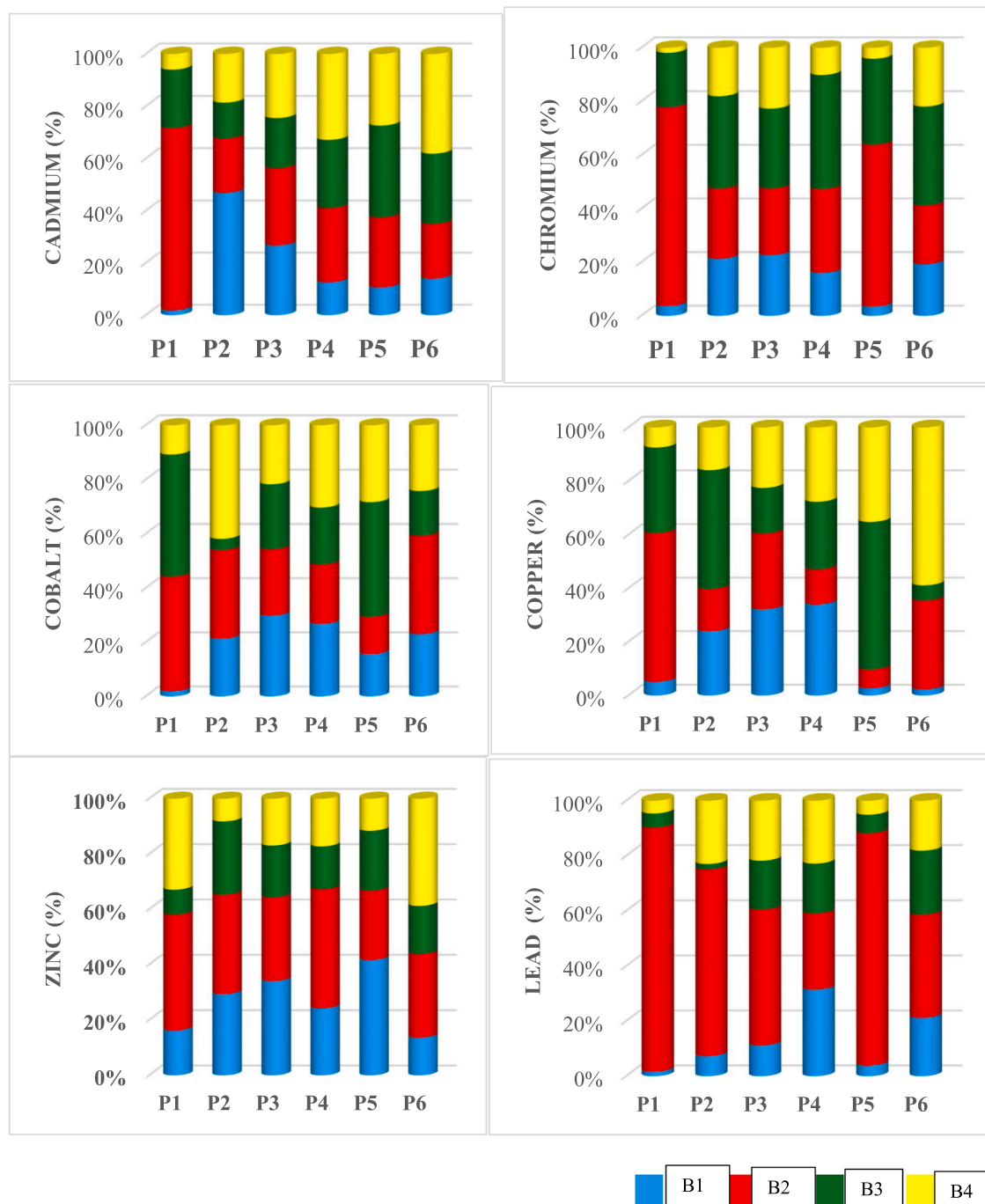


Fig. 7. Chemical distribution of Cd (a), Co (b), Cr (c), Cu (d), Pb (e), and Zn (f) in the different soil fractions (modified BCR scheme): B1 (acid-soluble), B2 (reducible), B3 (oxidizable), B4 (residual).

in Fig. 7 below. This figure shows the percentage content of the different elements extracted at each stage. The method used followed the modified BCR protocol. The corresponding operationally defined fractions were the exchangeable fraction associated with carbonates, the reducible fraction with Fe-Mn oxides, the oxidizable fraction associated with organic matter and sulfides and the residual fraction corresponding to elements strongly bound within the mineral matrix.

