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Contents of metallic trace elements and pollution parameters in the soils of the Komabangou gold mining area in Niger

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Abstract

The contents of metallic trace elements and the soil pollution parameters of the auriferous zone of the locality of Komabangou in Niger were determined. Soil samples were collected from 3 sites in the gold zone, 2 sites in the peripheral zone and 1 site for the control sample. A total of 26 soil samples were collected at depths of 0 to 5 cm, 5 to 10 cm, 10 to 20 cm, 20 to 30 cm and 0 to 30 cm. The contents of metallic trace elements in the soils were determined using an X-ray fluorescence spectrometer. The results of the analyzes showed that at the level of the cyanidation site where the gold mining activities take place, the metallic trace elements in soils have contents of 20.78 mg/kg, 9.25 mg/kg, 114.40 mg/kg, 207.71 mg/kg, 285.38 mg/kg, 10.77 mg/kg, 443.92 mg/kg, 53.21 mg/kg and 14255.53 mg/kg on the sub surface parts for As, Cd, Co, Cr, Cu, Hg, Mn, Ni and Zn respectively. In parallel, on the cyanidation site, the samples collected at depth have pollution index higher than 1 and the pollution parameters indicated very high contamination in Cu, Co, Cd, Hg and Zn. These high levels of metallic trace elements indicate soil contamination by gold mining activities.

1. Introduction

Human activity, linked to industrialization and economic development, is responsible for environmental pollution. Indeed, the diversity of industrial products leads to a considerable increase in the number of substances that contaminate the soil. The latter come from urban and industrial discharges or new agricultural practices and may consist of heavy metals (cadmium, copper, mercury, lead and zinc) and metalloids (selenium and arsenic) which accumulate and persist in the environment. These substances can migrate to groundwater or surface water or enter the food chain via plants and end up in animals and in the human body [1,2]. Although some metals such as iron, zinc, chromium and copper are necessary for life at low doses, their excesses can cause important functional complications and serious health disorders. Several other highly toxic metals such as lead, mercury or arsenic also contaminate soils, leading to their deterioration and the disappearance of some of their functions with possible contamination of resources [3].

In Niger, mining activities constitute a pole for the development of the national economy with oil, uranium and gold as the main natural resources. However, these activities, which often have no real economic benefits for local populations, degrade the environment and its components (soil, water, vegetation) [4,2]. This situation has pushed local populations to turn to illegal gold mining, thus aggravating an already worrying situation [5]. It is therefore necessary to study the fate of Trace Metal Elements (TME) in the different abiotic and biotic compartments and to define the mechanisms that condition their transfers, their bioaccumulation capacities and their toxic effects on the different biological levels of integration [5]. Recently, studies on the spatial distribution of heavy metals (As, Pb, Ni, Zn) in the Komabangou area showed that heavy metal concentrations in the soil of some sites exceeded the permissible levels of regulated thresholds [2,6]. However, these studies did not address the evaluation and variability of soil contamination by metallic trace elements according to soil depth.

The present study aims to assess the levels of pollution, according to the depth of sampling, of soils in the Komabangou mining area in Niger.

2. Materials and Methods

2.1 Site description

The study site is the gold-bearing area of the Komabangou locality in Niger (14°01′41″ and 14°07′56″ North latitude and 01° 02′12″ and 01°10′00″ East longitude). The locality of Komabangou is in the Tillaberi region, 150 km north-west of Niamey, the capital of Niger. Its surface area is 157 km^2 with an estimated population of 36,937 inhabitants distributed in 18 villages [7] (**Figure 1**).

