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Assessment of Arsenic, Lead, Mercury and Cadmium Pollution in Soils, Sediments and Mining Residues of the Lite-Bala Site Using the GRADSOD Approach

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Abstract

This study evaluates the trace element contents (cadmium, lead, mercury and arsenic) in soils, sediments and rock residues of the artisanal gold mining site of Lite-Bala in the Democratic Republic of Congo. Random sampling, physicochemical analysis and analysis of total and soluble trace elements by ICP-OES spectrometry as well as calculations of pollution indices (FE and Igeo) and partition coefficient (kd) were carried out in two areas in the dry season and in the rainy season. The soils and sediments of the site are acidic, oxidizing, poor in organic carbon with clayey to sandy textures. Artisanal gold mining at Lite-Bala does not affect, to date, the cadmium, lead, mercury and arsenic contents of soils and sediments. On the other hand, the presence of these elements in rock residues, even in low levels, and the mechanization of this exploitation will have an impact on them in the long term; in particular for Hg used as an input and whose levels are close to the higher standard in surface soils.

Keywords

Pollution, Spectrometry, Natural Enrichment, Geoaccumulation, Pollutant Indicators, Lite-Bala

1. Introduction

The assessment of pollution by the Global Assessment of Soil Degradation

(GRADSOD) approach is based on investigations of the studied site [1] [2]. Artisanal and small-scale gold mining (ASGM) plays an important role in the global economy, particularly in developing countries [3]. However, the informal nature of this mining and the difficult access to the sites make it difficult to have quantitative, up-to-date and reliable data on the environmental and health impacts of this activity, in particular on the trace element (TE) contents of gold sites [3]-[5]. Trace elements (TE) are naturally present in gold ores but due to their toxicity, several States and agencies have agreed to monitor and limit their emissions on the site [6]-[8]. The behaviour (mobility, migration, availability) of trace elements is defined by the essential characteristics of the soils and sediments of the site, namely acidity, electron exchange capacity, organic matter content and texture [9] [10]. In the Democratic Republic of Congo (DRC), the few studies on TE contents in this ASGM gold sector have been conducted in the eastern part of the country [4]. The present study aims to quantify the cadmium (Cd), arsenic (As), lead (Pb) and mercury (Hg) contents in soils, sediments and waters of the Lite-Bala gold site in the northwest of the DRC.

2. Materials and Methods

2.1. Presentation of the Study Area

The Lite-Bala gold site is located between 3˚43'20" - 3˚48'60" north of the equator and 23˚6'00" - 23˚9'60" east of the meridian in the Nord-Ubangi province of the DRC (**Figure 1**).

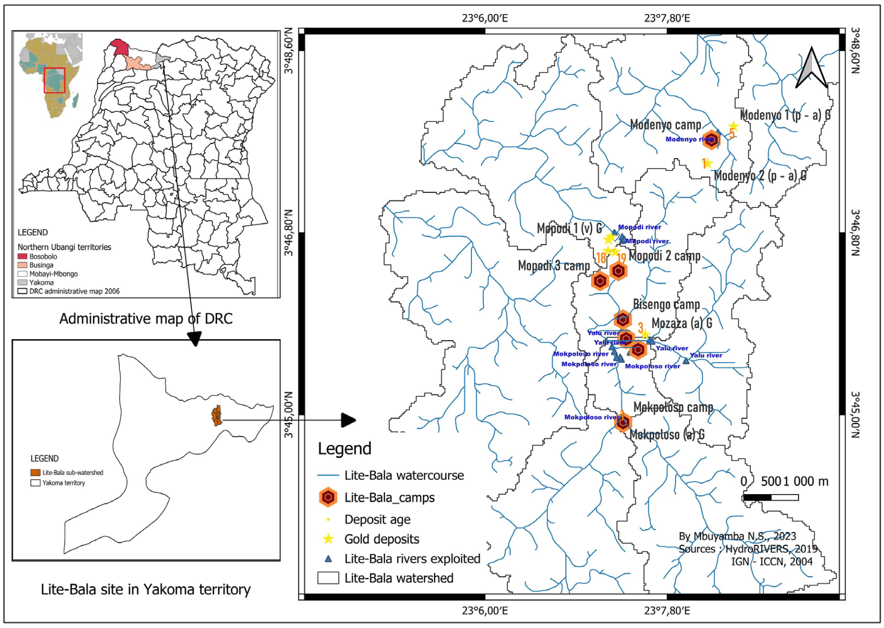


Figure 1. Location map of the Lite-Bala gold site.

The site is composed of 8 gold deposits, including two inactive (Modenyo 1 and Mokpoloso) and 6 active (Mopodi1 alluvial deposits and Mopodi 1 vein deposits, Mopodi 2 alluvial deposits and Mopodi 3 alluvial deposits, Modenyo 2 alluvial and alluvial deposits, Mokpoloso alluvial deposits) and 6 camps (Mopodi 1, Mopodi 2, Mopodi 3, Bisengo, Mozaza, Modenyo). It is covered by a warm tropical climate with a rainy season from March to October and a dry season from November to February. The annual total rainfall reaches 800 - 1600 mm, and the vegetation is dense forest [11] [12].

The relief of the site is that of the central basin of the DRC with low slopes and altitudes (350 - 700 m). The rocks of the gold site are metamorphic rocks, including schists and various sandstones. The soils have a red or yellow color characteristic of oxidation zones and belong to the Ferralsols group. The hydrographic network of the gold site is similar to that of the Congo Basin [11]-[13]. The population, estimated at around 6000 inhabitants, practices gold mining as its main activity. Cultivation (cassava and corn), livestock breeding and fishing are practiced around the site while small trade takes place there [4] [11].

2.2. Sampling

Simple random sampling was carried out at 0 - 25 cm for surface soils (SS) and 5 cm for sediments (RS) in zones 1 and 2, and stratified random sampling was carried out at 45 - 65 cm for deep soils (DS) in zone 2 using an auger during the rainy season (from 04 to 24/05/2023) and dry season (from 02 to 21/02/2024). Rock residues (RT) from mining deposits were collected in zone 1. The samples were dried and packed in plastic bags and a cooler [10] [14] [15]. The number (N) of soil samples is defined by the area of the area to be sampled (A) according to the formula N = $\sqrt{A}$ + 1 while that of sediments by the length of the river [2] [10] [16]. **Figure 2** gives the mapping of the sampling points in zones 1 and 2 on the gold site.