Soil fractionation

Operational speciation through sequential extraction quantifies trace metals in defined soil phases rather than their total content. The BCR results showed that Zn and Cd were mainly in exchangeable and reducible fractions ($F1 \pm F2 \geq 60\%$), reflecting high mobility and potential environmental risk (Fig. 6; Table 9). These forms are prone to leaching into groundwater or plant uptake, especially under acidic conditions like those at P5 and P6. In contrast, Cu and Cr were mostly associated with the residual fraction ($F4 \geq 70\%$), indicating a lithogenic origin, low short-term mobility, but long-term persistence. Cobalt was largely present in the reducible fraction at some sites (e.g., P6), linking its mobility to Fe-Mn oxides, which may release Co under reducing conditions. These patterns are consistent with established geochemical behavior: metals bound to carbonates and oxides are sensitive to pH or redox fluctuations, while residual-bound metals represent more stable pools [47].

Cadmium recovery across the BCR steps ranged from 54.5 % to 112.9 %, with the lowest in P2. Cd was concentrated in the reducible fraction, followed by oxidizable, residual, and exchangeable pools ($B2 \rightarrow B3 \rightarrow B4 \rightarrow B1$). Although the exchangeable pool represented the smallest share (2–25 %), its high solubility makes it the most phytoavailable. Chromium, Pb, and Zn showed similar distributions, with dominance in the reducible fraction. Cr accounted for 14–64 % in reducible and 16–35 % in oxidizable phases. Pb ranged from 20 to 93 % in the reducible fraction, but lower proportions ($\leq 30\%$) were observed in P4 and P6, suggesting partial stabilization in

Table 9
Trace metal element content (% of total) in the four operationally defined BCR fractions.

Sample	Exchangeable (% of total)	Reducible (% of total)	Oxidizable (% of total)	Residual (% of total)
Cadmium				
P1	2,01	78,90	25,27	6,67
P2	25,50	11,35	7,51	10,09
P3	20,01	22,23	14,38	18,32
P4	10,78	24,45	21,75	28,14
P5	8,48	21,57	28,16	21,88
P6	10,09	15,20	19,48	27,52
Chromium				
P1	3,16	63,93	17,55	1,59
P2	18,06	19,96	23,03	16,82
P3	12,34	13,63	16,23	12,34
P4	16,14	25,85	34,87	12,30
P5	3,54	62,02	32,82	4,17
P6	12,54	14,29	24,03	14,21
Cobalt				
P1	4,13	26,01	27,63	10,58
P2	12,14	18,69	7,36	23,81
P3	22,56	20,15	19,74	18,24
P4	25,12	22,45	21,89	27,12
P5	18,14	16,66	40,77	27,85
P6	18,21	28,88	13,06	19,15
Copper				
P1	4,51	49,60	28,44	6,65
P2	16,12	10,69	29,89	10,69
P3	24,43	21,93	14,34	17,98
P4	33,87	19,25	27,75	29,43
P5	2,43	6,54	50,69	32,37
P6	1,87	28,43	4,86	50,23
Lead				
P1	1,28	71,33	4,12	3,66
P2	9,38	46,02	6,18	18,83
P3	12,23	37,14	16,56	19,12
P4	22,87	20,21	13,21	16,57
P5	4,15	92,62	7,43	5,52
P6	16,51	29,29	18,17	14,10
Zinc				
P1	13,87	35,91	7,76	28,18
P2	21,80	26,78	19,77	6,09
P3	23,76	21,23	13,15	11,83
P4	19,32	34,45	12,43	13,78
P5	32,12	19,41	16,75	8,94
P6	11,45	25,57	14,79	32,76

residual pools [22,40,48–50].