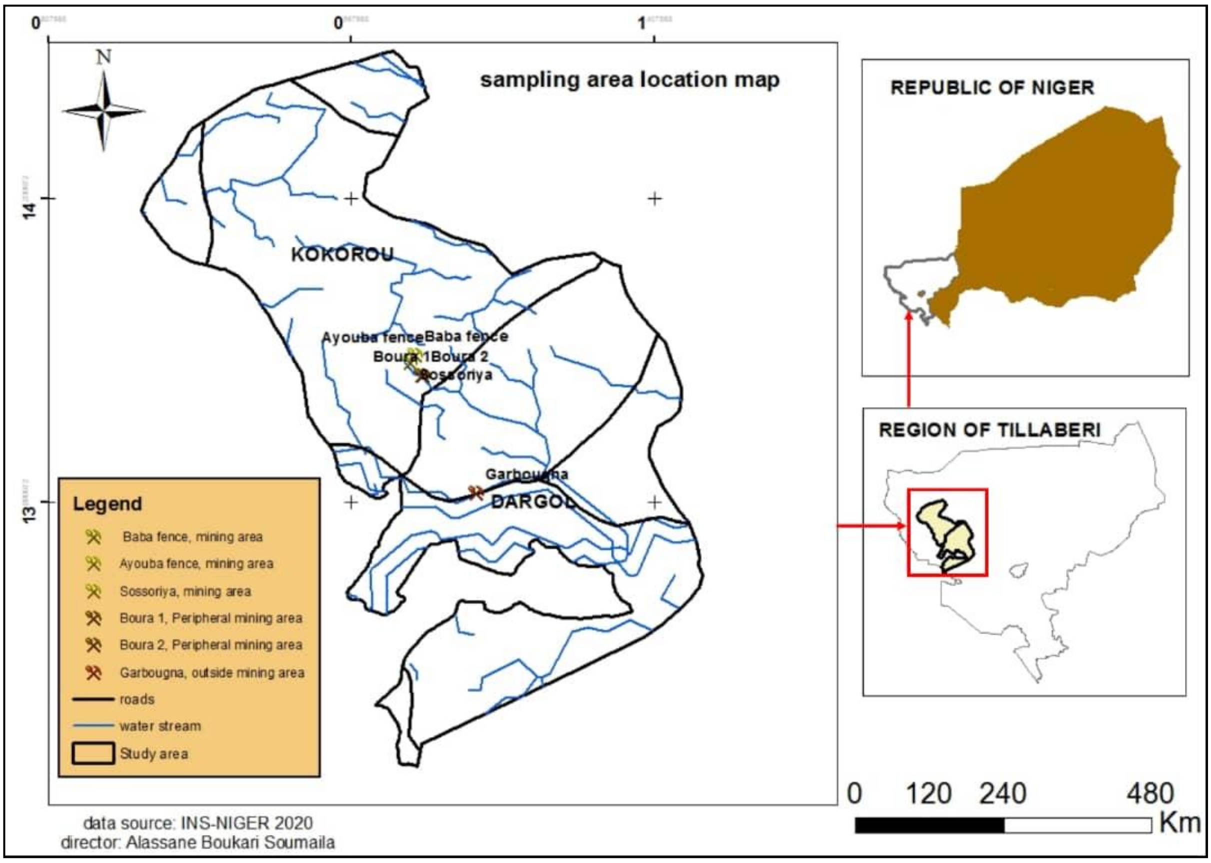

Figure 1. Location of the Komabangou gold site and sampling points.

The precambrian plinth of Liptako Gourma is formed in its biggest party by ancient rocks of granitic and alluvial origins occupying depressions and valleys characterizing the geological formation of the site. The site contains quartz veins, of which those containing gold are exploited.

The exploitation carried out is artisanal, which gives the site a wild and very disordered presentation of pits and quarries. Waste rock rejected during the digging of pits when the useful rock is found forms mounds of sand. Two main methods of gold extraction are used: gravity flow separation and cyanidation processing [8].

2.2. Collection of soil samples

The soil samples were collected from the cyanidation sites S1 and S2 called Baba Djallo grid and Ayouba grid respectively, from sites S3 and S4 in the peripheral areas called Boura 1 and Boura 2 respectively, and from site S5 in the Sossoriya mining area. A control sample (ET) was also collected from a greenfield site outside the mining area (**Figure 1**).

An auger was used for these samples at four (4) depths between 0 and 30 cm in a stepwise fashion: 0-5 cm, 5-10 cm, 10-20 cm and 20-30 cm. The sampling strategy was designed to evaluate the quantity of pollutants according to the soil profile.

At each site, a composite sample of 0.5 to 1 kg of soil was collected, packed in a clean plastic bag (LAB LOC brand) and well labelled. A total of 26 composite soil samples were collected, including fifteen (15) in the mining area, ten (10) in the peripheral area and one (1) outside the mining area (control). The positions of the sampling points were recorded using a GARMIN geographic positioning system (GPS).

2.3 Sample processing and analysis

Soil samples collected from each site were transported, dried at ambient laboratory temperature (35 ±2°C), crushed and sieved using a sieve (brand Saulas) with a mesh size of 2 mm. The sieved soil samples were analyzed using a Niton XL3t portable X-ray fluorescence spectrometer (Thermo Scientific) according to the United States Environmental Protection Agency Method 6200 [9,10]. A portion of the sieved sample was placed in a small polyethylene container (~ 3 cm) with a propylene film so that it was three quarters (3/4) full. It was then placed in the instrument housing and scanned for 180s [11]. Thus, the concentrations of As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb and Zn were determined. The detection limits of the method vary according to the metal (Pb: 5 mg/kg, Ni: 25 mg/kg, Mo: 3 mg/kg; Cu: 10 mg/kg).