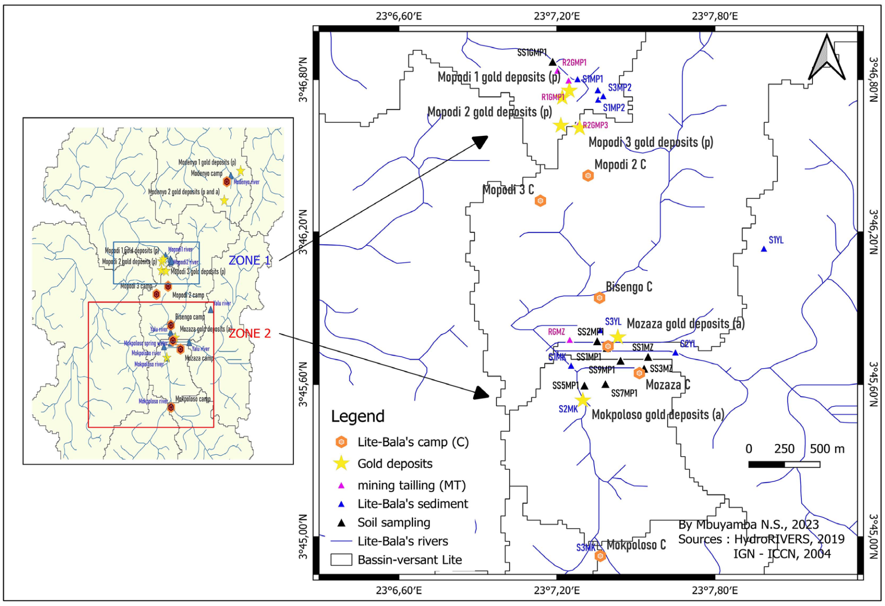


Figure 2. Mapping of sampling areas and points at the Lite-Bala site.

2.3. Soil and Sediment Analyses

2.3.1. Physicochemical Parameters

The essential parameters of soils and sediments, determined for this study, are those which directly influence mobility, sorption and desorption phenomena, the valence of cations in solution as well as the infiltration rate of water containing trace elements. In the field, the determination of acidity (pH) and redox power (Eh) was carried out with a multiparameter probe Oyster Meter, Model 341,350 A are pH (NF T 90 008) and ORP (ISO 11271: 2002) by potentiometry with an Ag/AgCl electrode, saturated in KCl (E_0 = 0.199 mV) on a soil or sediment suspension in a solid-water ratio of 1:5 (v/v) while in the laboratory, organic carbon and particle size were determined respectively by the Walkley and Black method (not standardized) and by the sedimentation method (NF P 94-057) [10] [13] [17].

2.3.2. Analyses Arsenic (As), Cadmium (Cd), Lead (Pb) and Mercury (Hg)

The soil, sediment and rock residue samples (fraction < 2 mm) were mineralized with aqua regia after grinding, heated in a water bath at 100˚C for two hours, taken up in HCl diluted water (0.1 N) then filtered and diluted before analysis by high-frequency inductively coupled plasma atomic emission spectrometry (ICP-OES) at the Laboratory of Industrial Processes, Synthesis, Environment and New Energies (LAPISEN) of the Félix Houphouët-Boigny National Polytechnic Institute of Côte d'Ivoire [8] [10] [18] [16].

The assessment of soil and sediment quality was carried out using grids and indices but also by determining the background pedogeochemical contents of soils and sediments by the "Median + 2* MAD" method (where MAD: median absolute deviation) (MM) and the "Tukey Inner Fence" (TIF) method. The anthropogenic inputs (%) due to exploitation were calculated from the EF (Equation (1)) while the pollution levels were determined using the geoaccumulation index (Igeo) (Equation (2)). The partition coefficient (kd) of ETM in soils and sediments was calculated by the ratio of total ETM ($C_{\text{ET total}}$) and soluble ETM ($C_{\text{ET soluble}}$) (Equation (3)) [8] [10] [14] [15] [19]. The different mathematical relations used are:

$$\text{FE} = \frac{\left[\dfrac{C_{\text{TE}}}{C_{\text{Normalizing element}}}\right]_{\text{sample}}}{\left[\dfrac{C_{\text{TE}}}{C_{\text{Normalizing element}}}\right]_{\text{reference}}}. \qquad \text{(Equation (1))}$$

With C_{TE} is concentration in trace element

$C_{\text{Normalizing element}}$ is concentration of normalizing element

$$\text{Igeo} = \log_2\left[\frac{C_{\text{TE sample}}}{1.5 * C_{\text{TE FPGN}}}\right] \qquad \text{(Equation (2))}$$

With FPGN the natural pedogeochemical background content

$$\text{kd} = \frac{C_{\text{TE total}}}{C_{\text{TE soluble}}} \qquad \text{(Equation (3))}$$

With kd in [L/kg], and C in mg/kg (total ET) and mg/L (soluble TE)

The different classes of FE are: FE < 2 no enrichment, 2 < FE < 5 moderate enrichment, 5 < FE < 20 significant enrichment, 20 < FE < 40 very high enrichment and FE > 40 extremely high enrichment. Those of Igeo are: Igeo < 0 substrate or no pollution, 0 < Igeo < 1 unpolluted to slightly polluted, 1 < Igeo < 2 slightly to moderately polluted, 2 < Igeo < 3 moderately polluted, 3 < Igeo < 4 moderately to heavily polluted, 4 < Igeo < 5 heavily polluted, 5 ≤ Igeo extremely polluted [14] [19]-[21].

2.4. Statistical Processing

Statistical processing of the data was carried out using R 4.3.2 and Excel 2013 software. It consisted of visualizing the data with barplots and calculating the means and medians [1] [17].

3. Results

3.1. Physico-Chemical Analyses

Figure 3 gives the acidity (pH) of the soils and sediments of the gold site.