For Co and Cu, the oxidizable fraction predominated (7–41 % for Co; 7–50 % for Cu), followed by reducible and residual phases (B3 → B2 → B4 → B1). This indicates strong associations with organic matter and sulfides, which may become unstable under oxidative conditions. Similar patterns have been reported in other mining soils [51,47,28].

Analysis of plants collected at soil sampling points

Table 10 below presents the total concentrations of trace metal elements in the plant samples collected from the various soil sampling sites in October 2021.

This study revealed that plant samples were not contaminated with Pb, Cd, or Zn beyond critical limits. Lead concentrations were below 1 ppm, Cd below 1 ppm (maximum 0.08 ppm), and Zn below 50 ppm, with the highest Zn value recorded at 33.7 ppm. These levels remain within permissible ranges [24,52]. Although Pb and Cd occur naturally in soils and may also derive from anthropogenic activities, their detection at low levels is encouraging, particularly since both metals are highly toxic. In contrast, studies conducted elsewhere (e.g., Malaysia) reported Pb levels in plants exceeding 100 ppm [24].

Cobalt, chromium, and copper exhibited higher accumulation across several species. *Persea americana*, *Tithonia diversifolia*, *Melissa officinalis*, and *Lanea discolor* showed elevated Co (0.22–1.64 ppm) and Cr (1–2.9 ppm) concentrations, with Cu ranging from 12 to 17 ppm. *Bamboussa vulgaris* and *Anisophilea boehmii* also accumulated Co (~0.2–0.7 ppm) and Cr (~1 ppm), but their Cu contents remained below 10 ppm, despite growing in Cu-enriched soils. These patterns suggest species-specific uptake strategies: some taxa accumulate metals efficiently (bioaccumulators), while others limit translocation (excluders) [24,52].

From a physiological perspective, Co plays a key role in nitrogen fixation processes in legumes, yet excessive levels may impair plant metabolism. In this study, Co exceeded background thresholds in all samples, suggesting both geogenic and anthropogenic contributions. Cu, although an essential micronutrient, can become toxic when foliar concentrations surpass 20–30 ppm [53]. The observed values (≤ 17 ppm) remain below this phytotoxic threshold. Chromium, however, is highly toxic to plants even at low levels, disrupting photosynthesis and nutrient uptake [54,55].

Accumulation patterns further illustrate ecological strategies: *Persea americana* efficiently absorbed Zn and Co, reflecting high soil bioavailability; *Tithonia diversifolia* showed strong Co uptake, making it a potential candidate for phytostabilization; while *Bamboussa vulgaris* demonstrated exclusion of Cu despite high soil concentrations, limiting transfer into the food chain. These results highlight the interplay between soil geochemistry and plant physiology in shaping metal uptake. They also emphasize the need for careful species selection in phytoremediation: accumulator species may support phytoextraction, whereas tolerant excluders such as *B. vulgaris* are more suitable for phytostabilization strategies [55]. Metal accumulation patterns varied across species. *Persea americana* showed high Zn and Co uptake, correlating with their high bioavailable fractions in soil. *Tithonia diversifolia* also accumulated Co efficiently, making it a potential candidate for phytostabilization in Co-contaminated sites. *Bamboussa vulgaris*, despite growing in soils with elevated Cu levels, showed limited Cu accumulation, suggesting exclusion mechanisms or poor translocation. This characteristic may be valuable for phytostabilization purposes, preventing metal entry into the food chain. These findings highlight the interplay between geochemical availability and plant-specific uptake strategies. The environmental risk increases when species that accumulate mobile metals (e.g., Zn, Cd) are used in human-consumed ecosystems or when bioavailable metals risk leaching into aquifers.

We used Pearson correlation matrix to assess the correlation between different parameters measured in this study. The values of this different correlations are shown in Fig. 8 below.