2.4. Calculation of the different pollution parameters

Heavy metal contamination at the soil surface, particularly at mine sites, can be assessed either by comparing site-specific data with background reference data or by using pollution parameters and enrichment factors. To assess this factor and the overall toxicity of contaminated soils, the combination of metals rather than a single metal has been considered. Thus several authors have introduced and used the concept of soil pollution index (PI), geo-accumulation index (Igeo), contamination factor (CF) and potential ecological risk index (PERI) [12,3,13,14].

2.4.1. Soil pollution index

The soil pollution index provides an overall assessment of soil contamination. It has been calculated from the average of the ratios of metal concentrations in the soil samples to the guideline values corresponding to the supposed tolerable levels in the soil. The pollution index is calculated from **Eqn. 1** [12]:

$$\mathrm{PI}=[(\mathrm{As}/6+\mathrm{Cd}/1+\mathrm{Co}/30+\mathrm{Cr}/150+\mathrm{Cu}/100+\mathrm{Ni}/50+\mathrm{Pb}/100+\mathrm{Zn}/300)/8] \quad \textbf{Eqn. 1}$$

An PI value greater than 1 corresponds to a soil polluted by several metals.

2.4.2. Geo-accumulation index

The geo-accumulation index (Igeo) has been determined to estimate elemental pollution in soil [15]. It is calculated according to **Eqn. 2** :

$$\text{Igeo} = \log_2\left(\frac{C_n}{1.5XB_n}\right) \qquad \textbf{Eqn. 2}$$

Cn is the concentration of the metal (n) in the sample, Bn is the geochemical background concentration or reference value of the metal (n). The constant 1.5 makes it possible to analyze the possible variations of background values for a given metal in the environment as well as very small anthropogenic influences [16].

The B_n value (in mg/kg) of the metals is: As = 4; Cd = 0.52; Co = 4.3; Cr = 58.4; Cu = 15.75; Hg = 0.06; Mo =1.03; Ni = 14.2; Pb = 4.5; Zn= 63 [10].

According to the value of the geo-accumulation index, the soil quality is given in **Table 1** [17].

Table 1. Geo-accumulation index classes

Classes	Geo accumulation index	Soil quantity
0	Igéo ≤ 0	Not contaminated
1	0 < Igéo ≤ 1	Not contaminated to moderately contaminated
2	1 < Igéo ≤ 2	Moderately contaminated
3	2 < Igéo ≤ 3	Moderately to heavily contaminated
4	3 < Igéo ≤ 4	Heavily contaminated
5	4 < Igéo ≤ 5	Heavily to extremely contaminated
6	Igéo >5	Extremely contaminated

2.4.3. Contamination factors

The contamination factor (CF) has been used to assess metal contamination. It was calculated using **Eqn. 3** : $\mathbf{CF} = \frac{\mathbf{Chm}}{\mathbf{Ccrustal}}$ **Eqn. 3**

Where Chm and Ccrustal represent the concentrations of the heavy metal in the sample and in the geochemical background, respectively [16]. If CF < 1, the contamination is absent to low; if 1 ≤ CF < 3, the contamination is moderate; if 3 ≤ CF < 6, the contamination is considerable and if 6 ≤ CF the contamination is very high [18,19].

2.4.4. Potential ecological risk

The Potential Ecological Risk Index (PERI) was used to assess the degree of heavy metal pollution in soils based on the contamination factor of heavy metal (CF) and the response of the environmental to the contaminant (TrF). The PERI was calculated as the sum of the individual risk indices (RI) from **Eqn. 4** : $\text{PERI} = \sum_{i=1}^{n}(\text{TrF} \times \text{CF})$ **Eqn. 4**

TrF represents the toxic response factor of the metal. Its values for some trace metals are Zn = 1; Cr = 2; Co = Cu = Pb = 5; Ni = 6; As = 10; Cd = 30 and Hg = 40. CF is the contamination factor and n is the number of metals studied.

The degree of ecological risk is classified as low if PERI ≤ 40, moderate if 40 ≤ PERI ≤ 80, considerable if 80 ≤ PERI ≤ 160, high if 160 ≤ PERI ≤ 320 and very high if PERI ≥ 320 [20].