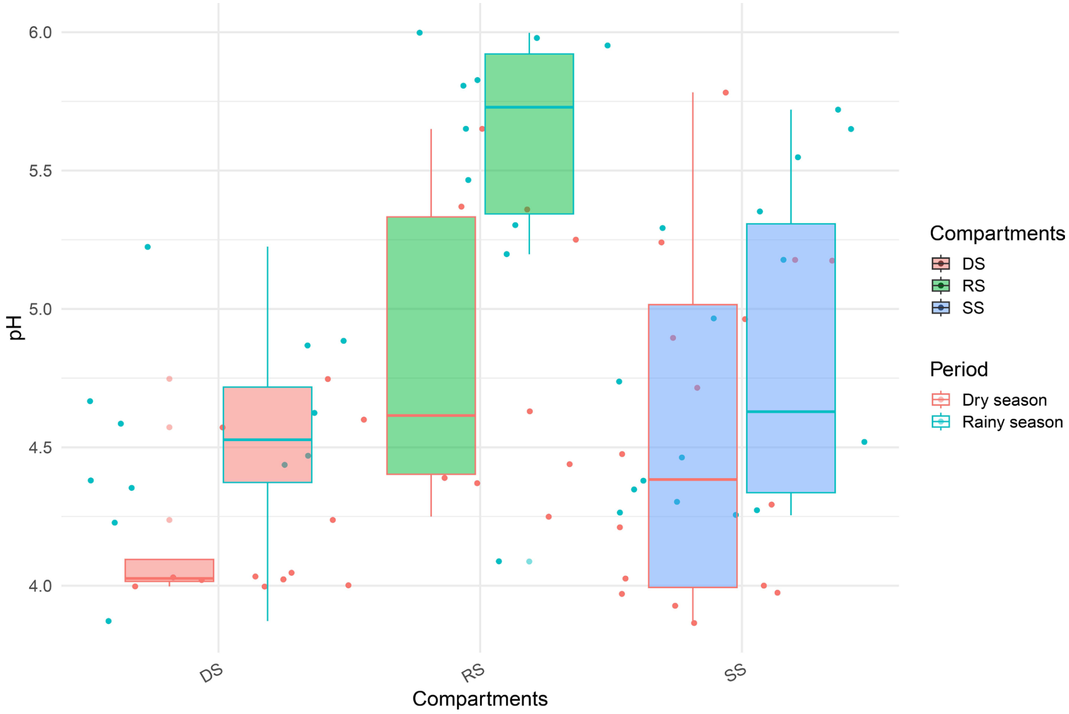


Figure 3. pH of soils and sediments at the gold site.

From **Figure 3**, it is clear that the pH of soils and sediments is between 3.86 and 5.99 with low values in the dry season, respectively 4.14 ± 0.25 for deep soils (DS), 4.54 ± 0.60 for surface soils (SS) and 4.83 ± 0.52 for sediments (RS). Furthermore, in the rainy season, the pH values are 4.55 ± 0.35 for deep soils (DS), 4.83 ± 0.55 for surface soils (SS) and 5.53 ± 0.58 for sediments (RS). **Figure 4** illustrates the redox power of soils and sediments at the Lite-Bala site.

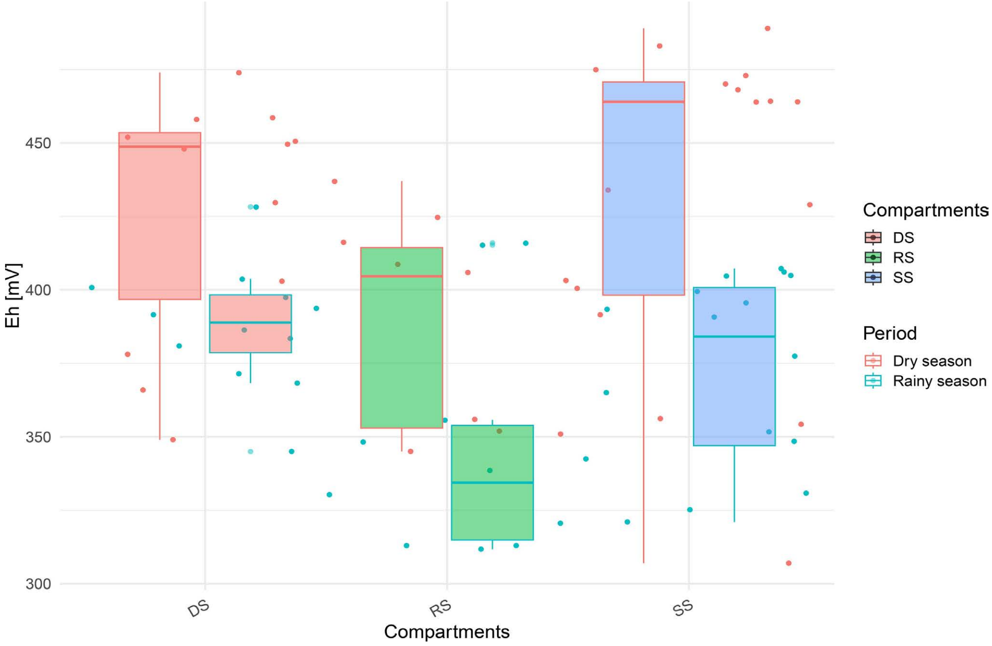


Figure 4. Redox power (Eh) of soils and sediments from the Lite-Bala site.

This figure shows that the redox power varies, overall, between 216.36 and 576.63 mV with an average of 426.35 ± 41.64 and 387.58 ± 20.78 mV for deep soils (DS), 432.67 ± 54.93 and 372.78 ± 31.70 mV for surface soils (SS), and finally 390.00 ± 35.02 and 346.23 ± 39.58 mV for sediments (RS) respectively in the dry season and in the rainy season. The redox potentials in the dry season are higher than in the rainy season. **Figure 5** shows the organic carbon contents of the soils and sediments of the Lite-Bala site.