Several notable correlations were observed among heavy metals in the soil. Cadmium (Cd) was strongly correlated with zinc (Zn, $r = 0.941$) and moderately with chromium (Cr, $r = 0.597$), suggesting a common anthropogenic source or similar geochemical behavior. In contrast, no correlation was found between Cd and Pb ($r = 0.000$), indicating distinct origins or different soil-binding mechanisms. Chromium (Cr) showed moderate associations with copper (Cu, $r = 0.333$) and Zn ($r = 0.690$), pointing to potential co-contamination or shared mobility pathways. Cobalt (Co) was positively related to manganese (Mn, $r = 0.524$), reflecting a possible geochemical linkage, but negatively related to Cu ($r = -0.321$), suggesting contrasting mobility or competition for adsorption sites. Lead (Pb) did not correlate significantly with other metals ($r = 0.000$), highlighting its independent behavior in the soil environment. Finally, Cu exhibited a negative correlation with Mn ($r = -0.425$), which may reflect competition for sorption sites or differences in redox-controlled processes.

Phytoremediation potential: evaluation based on bioconcentration factors

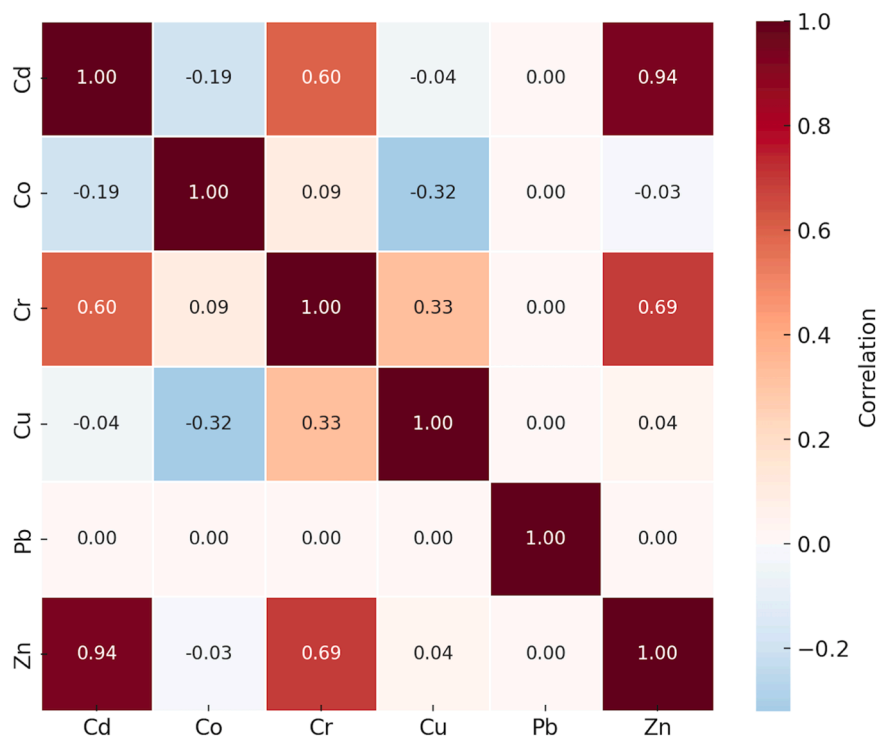
The concentrations of trace metals in the leaves of six native species were used to calculate bioconcentration factors (BCF), defined as the ratio of metal content in plant tissues to that in soils. A BCF > 1 denotes hyperaccumulation, while values between 0.1 and 1 indicate moderate uptake, relevant for phytoremediation. Among the studied species, *Persea americana* exhibited the highest multi-purpose potential, with BCFs of 0.15 for Zn, 0.11 for Cu, and 0.13 for Cd. *Lanea discolor* showed particularly strong uptake of Cu (BCF = 0.20), identifying it as a promising candidate for copper remediation. *Melissa officinalis* demonstrated efficient chromium accumulation (BCF = 0.29), a remarkable result given the low mobility of Cr in soils. In contrast, *Tithonia diversifolia* and *Anisophilea boehmii* displayed low BCF values (e.g., Zn = 0.01; Cu = 0.09 for *Tithonia*), reflecting limited uptake. Nevertheless, their tolerance to metal-rich soils suggests suitability for phytostabilization, where metals are immobilized in the rhizosphere and prevented from dispersing into the food chain or groundwater. Overall, the results indicate that certain native plants are well adapted to the contaminated soils of Kipushi and can be integrated into cost-effective ecological restoration programs. A combined approach using accumulator species for phytoextraction and tolerant species for phytostabilization would maximize phytoremediation efficiency and promote long-term

Table 10

Trace metal element content in plants.