2.5. Data processing

The data obtained were analyzed using several software packages. The Microsoft Excel suite was used for the descriptive analysis of the results, the calculations of the mean, maximum and minimum value for each chemical element. Oringin 2018 and R. 4.04 software were used to produce the graphs. Spatial distribution maps of the sample collections were developed using Arc-Gis mapping software.

3. Results and Discussion

3.1. Physical and chemical properties of soils

The Cation Exchange Capacity (CEC), exchangeable bases and hydrogen potential (pH) of the soils at the different sites studied are given in **Table 2**.

Table 2. CEC and exchangeable bases of the soils of the different sites at 0-30 cm depth

Sites (0-30 cm)	**Absorbent complex (cmol/kg)**						
	pH	**CEC**	**Sum**	**Ca^{2+}**	**Mg^{2+}**	**K^{+}**	**Na^{+}**
S1	2.9	8.24	7.290	2.456	4.612	0.065	0.157
S2	5.1	7.36	6.503	2.801	3.449	0.077	0.176
S3	4.5	2.24	1.247	0.586	0.441	0.115	0.105
S4	4.9	3.68	1.264	0.691	0.463	0.054	0.056
S5	5.2	3.68	1.482	0.977	0.393	0.053	0.059
ET	5.6	3.00	1.202	0.748	0.336	0.062	0.056

The soil pH plays a major role in the adsorption of micropollutants by soil constituents. It facilitates the adsorption of metal cations onto soil surfaces by Coulomb-type electrostatic attractions. Soils from different sites and the control soil are acidic with pH values ranging from 2.9 for S1 to 5.6 for ET (**Table 2**). Similar results were obtained with pH values of 6.34 to 6.94 in soils from gold sites studied in China [21] and a pH value of 5.38 for soils at a depth of 0-50 cm [2]. Indeed, the more the soil is acid, the more TMEs are put into solution and vice versa. The decrease in pH causes the mobilisation of TMEs [22].

Table 2 shows that the CEC of the samples varies from 2.24 for S3 to 8.24 for S1. The highest values are obtained in the soils of sites S1 and S2 with values of 8.24 and 7.36 respectively. This could be explained by the relatively high clay content and the effect of organic matter in these two cyanidation sites [23]. The low CEC values of sites S3, S4, S5 and the control site, respectively 2.24; 3.68; 3.68 and 3, could be explained by their sandy textures [24]. The sum of exchangeable bases is only significant for sites S1 and S2 with high values of Mg^{2+} and Ca^{2+}. The latter ensures the stability of cell membranes, allows elongation and cell division and plays a decisive role in the adaptation to environmental responses of plants [25]. Mg is an essential constituent of chlorophyll [26] and may also contribute to tolerance to toxic stress [27]. The presence of these cations in soils promotes the availability of nutritional elements that probably contribute to the proper development of a plant even in the presence of soil pollution stress [24]. Indeed, the 2:1 clay minerals (illite, smectite, vermiculite), which have many permanent negative charges, have a higher CEC than the 1:1 clays (kaolinite), whose CEC depends only on the dissociation of the edge sites of the sheets.

3.2. Trace metal concentrations

Figure 2 shows the average trace metal element (TME) content of the five (5) study sites. **Figure 2** shows that Zn, Cr, Cu, Sr, Pb and Hg contents are much higher at site 1 where cyanidation activity is conducted. However, metals such as Mn, Ni, As are more abundant at site 2. The Zn content of site

1 is 2.7 times higher than that of the soils of a mining site in Lubumbashi which has a Zn content of 209.6 mg/kg [28]. The results obtained show that the TME content of the soils varies significantly depending on whether the soil samples are taken in the mining area or on the periphery of the mine. Our MTE contents are higher than those obtained by Ali [29] and Tankari Dan-Badjo et *al.* [13] on cyanidation soil from the same area, except for As (264 mg/kg) and Pb (62.4 and 1659 mg/kg) obtained by these authors. On the other hand, the Pb content of Site 1 is close to that of a young gold mine in Umuahia, Nigeria, which is 4.6 mg/kg [30]. These results could be explained by the choice of sampling period and method as well as the proliferation of gold miners who have overused chemicals in recent years at Site 1.