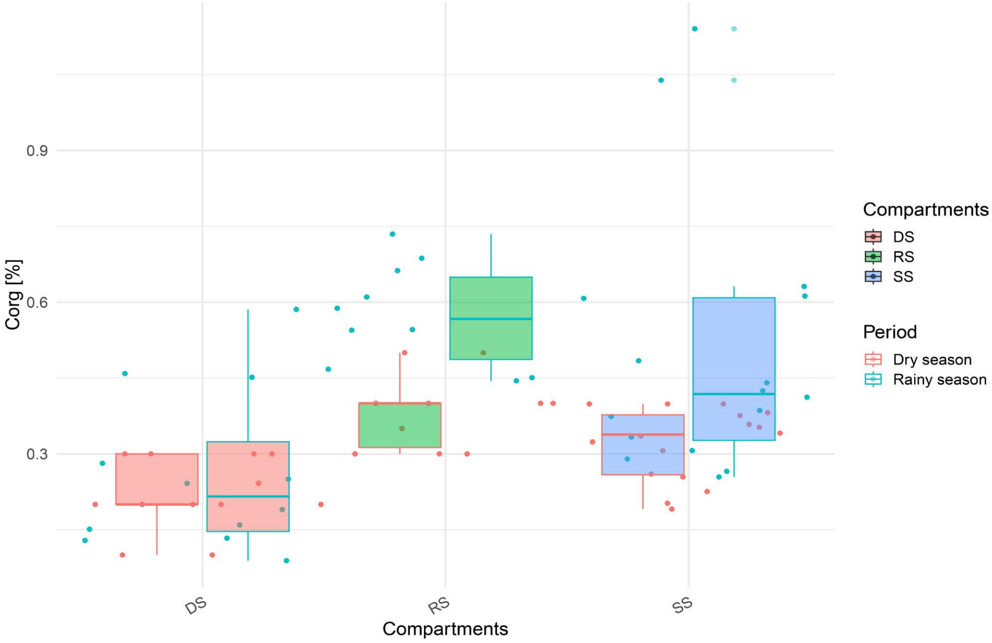
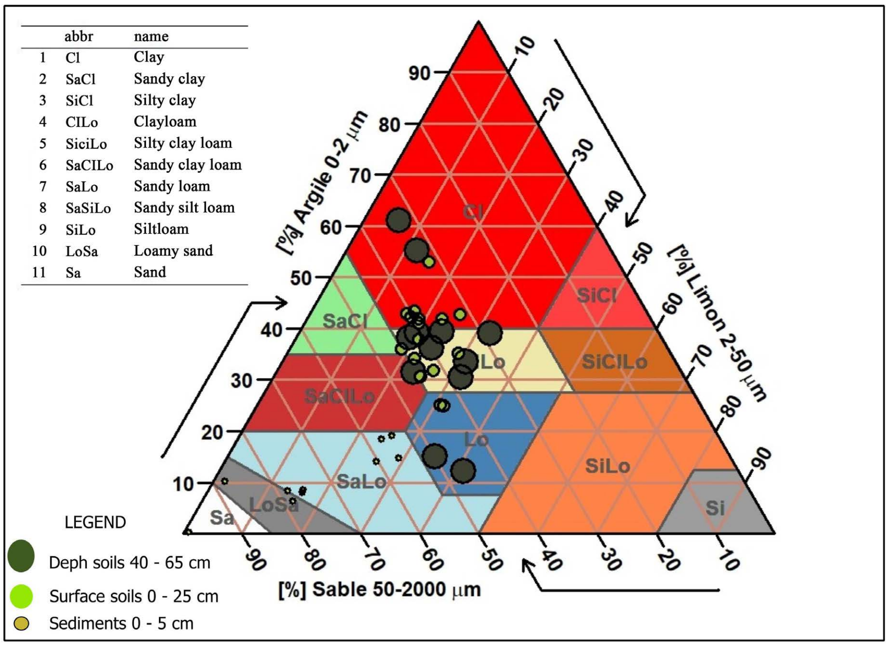


Figure 5. Organic carbon contents of soils and sediments at the Lite-Bala site.

The figure above reveals that the organic carbon contents of soils and sediments are between 0.11% and 0.80%. Deep soils display contents ranging from 0.22% ± 0.07% in the dry season and 0.26% ± 0.16% in the rainy season while surface soils (SS) have contents oscillating around 0.32% ± 0.07% in the dry season and 0.50% ± 0.26% in the rainy season. As for sediments, they have an average organic carbon (Corg) of 0.39% ± 0.07% in the dry season and 0.57% ± 0.10% in the rainy season. Corg contents are high in the rainy season than in the dry season and higher in sediments (RS). Figure 6 gives the texture of soils and sediments of the Lite-Bala site.



	abbr	name
1	Cl	Clay
2	SaCl	Sandy clay
3	SiCl	Silty clay
4	CILo	Clayloam
5	SiciLo	Silty clay loam
6	SaCILo	Sandy clay loam
7	SaLo	Sandy loam
8	SaSiLo	Sandy silt loam
9	SiLo	Siltloam
10	LoSa	Loamy sand
11	Sa	Sand

Figure 6. Textural diagram of Lite-Bala soils and sediments.

This figure indicates that the dominant texture for deep soils and surface soils is the silt-clay texture while for sediments, the texture is sand-silt and silt-sand.

3.2. Traces Element Analyses

Distribution of cadmium, lead, mercury and arsenic in soils, sediments and rock residues

Figure 7 shows the proportions of cadmium (Cd), lead (Pb), mercury (Hg) and arsenic (As) in soils, sediments and rock residues.

This figure shows that arsenic (As) levels are high in surface soils (SS) and in mine tailings (MT), cadmium (Cd) levels in mine tailings (MT) and in sediments (RS), mercury (Hg) levels are high in surface soils (SS) and finally, lead (Pb) levels in deep soils (DS).

Cadmium, lead, mercury and arsenic contents in the different compartments studied

Figure 8 gives the cadmium (Cd), lead (Pb), mercury (Hg) and arsenic (As) contents in the different mining residues of the Mopodi 3 deposit (GMP3) and the Mopodi 1 deposit (GMP1) of zone 1.

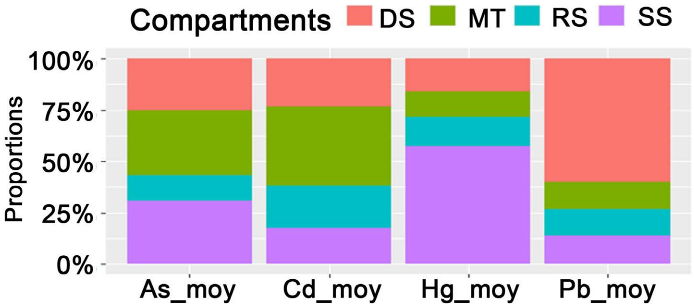


Figure 7. Distribution of TEs in Lite-Bala compartments.

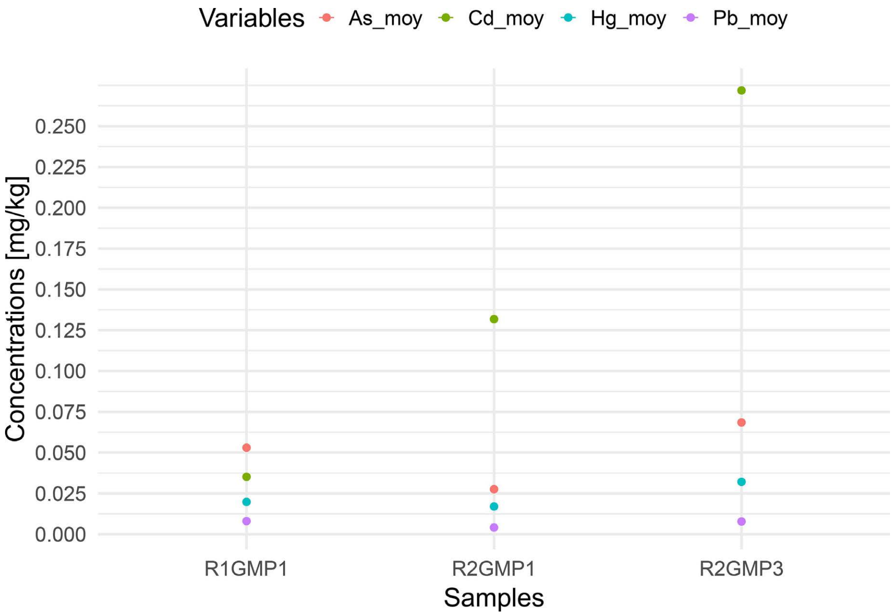


Figure 8. Hg, As, Cd and Pb contents in mining residues from deposits.