Plant leaf sample	Trace metal element concentration in plants (mg/kg)					
	Cd	Co	Cr	Cu	Pb	Zn
<i>Persea americana</i>	0,08 ± 0,01	0,54 ± 0,02	1,56 ± 0,14	17,00 ± 1,11	ND	33,68 ± 2,23
<i>Titoria diversifolia</i>	0,02 ± 0,00	0,22 ± 0,3	1,01 ± 0,08	14,42 ± 0,99	ND	2,33 ± 0,05
<i>Melussa officialise</i>	0,02 ± 0,00	1,64 ± 0,12	2,88 ± 0,32	12,23 ± 0,87	ND	2,08 ± 0,76
<i>Lanea discolorae</i>	0,02 ± 0,00	0,37 ± 0,01	1,05 ± 0,00	32,08 ± 1,32	ND	5,08 ± 0,87
<i>Bamboussa vulgarise</i>	ND	0,65 ± 0,09	1091 ± 0,09	7,71 ± 0,78	ND	6,53 ± 0,43
<i>Anisophilea boehemi</i>	ND	0,21 ± 0,00	1,21 ± 0,07	3,25 ± 0,32	ND	5,03 ± 0,66
Standards [24]	0,01–1	0,2	0,1	10	1,0	50

Legend: ND: no detected.

**Fig. 8.** Correlation matrix of metals in plants.

recovery of degraded mining landscapes.

Conclusion

This study provides an integrated assessment of heavy metal contamination in soils and plants from the Kipushi mining area, DR Congo. The findings confirm three key outcomes: 1) Soil contamination –Concentrations of Cu, Zn, and Co frequently exceeded international thresholds, with pollution indices (CF, EF, Igeo) and PERI values indicating considerable to very high ecological risk at several sites. Sequential extraction showed that Cd, Pb, and Zn were largely bound to labile fractions, making them prone to mobilization under fluctuating redox and pH conditions. 2) Soil–plant interactions–Native plants displayed contrasting accumulation behaviors. *Persea americana* and *Melissa officinalis* demonstrated notable uptake of Zn, Cu, and Cr, suggesting potential for phytoextraction, whereas *Bamboussa vulgaris* exhibited tolerance with limited translocation, making it suitable for phytostabilization. These dual strategies highlight the feasibility of integrated phytoremediation approaches using local species. 3) Environmental and health implications –The coexistence of mobile fractions in soil and metal accumulation in edible or medicinal plants underscores risks of transfer into the food chain, with Pb and Cd posing the most critical threats. These findings call for urgent interventions to reduce exposure, including soil monitoring, controlled land use, and community awareness.

Recommendations

To mitigate ecological and human health risks, we recommend: 1) Deploying phytoremediation programs combining accumulator and stabilizer species adapted to the local environment; 2) Strengthening environmental monitoring with periodic soil and plant assessments to detect seasonal variations and prevent contamination of agricultural lands; 3) Enforcing stricter regulations on waste disposal and tailings management in mining areas; 4) Conducting further studies integrating isotopic fingerprinting and long-term ecological monitoring to better differentiate anthropogenic from lithogenic contributions.

CRediT authorship contribution statement

Jean-Noël Mputu Kanyinda: Writing - original version, formal analysis, conceptualization. **Lumière NKutu Kembisa:** Proof-reading and editing, formal analysis. **Trésor Kisimba Ngobola:** Editing and laboratory analysis. **Merveille Kongolo Masudi:** Proofreading and editing, formal analysis. **Séverine Papier:** Writing and editing, formal analysis. **Arthur Kaniki Tshamala:** Proof-reading and editing, formal analysis supervision. **Jean-Marc Baele:** Writing and supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The author is for and was not involved in the editorial review or the decision to publish this article.

The authors declare the following financial interests (e.g., any funding for the research project)/personal relationships (e.g., the author is an employee of a profitable company) which may be considered as potential competing interests:

The authors hereby declare that this work does not suffer from any conflict of interest and has not received any funding from a third party. The research was conducted by the authors' own funds.

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