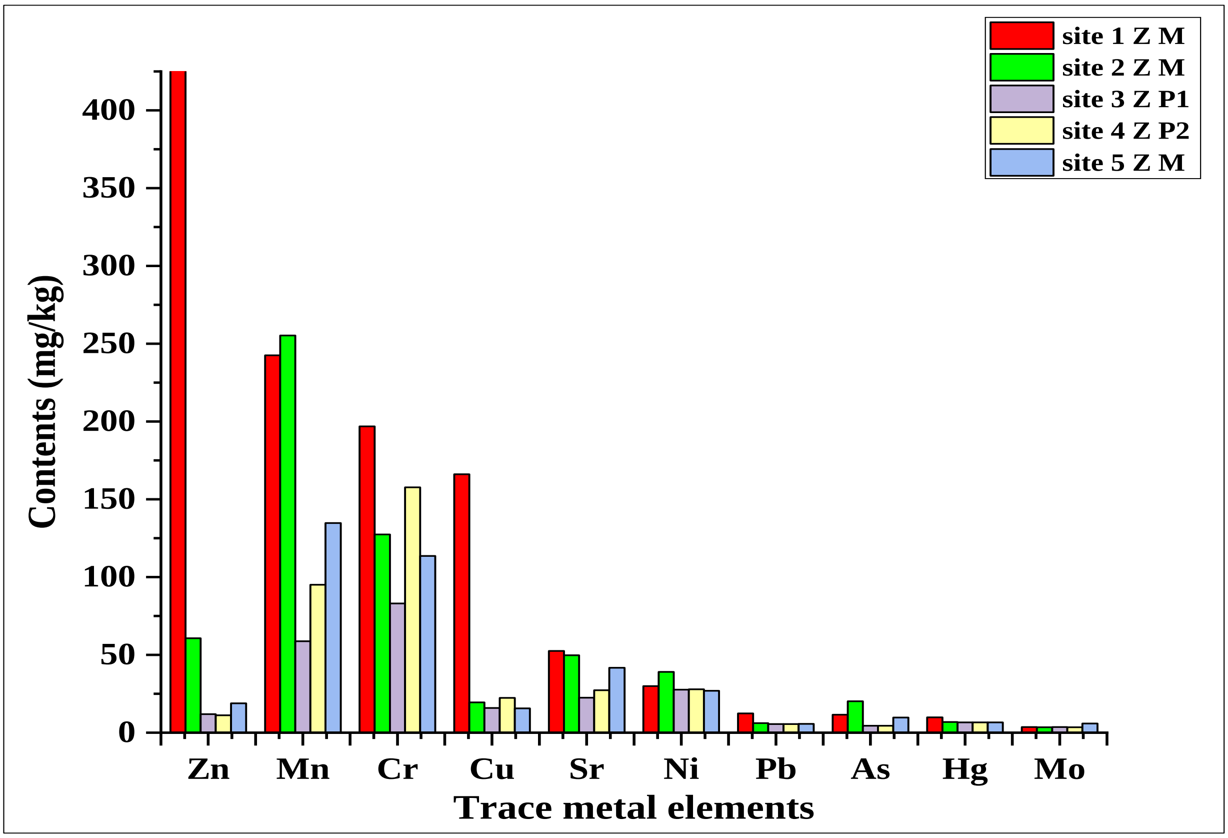

Figure 2. Average content of trace metal elements in the different sites (0-30 cm).

The Zn, Cu, Sr, Ni, As, Hg, Pb and Mo contents of the peripheral soils are slightly similar to those found by Zakaria Ibrahim et *al.* [2] in the same mining area except for the Cr content which is 2 to 7 times higher in the periphery. These results reflect the transfer of metals from the cyanidation area to the periphery of Komabangou village. Thus, a study on the distribution of these trace metals at different depths for the mining sites (cyanidation and gold extraction site) and periphery is necessary to better appreciate this diffuse contamination.

3.3. Concentrations and distribution of trace metals in site soils as a function of depth

The TME contents of sites 1 to 5 according to the sampling depths (0-5, 5-10, 10-20, 20-30 cm) are given in **Table 3**. This table shows that all the TMEs investigated were detected independently of depth, except for Hg, whose levels were not determined after a depth of 5 cm. The study shows that the TME content of the different soil samples varies with depth and metal.