Figure 8 shows that the tailings from Mopodi 3 deposits (RGMP3) have elevated levels of arsenic (As) (0.069 mg/kg), cadmium (Cd) (0.272 mg/kg), mercury (Hg) (0.032 mg/kg) and lead (Pb) (0.008 mg/kg) compared to the tailings from Mopodi 1 deposits (RGMP1). Cadmium is the most abundant element in the tailings with an average of 0.1463 mg/kg. **Figure 9** shows the levels of cadmium (Cd), lead (Pb), mercury (Hg) and arsenic (As) in soils, sediments and rock tailings from zone 1 and zone 2 of the Lite-Bala gold site.

It should be noted that the high levels in zone 1 are those of cadmium (Cd) with respectively 0.1463 ± 0.1190 mg/kg in mining residues (MT), 0.0894 ± 0.0011 mg/kg in sediments (RS) and 0.0808 ± 0.0197 mg/kg in surface soils (SS) while in zone 2, the cadmium (Cd) levels are notable for deep soils (DS) and sediments with respectively 0.0885 ± 0.0304 mg/kg and 0.0782 ± 0.0610 mg/kg. Surface soils in zone 2 have high mercury levels (0.1380 ± 0.1093 mg/kg).

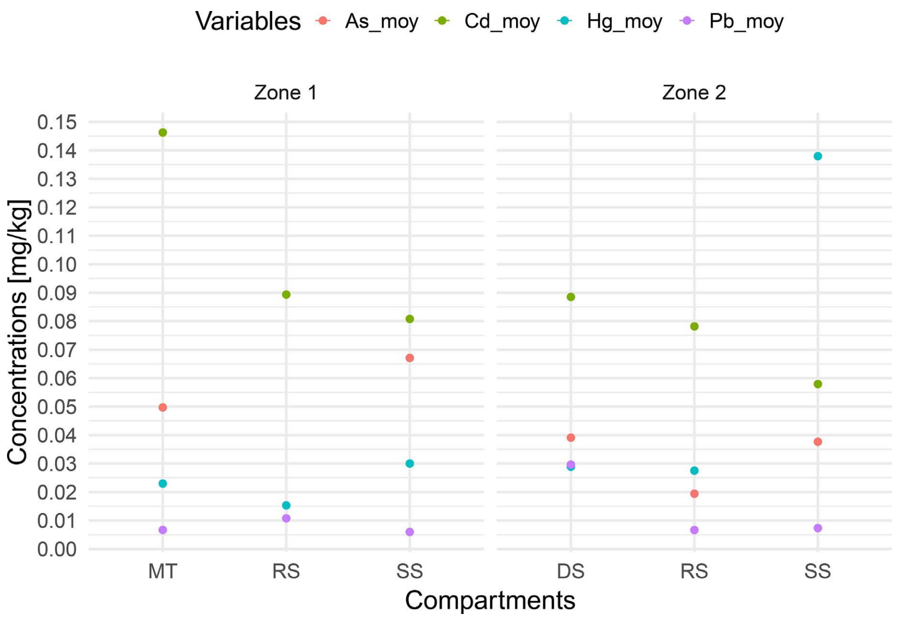


Figure 9. As, Hg, Pb and Cd contents of soils, sediments and residues.

3.3. Background Pedogeochemical Contents of Cadmium, Lead, Mercury and Arsenic in Lite-Bala Soils

Table 1 reveals the background pedogeochemical content of the soils at the Lite-Bala site.

Table 1. Pedogeochemical background content of soils at the Lite-Bala site.

ETM (DS)	Min.	1st quartile	median	Avg.	3rd quartile	Max.	Standard deviation	MAD	**TIF**	**MM**	**FGN (CUC)**
Hg	0.0038	0.0195	0.0305	0.0289	0.0342	0.0605	0.0176	0.0139	0.05625	0.0583	0.02 - 0.1
Cd	0.0298	0.0782	0.0974	0.0885	0.1081	0.1197	0.0304	0.0206	0.15295	0.1386	0.05 - 0.47
As	0.0155	0.0262	0.0342	0.0391	0.0525	0.0671	0.0207	0.0271	0.09195	0.0884	1 - 25
Pb	0.0006	0.0032	0.0046	0.0296	0.0094	0.1543	0.0612	0.0042	0.0187	0.013	9 - 50

This table shows that the basic pedogeochemical contents of Lite-Bala soils are within the range of mercury (Hg) and cadmium (Cd) contents of the upper continental crust (UCC) reference material but have lower values for lead (Pb) and arsenic (As). Table 2 shows the linear regression of iron (Fe) and aluminum (Al) with cadmium (Cd), lead (Pb), mercury (Hg) and arsenic (As).

Table 2. Linear regression of Al and Fe with Hg, Cd, Ps and As.

	Al		Fe	
ETM	r^2	p-value	r^2	p-value
Hg	0.0041	0.782	0.049	0.335
Cd	0.0013	0.877	0.4666	**0.0009**
Pb	0.074	0.2749	0.3312	**0.0124**
As	0.1289	0.1569	0.0736	0.2921

The p-value in this table shows that there is an acceptable correlation between cadmium (Cd), lead (Pb), mercury (Hg) and arsenic (As) with iron (Fe) as well as with aluminum (Al). Therefore, iron (Fe) was used as the normalizing element.

3.4. Enrichment Factor for Cadmium, Lead, Mercury and Arsenic

Table 3 gives the enrichment factors for cadmium (Cd), lead (Pb), mercury (Hg) and arsenic (As) in soils and sediments from the gold site.

Table 3. Enrichment factors (EF) of ETMs from Lite-Bala soils and sediments.