For site 1 (Baba Djallo cyanidation grid area), As (20.78 mg/kg), Cd (9.25 mg/kg), Co (114.40 mg/kg), Cu (285.38 mg/kg), Hg (10.77 mg/kg), Mn (443.92 mg/kg), Mo (3.80 mg/kg), Pb (35.09

(mg/kg) and Zn (14255.53 mg/kg) are higher in the surface layer (0-5 cm). Ni (53.58 mg/kg) and Fe (35340.47 mg/kg) contents are higher at the 5-10 cm depth. However, Cr (218.80 mg/kg) is predominantly present at the 20-30 cm depth. For As, Cr and Mo, the lowest levels were observed at the depth of 5-10 cm. The vertical variation of these three metals shows that from the surface to a depth of 10 cm, their contents decrease and then increase to 11.33 mg/kg for As, 218.80 mg/kg for Cr and 3.70 mg/kg for Mo at a depth of 20-30 cm. For site 2 (Ayouba cyanide grid area), the Fe content (31513.68 mg/kg) is the highest, followed by Mg (345.14 mg/kg), Cr (161.44 mg/kg), Co (101.76 mg/kg), Cu (63.88 mg/kg), Zn (61.04 mg/kg), Ni (38.19 mg/kg), As (18.61 mg/kg), Pb (9.57 mg/kg), Cd (8.68 mg/kg), Hg (6.62 mg/kg) and Mo (4.20 mg/kg). The Fe, Cr and Co contents increase strongly with the depth of sampling, unlike the Cu content. The Mn content increases at a depth of 5-10 cm, decreases at a depth of 10-20 cm and then increases.

The studies carried out on sites 1 and 2 show that, in general, TMEs are concentrated in the first five centimeters of the soil where the organic matter content is high [31,32]. This vertical arrangement of TMEs is due to the phenomenon of infiltration, leaching or washing, which carries metals from the upper to the lower parts of the soil. This decreasing metal pollution could be largely explained by the adsorption process of metal elements on clays and organic substances [33]. The rapid decrease in TME content from surface to depth could be due to anthropogenic contamination, coupled with the variation of hydrogen potential (pH) and organic matter [34]. The presence of Zn could be justified by the use of zinc pellets in the process of recovering gold from acidic ore leaching solutions. For mercury, due to its volatility and solubility during the gold purification process, it can easily be deposited on the sub-surface layer of the soil. For the other elements (Cd, Pb, Ni), they are probably associated with contamination by trace metal elements contained in zinc pellets [8].

For site 3 (peripheral zone of the Boura 1 mining operation), the elements detected at different depths are: Cr, Cu, Mn, Mo and Fe. The highest contents are those of Fe (12884.97 mg/kg) recorded at the depth of 20-30 cm, followed by Cr (89.99 mg/kg) and Mn (61.83 mg/kg) to the same depth. The Cr content increases with depth unlike that of Mo. The iron content decreases up to the depth of 10-20 cm and then increases at the depth of 20-30 cm. Although copper was not detected at the first two depths, it appears with contents of 18.05 and 15.51 mg/kg at depths of 10-20 and 20-30 cm respectively. Trace metals such as As, Cd, Co, Hg, Pb and Zn were not detected at any of the depths of this peripheral site probably due to its distance from the gold ore processing area.

The ETM elements present at site 4 (peripheral zone of the Boura 2 mining operation) are: As, Cr, Cu, Fe, Mn, Mo, Ni and Zn. The highest values of TMEs recorded are for Fe (13925.91 mg/kg) followed by Mn (142.59 mg/kg), Cr (108.78 mg/kg), Ni (43.63 mg/kg), Zn (18.08 mg/kg), Cu (17.12 mg/kg), Mo (4.74 mg/kg) and As (4.63 mg/kg). The Cr, Fe and Ni contents increase with depth unlike those of Mo and Zn. The Cu content is below the detection limit in the first three depths, whereas the Mo and Ni contents are below the detection limit in the first two depths. The presence of TMEs at different depths indicates their transfer to the peripheral zone where gold panning activities are not carried out. Furthermore, site 4 is more contaminated with trace metals than site S3. This could be explained by the topography of the area, which favors the transfer and deposition of TMEs through a water network (streams) during the rainy season on the downstream part of the peripheral zone [2].

The trace metals recorded at site 5 (Sossoriya site of the mining area) are: As, Cr, Cu, Fe, Mn, Mo, Ni, and Zn. Co, Cd, Hg and Pb were not determined. The highest TME content was obtained with Fe (18778.29 mg/kg) followed by Mn (292.95 mg/kg), Cr (152.17 mg/kg), Ni (45.16 mg/kg), Zn (41.17 mg/kg), Cu (22.07 mg/kg), As (21.29 mg/kg) and Mo (5.42 mg/kg). The contents of As, Cr, Cu, Fe, Mn and Zn increase with depth unlike those of Mo and Ni. These results are similar to other studies in the literature [14,35]. The distribution of TMEs in the soils of all the sites according to depth, as well as their content, shows that the superficial part of the soil, particularly in the first 5 cm (0-5 cm), is the most contaminated, with high levels of trace metals that decrease overall with depth (**Table 2**).

Table 3. Trace metal contents of sites according to depth

		Contents of Metallic Trace Elements (mg/kg)											
Sites	**Depths (cm)**	**As**	**Cd**	**Co**	**Cr**	**Cu**	**Fe**	**Hg**	**Mn**	**Mo**	**Ni**	**Pb**	**Zn**
Site S1	**0-5**	20.78	9.25	114.4	207.71	285.38	32683.31	10.77	443.92	3.8	53.21	35.09	14255.53
	5-10	10.20	8.96	111	185.26	130.24	35340.47	lt	322.23	3.64	53.58	23.95	5230.71
	10-20	10.32	8.85	106.9	193.29	73.95	33001.04	lt	215.03	3.78	39.75	6.28	2563.86
	20-30	11.33	8.55	106.2	218.8	39.73	33073.8	lt	241.44	3.7	35.12	5.84	1315.76
Site S2	**0-5**	18.61	8.68	76.37	117.43	63.88	17475.52	6.62	176.77	4.2	38.19	9.57	61.04
	5-10	18.15	8.57	92.3	138.81	27.6	24867.59	lt	253.45	3.51	31.54	5.96	56.35
	10-20	15.7	8.45	95.5	156.39	22.99	27302.25	lt	213.72	< LOD	28.99	5.64	54.36
	20-30	17.49	8.4	101.8	161.44	21.23	31513.68	lt	345.14	< LOD	27.14	5.78	47.36
Site S3	**0-5**	lt	lt	lt	75.55	< LOD	9524.82	lt	lt	5.89	< LOD	lt	lt
	5-10	lt	lt	lt	82.21	< LOD	9281.95	lt	lt	4.87	lt	lt	lt
	10-20	lt	lt	lt	84.77	18.05	9190.37	lt	lt	4.02	lt	lt	lt
	20-30	lt	lt	lt	89.99	15.51	12884.97	lt	61.83	< LOD	lt	lt	lt
Site S4	**0-5**	lt	lt	lt	75.25	< LOD	7551.33	lt	63.45	< LOD	< LOD	lt	18.08
	5-10	lt	lt	lt	91.88	< LOD	10439.39	lt	96.17	< LOD	< LOD	lt	11.98
	10-20	lt	lt	lt	105.89	< LOD	11969.87	lt	142.59	4.74	29.5	lt	11.25
	20-30	4.63	lt	lt	108.78	17.12	13925.91	lt	126.06	4.27	43.16	lt	11.05
Site S5	**0-5**	8.76	lt	lt	89.15	16	9947.61	lt	141.34	5.42	45.16	lt	17.04
	5-10	16.5	lt	lt	95.46	17.11	11812.99	lt	175.42	4.42	40.2	lt	21.04
	10-20	19.63	lt	lt	114.72	18.01	16292.55	lt	238.45	< LOD	29.27	lt	31.8
	20-30	21.29	lt	lt	152.17	22.07	18778.29	lt	292.95	< LOD	26.57	l	41.17
Standards		6 **(1)**	1 **(2)**	30 **(3)**	150 **(4)**	100 **(5)**	-	1 **(6)**	-	-	50 **(7)**	100 **(8)**	300 **(9)**

< LOD: Level below detection limit (5 mg/kg for Pb; 25 mg/kg for Ni; 3 mg/kg for Mo; 10 mg/kg for Cu); lt: low trace; -: no standard.

***(1)** World average of soils not contaminated with As [36] ; **(2)** UK Agency reference value for Cd for soils in urban areas; **(3)** Cobalt limit value (NFU 44-041); **(4)** Cr limit value (Dutch guidelines) [37] ; **(5)** Tolerable level of Cu concentration in soils (NFU 4405); **(6)** Guide values in Hg (AFNOR U 44-041); **(7)** Limit value in Ni indicated by WHO [37] ; **(8)** Critical value in Pb indicated by WHO [38] ; **(9)** Guide values in Zn indicated by WHO [32].*

The highest levels are recorded at cyanidation sites 1 and 2, where all twelve (12) of the elements investigated are present at different concentrations. Sites 3 and 4 in the peripheral zone and the site outside the mining zone have low TME levels. These results show the impact of gold panning, which is a real source of soil pollution. The high Zn levels could be explained not only by the fact that Zn ores such as blende (ZnS) are closely associated with gold ores but also by the use of zinc chips on the mining sites for gold cementation [2,6]. The Pb detected at the two cyanidation sites 1 and 2 could be from sulphide ore such as galena (PbS), sometimes associated with gold. The TME contents of the different sites could be related to the organic matter, as well as to the acidity of the soils (**Table 2**). At such pH, most trace elements are found in soils as oxides and are fixed on the solid phase of the soil [22].