SAMPLES	As	Hg	Pb	Cd
SS1MP1	nd	72.51	nd	5.45
SS2MP1	nd	0.62	nd	nd
SS5MP1	1.11	1.92	0.52	0.70
SS5MP1	nd	1.77	1:15 p.m.	0.94
SS7MP1	2.44	0.81	0.04	0.56
SS9MP1	1.39	0.99	6.57	0.78
SS1MZ	1.25	1.63	3.12	0.65
SS3MZ	0.60	1.05	2.70	1.00
SS3MZ	nd	1.15	2.20	0.58
SS1GMP1	0.73	2.17	0.25	0.74
SS2GMP1	1.26	0.64	nd	0.83
SS1GMP3	nd	0.47	2.40	1.13
SS2GMP3	9:30 a.m.	1.31	0.04	0.95
S1YL	0.43	2.08	2.93	1.39
S2YL	nd	0.65	nd	1.03
S2YL	nd	2.93	21.04	1.33
S3YL	nd	1.19	14.75	1.36
S1MK	2.24	0.73	nd	0.64
S2MK	0.41	1.75	1.92	1.20
S3MK	nd	1.99	−0.21	1.00
S1MP2	nd	1.58	0.39	1.18

This table shows that 79% of FE values are below 2, 13% between 2 and 5, 7% between 5 and 20 and finally less than 1% above 40. Sediments S1YL and S3MK are local control samples taken respectively at 1048 m and 1154 m from zone 2. The ETM enrichment studied is natural (substrate), with the exception of Pb in sediments (S2YL and S3YL) and As in soils of the Mopodi 3 deposit (SS2GMP3). Table 4 presents the contributions of cadmium (Cd), lead (Pb), mercury (Hg) and arsenic (As) related to artisanal gold mining compared to the local pedogeochemical background of Lite-Bala.

Table 4. Inputs of cadmium, lead, mercury and arsenic from artisanal gold mining into soils and sediments.

SAMPLES	**As**	**Hg**	**Pb**	**Cd**
SS1MP1	nd	98.62	nd	81.64
SS2MP1	nd	nd	nd	nd
SS5MP1	9.95	47.92	nd	nd
SS5MP1	nd	43.46	92.39	nd
SS7MP1	58.98	nd	nd	nd
SS9MP1	27.86	nd	84.77	nd
	32.26	**63.34**	**88.58**	**81.64**
SS1MZ	19.92	38.53	67.93	nd
SS3MZ	nd	4.95	63.03	nd
SS3MZ	nd	13.28	54.48	nd
	19.92	18.92	**61.82**	nd
SS1GMP1	nd	53.94	nd	nd
SS2GMP1	20.64	nd	nd	nd
SS1GMP3	nd	nd	58.25	11:30 a.m.
SS2GMP3	89.25	23.38	nd	nd
	54.95	38.66	**58.25**	11:30 a.m.
S1YL	nd	52.00	65.91	28.16
S2YL	nd	nd	nd	2.46
S2YL	nd	65.81	95.25	24.85
S3YL	nd	15.68	93.22	26.58
S1MK	55.45	nd	nd	nd
S2MK	nd	42.74	48.03	16.88
S3MK	nd	49.64	nd	0.27
S1MP2	nd	36.53	nd	15.54
	55.45	43.73	**75.60**	16.39

This table shows that the contributions of lead (Pb) are significant for most of the soil samples (Mopodi 1 and Mozaza camps noted respectively MP1 and MZ, Mopodi 3 deposits noted MP3) as well as in the river sediments (Yalu and Mokpoloso whose codes are YL and MK). Arsenic shows a slight increase in the surface soils of the deposits (SSGMP1-SSGMP3) of zone 1 while Hg shows an increase in the surface soils of Mopodi 1 of zone 2 (SSMP1) compared to the pedogeochemical background contents of Lite-Bala.

3.5. Geoaccumulation Index (Igeo) of Cadmium, Lead, Mercury and Arsenic

Table 5 illustrates the level of pollution (Igeo) of soils and sediments in cadmium (Cd), lead (Pb), mercury (Hg) and arsenic (As) of the gold site.

Table 5. Pollution level (Igeo) in Cd, Hg, Pb and As of soils and sediments.

SAMPLES	**As**	**Hg**	**Pb**	**Cd**
SS1MP1	nd	3.59	nd	−0.14
SS2MP1	nd	−3.37	nd	nd
SS2MP1	nd	−3.37	nd	nd
SS5MP1	−0.08	0.71	−1.17	−0.74
SS5MP1	nd	−0.12	2.77	−1.03
SS7MP1	−0.20	−1.80	−6.08	−2.33
SS9MP1	−1.29	−1.77	0.96	−2.11
	nd	nd		
SS1MZ	−1.58	−1.20	−0.26	−2.53
SS3MZ		−0.87	0.06	−1.85
SS3MZ	−1.69	−0.89	0.47	−0.96
	−1.64	−0.99	0.09	−1.78
SS1GMP1	0.36	1.93	−1.19	0.38
SS2GMP1	0.42	−0.56		−0.18
SS1GMP3		−2.15	0.22	−0.87
SS2GMP3	2.08	−0.75	−5.64	−1.21
S1YL	−3.60	−1.32	−0.83	−1.91
S2YL		−1.71		−1.06
S2YL		−0.08	2.77	−1.22
S3YL		−0.58	3.06	−0.38
S1MK	−0.22	−1.84		−2.03
S2MK	−1.04	1.04	1.18	0.51
S3MK		−0.44		−1.43
S1MP2		1.41	−0.60	1.00

Table 5 shows that 72% of the Igeo index values are below zero, 15% are between 0 and 1 and 6% are between 1 and 2. These values indicate that there is virtually no anthropogenic pollution on the site.

3.6. Partition Coefficient (kd) of Cadmium, Lead, Mercury and Arsenic

Table 6 gives the decimal logarithm of the partition coefficient of each trace element between the solid phase and the dissolved phase of each compartment.

Table 6. Partition coefficient (kd) of cadmium (Cd), lead (Pb), mercury (Hg) and arsenic (As) between the solid phase and the liquid phase (log kd).

Compartments	Samples	Hg	As	Cd	Pb
SS	SS1MP1	nd	nd	6.61	nd
SS	SS2MP1	3.33	nd	nd	nd
SS	SS3MZ	7.49	nd	9.50	1.62
SS	SS5MP1	nd	nd	nd	1.23
SS	SS5MP1	5.29	nd	7.37	3.61
SS	SS7MP1	nd	3.61	7.11	1.26
SS	SS9MP1	nd	4.34	7.24	3.69
SS	SS1MZ	5.66	nd	7.53	2.51
SS	SS3MZ	4.15	4.36	nd	3.28
		5.44	3.98	7.56	2.32
SS	SS1GMP3	nd	nd	nd	2.84
SS	SS2GMP3	nd	5.95	8.34	3.97
SS	SS1GMP1	nd	nd	8.33	1.35
SS	SS2GMP1	4.49	nd	7.08	1.48
		4.32	5.16	7.92	2.59
RS	S2MK	nd	3.45	nd	3.52
RS	S2YL	4.99	4.23	7.37	0.96
RS	S3YL	nd	nd	8:45 a.m.	1.99
RS	S1YL	nd	nd	9.48	2.53
RS	S2YL	5.46	nd	6.87	0.71
RS	S1MK	3.65	nd	7.16	nd
RS	S3MK	nd	nd	nd	nd
RS	S1MP2	nd	nd	nd	3.83
		4.70	3.84	7.86	2.26

This table shows overall that cadmium (Cd) with respective log coefficients of 7.56, 7.92 and 7.86 in the surface soils of the camps and deposits and in the sediments, is the most immobile of the four trace elements studied while lead (Pb) is the most mobile with respective log coefficients of 2.32, 2.59 and 3.83.

3.7. Analysis of the Principal Components of the Total Extractable Contents of Cadmium, Lead, Mercury and Arsenic

Figure 10 shows the level of correlation between pseudo-total cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As) and gold (Au) contents and the similarities between surface soil (SS) and river sediment (RS) samples.

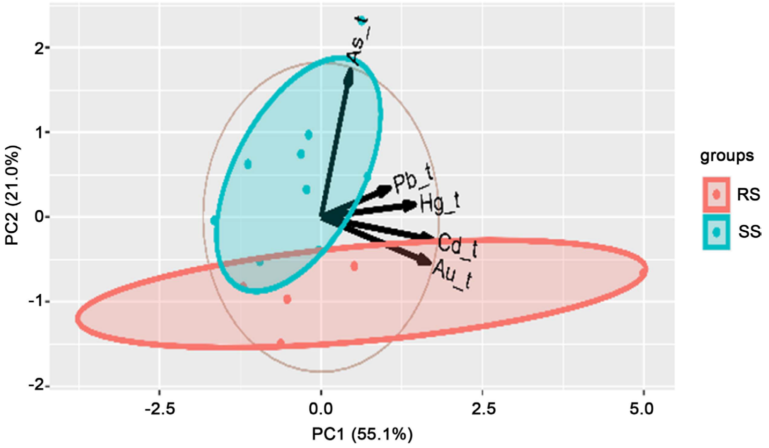


Figure 10. Correlation circle between Cd, Hg, Pb, As and Au at Lite-Bala.

This figure shows a strong correlation between cadmium (Cd) and gold (Au) levels. Surface soil samples have high levels of cadmium, while river sediments have high levels of both cadmium and gold. The total inertia rate of 76.1% indicates that this information is reliable.

4. Discussion

Several scientific studies indicate that the soils of the Lite-Bala gold site, located in a humid tropical zone, belong to the group of ferralsols, acidic soils (pH ~ 4.5), characterized by low mineralization and rich in kaolinite. The rocks most present on the site are schists and/or sandstones with little or no metamorphosis [12] [13] [22] as illustrated in **Figures 1-3**. In addition, several authors affirm that the geomorphological, geological, human and climatic characteristics of the site are important in the formation of soils (composition and physicochemical structure), in the mobility and migration of trace elements (distribution) and in the process of spreading pollution on a site [2] [13] [22]-[24]. In addition, the use of random sampling allows for the acquisition of data on the contamination or pollution of a site in the absence of previous data or in the absence of sufficient data [1] [2] (**Figure 2**). The trace element content results are directly related to the nature of the bedrock that has undergone degradation under the climatic conditions of the site. Some authors also argue that over time, soils tend to become more acidic following the leaching of rainwater and the contribution of acidic materials and other oxides [17] [18] [24]. The geomorphological characteristics listed in the site presentation indicate that the Lite-Bala soils, located in the tropical humic zone (**Figure 1**), are acidic, poorly mineralized and have low cation exchange capacities.

This study shows that Lite-Bala soils have pH and organic carbon values close to those of soils from a former gold mine in Sumbawa, Indonesia (pH: 4.25 - 5.53 and OM: 0.95% - 1.75%) [10], soils from mining sites in the Yimiougou village in Burkina Faso (pH: 4.62 - 5.54 and OM: 0.7% - 0.94%) [20] and soils from some gold mining sites on the Adamawa Plateau in Cameroon (pH: 4.25 - 5.53 and OM: 0.95% - 2.05%) [25]. Furthermore, Lite-Bala sediments display a more acidic character than sediments from the Gankombol gold site in Cameroon (5.73 - 7.63) [26]. In addition, several authors have demonstrated that in the humic tropical zone, ferruginous soils of red or reddish yellow color generally have an oxidizing character with high redox power values [1] [13] [20] (**Figure 3** and **Figure 5**). The geographical position and the redox potential values obtained confirm the oxidizing character of the soils of the Lite-Bala site (**Figure 4**) as reported by these cited authors.

Several authors have also demonstrated the role of texture in the mobility of trace elements. For these authors, a clayey texture has a negative influence on the circulation of seepage water containing these elements [10] [27]. The clayey texture of the soils and the sandy-loam texture of the sediments at the Lite-Bala site (**Figure 6**) correspond respectively to a permeability (K) $< 4 \times 10^{-5}$ m/s and to a permeability $6 \times 10^{-5} < K < 2 \times 10^{-4}$ m/s) according to the texture triangle establishing the correlation between texture and permeability [2]. The texture of Lite-Bala soils reduces the migration of trace elements from the surface to depth, as is the case for Yimiougou soils in Burkina Faso (Clays: 19.72% - 49.12%, Silts: 25.32% - 53.96% and Sand: 25.03% - 39.36%) [20], compared with the more permeable silty texture of soils from the former Sumbawa gold mine in Indonesia (clays: 18%, silts: 39% and sand: 41%) [10]. The mobility of trace elements in the solution of Lite-Bala sediments is significant in relation to the permeability value.

As for the metallic trace elements that are the subject of this study, several studies have shown that they are naturally present in all environmental compartments, particularly in soils, sediments and rock residues at different levels depending on the geological, geomorphological, climatic and hydrographical characteristics of each site, as shown in **Figures 7-9**. Naturally, according to some authors, the geological context of sediments and the pedogeochemical context of soils in trace elements constitute the geochemical signatures of these compartments which, in the case of sediments, derive from soils, and the soils themselves from the parent rock. However, in environments subject to high anthropogenic pressure, such as mining sites, the recycling processes for trace elements are severely disrupted, leading to an accumulation of trace elements. [1] [10] [17] [21] [22]. In addition, total ET levels have been widely used to assess soil and sediment pollution. In fact, natural ET levels in various environmental compartments, known as geochemical or pedogeochemical background levels, are low, as shown in **Table 1**, and are generally added to trace metals of anthropogenic origin. However, only the fraction that is soluble or extractable by water can pose a risk to human health and the environment [8].

Under Lite-Bala conditions, the decreasing order of ET contents is Hg > As > Cd > Pb for soils, then Cd > Pb > As > Hg for sediments, and finally Cd > As > Hg > Pb for residues (**Figure 8** and **Figure 9**). The background pedogeochemical contents of Lite-Bala soils are in agreement with the contents of reference soils (UCC) for mercury and cadmium. The levels of trace elements in the soil and sediment are low compared to the levels of arsenic (90 - 110 mg/kg) and lead (40

- 50 mg/kg) at the Yimiougou site in Burkina Faso [20] and the levels of arsenic (2 - 7.04 mg/kg), cadmium (0.04 - 0.30 mg/kg) and lead (9.74 - 26.24 mg/kg) at the Sumbawa site in Indonesia [10].

Studies of soils, sediments, and dust from artisanal gold mining sites in Butuzi, South Kivu, and Some, Ituri, eastern DRC, show that pedogeochemical background mercury (Hg) concentrations in Lite-Bala soils are lower than those found in deep soils (10 - 20 cm) in the South Kivu region (0.018 - 0.34 mg/kg) and Butuzi, but closer to those in Some (~0.1 mg/kg) in Ituri. Mercury concentrations in Lite-Bala sediments (0.026 ± 0.004 mg/kg) are also lower than those in Luzinzi River (Butuzi) sediments (0.064 - 0.091 mg/kg) and Some streams (0.3 mg/kg). Arsenic (As) concentrations in the waters of the Luzinzi River are also high (3.1 - 572 mg/L) [7]. In addition, at Some, Hg levels in mining waste and sediments are very high, >6 mg/kg and >5 mg/kg respectively, and Arsenic levels are also high in gold tailings (>310 mg/kg) compared to those in Lite-Bala tailings (0.0497 mg/kg). The Lite-Bala gold site has very low pollution compared to artisanal sites in eastern DRC [5] [28]. This low pollution is corroborated by the low values of the enrichment factor and the geoaccumulation index (**Tables 3-5**) as suggested by some authors [14] [15] [19] [21].

As for the choice of the normalizing element, several authors have shown that the major elements (Fe Al and Mn) released during the alteration of the parent rock form stable oxides, hydroxides and hydro-oxides depending on the environmental conditions. These trap particles affect the ETs contents on the site by adsorption depending on the specificities of each site (physicochemical and biological conditions, climatic, topographical conditions). Indeed, some authors have noted that the high contents of Fe and Mn oxidize the trace metal elements favoring their adsorption on the trap particles [1] [8] [10].

Other authors have shown that the correlation between major element contents and ET varies from site to site. Linear regression and correlation test identify the major element most correlated with ETs. The low p-values for iron (Fe) in **Table 2** (0.0009 and 0.0124) indicate that it is better correlated with ET at the Lite-Bala site. It was therefore chosen as a normalizing element for the calculation of pollution indices (Igeo and FC) [1] [14] [17] [19]. To differentiate natural from anthropogenic contributions and assess the intensity of contamination independently of the granulometry and mineralogy of the sites, several authors use the enrichment factor (EF) and the geoaccumulation index (Igeo) to measure the degree of metal pollution. Indeed, as indicated above, ET contents depend on several site parameters [1] [14] [17] [19]. In the case of the Lite-Bala site, the high percentage of the enrichment factor (EF) class is less than 2 (70%) and the geoaccumulation index (Igeo) less than 0 (~75%) (**Tables 3-5**) demonstrates an absence of pollution in these elements to date.

The parameters used to assess the level and origin of pollution (Igeo and FE) make it possible to minimize differences in soil granulometry or texture, and to take into account the geochemical or pedogeochemical background of each site

[8] [14] [20] [21]. Thus, the values of the geoaccumulation indices and enrichment factors for the Lite-Bala soils and sediments are of the same order of magnitude as the geoaccumulation indices and enrichment factors for the discharges from the Kombo-Laka mining site in Cameroon and the Yimiougou mining site in Burkina Faso, respectively −0.40 - 3.93 for arsenic, −1.91 - 0.55 for cadmium and −1.43 - 0.04 for lead for Igeo, and −1.42 - 10.54, 0.33 - 4.79 and 0.47 - 4.62 for FE on the first site [25], and Igeo varying between −0.48 and −0.18 for cadmium, between 1.30 and 1.54 for Pb but slightly high for arsenic (1.63 and 1.69) at the second site [20]. The Igeo values for mercury at the Lite-Bala site, indicating the absence of pollution, are close to the values found for soils at a mining site in the town of Darmali in Sudan (~66% Igeo < 0, 17% Igeo < 1 and 17% < 2) in comparison with several gold mining sites [8] [18] [23] [29].

Several authors demonstrate that in the case of soils and river sediments contaminated by ETs, the risk of dispersion of the latter in the environment is indicated by the affinity of each ET for the solid phase (kd). Several authors provide information on an order of affinity of ETs for the solid phase, in contaminated soils, which varies with the characteristics of the soil. The order of content and affinity of trace elements depends on the bedrock and the physico-chemical characteristics of the site studied [10] [17]-[19]. In the case of soils and sediments from the Lite-Bala gold site, where ET levels are low, the order of affinity is Cd > Hg > As > Pb (**Table 6**).

In summary, Lite-Bala soils, acidic and low in organic carbon, are less adsorbent and contain few trace elements. Another important factor explaining the low pollution levels is the duration of operation of the site and the resources used. The Lite-Bala site, has been in operation since 1985, only started using crushers, modern equipment, and dynamite in 2020. Cadmium is highly mobile in soils and sediments. However, its mobility is limited by sorption phenomena in soils. In the case of very acid soils, it is leached into watercourses by run-off and accumulates in river sediments along with gold particles [10] [17]. This is reflected in a strong correlation between cadmium (Cd) and gold (Au) contents in river sediments (**Figure 10**).

5. Conclusion

This first study on the impact of gold panning activities carried out on the Lite-Bala gold site shows that the site is still little polluted with cadmium (Cd), lead (Pb), mercury (Hg) and arsenic (As) but with an upward trend for mercury (Hg) used as an input in gold panning. Climatic conditions (heavy rainfall, winds, significant temperature gradients, etc.) certainly have an impact on the levels and dispersion of TEs. The high levels of cadmium (Cd) in sediments and mercury (Hg) in surface soils constitute an alert to monitor gold panning activities at Lite-Bala. However, apart from the mercury used in gold panning, the use of explosives containing lead (Pb), antimony (Sb), arsenic (As), copper (Cu) and cadmium (Cd) is a source of TEs pollution to be monitored. The pace of mechanization and the discovery of new deposits (placers and veins) are all factors that can affect trace element contents independently of long-term geomorphological and climatic conditions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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