The TME contents (mg/kg) of the different sites over the depth of 0-5 cm were compared to the different international standards. Table 3 shows that As levels range from 8.76 mg/kg to 20.78 mg/kg for sites 5 and 1 respectively. The two cyanidation sites S1 and S2 as well as site S5 show values above the standard of 6 mg/kg [36]. Cd levels at the two cyanidation sites (8.68 and 9.25 mg/kg) are 8-9 times higher than the UK Environment Agency threshold. The Co content of the two (2) cyanidation sites S1 and S2 (114.40 and 76.37 mg/kg) is higher than the NFU 44-041 standard. Concerning Cr and Cu, only site 1 is out of specification with respective contents of 207.71 mg/kg [37] and 285.38 mg/kg (NFU 4405). For the two peripheral sites S3 and S4, the Cu contents are below the detection limit. The iron contents vary from 9947.61 mg/kg for site S5 to 32683.31 mg/kg for site S1. Unfortunately, we did not find a standard for this metal. The Hg contents of the two (2) cyanidation sites (6.62 and 10.77 mg/kg) are 6 to 10 times higher than the French standard AFNOR U 44-041 set at 1 mg/kg. The Mn contents vary from 63.45 mg/kg for site S4 to 443.92 mg/kg for site S1. Unfortunately, we did not find a standard for this metal. Mo contents vary from 3.80 mg/kg for site S1 to 5.89 mg/kg for site S3. Site 4 has a content below the detection limit. Unfortunately, no standard was found for this metal. For Ni, only site 1 is out of range with a content of 53.21 mg/kg [37]. Sites 3 and 4 have Ni contents below the detection limit. The Pb content of the soil at sites 1 and 2 (9.54 and 35.09 mg/kg) and the Zn content of the soil at sites 2, 4 and 5 (17.04 to 61.04 mg/kg) are below the standard. However, the soil at site 1 is polluted with Zn, whose content is 47.5 times higher than the standard [32]. The zinc content of site 1 is slightly higher than that reported in a study of Niamey soils (12220 mg/kg) [13]. To better assess the TME contamination of the sites, we calculated the soil pollution parameters over the depth (0-5 cm).

3.4. Assessment of metallic contamination of TMEs on 0-5 cm

3.4.1. Chon Pollution Index

The pollution indexes (PI) of the five (5) sites in the depth range (0-5 cm) were calculated from **Eqn. 1**. The results obtained are presented in **Table 4**. The highest pollution index value was 8.94 for cyanidation site 1 followed by 2.60 for cyanidation site 2, 0.63 for the gold mining site as well as 0.50 and 0.28 respectively for the two peripheral sites S3 and S4. These results are slightly lower than those reported for the same cyanidation sites (PI between 3.10 and 12.31) but slightly higher for the peripheral sites (PI between 0.09 and 0.43) [2].

Table 4. Soil pollution index for the five sites over the 0-5 cm depth range

Parameter	**Sites**				
	Site 1	Site 2	Site 3	Site 4	Site 5
Pollution Index	**8.94**	**2.60**	**0.50**	**0.28**	**0.63**

However, these results are quite low compared to those of a mining area in eastern Morocco (PI between 0.08 and 47.69) [3]. These results show that the soils of the two cyanidation sites have PI values 2 to 9 times greater than 1, indicating that they are polluted by multi-elements (As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb and Zn) [12]. However, for the two peripheral sites S3 and S4 as well as for the Sossoriya mining site S5, these values are lower than 1, indicating a low accumulation of TMEs at these sites.

3.4.2. Geo-accumulation index of the different sites

The geo-accumulation Index (Igeo) values for the soils of the cyanidation (S1 and S2), peripheral (S3 and S4) and non-mining (S5) sites at the 0-5 cm depth are presented in **Figure 3**. The values and ranking of the geo-accumulation Index indicate an overall irregular fluctuation of TMEs at the different sites. The Igeo values for site S1 (**figure 3A**), ranging from 0.86 to 5.01, show high contamination of the metals investigated in the order Zn > Hg > Co > Cu > Cd > Pb > As > Mo > Ni > Cr indicating moderately to extremely contaminated soils.

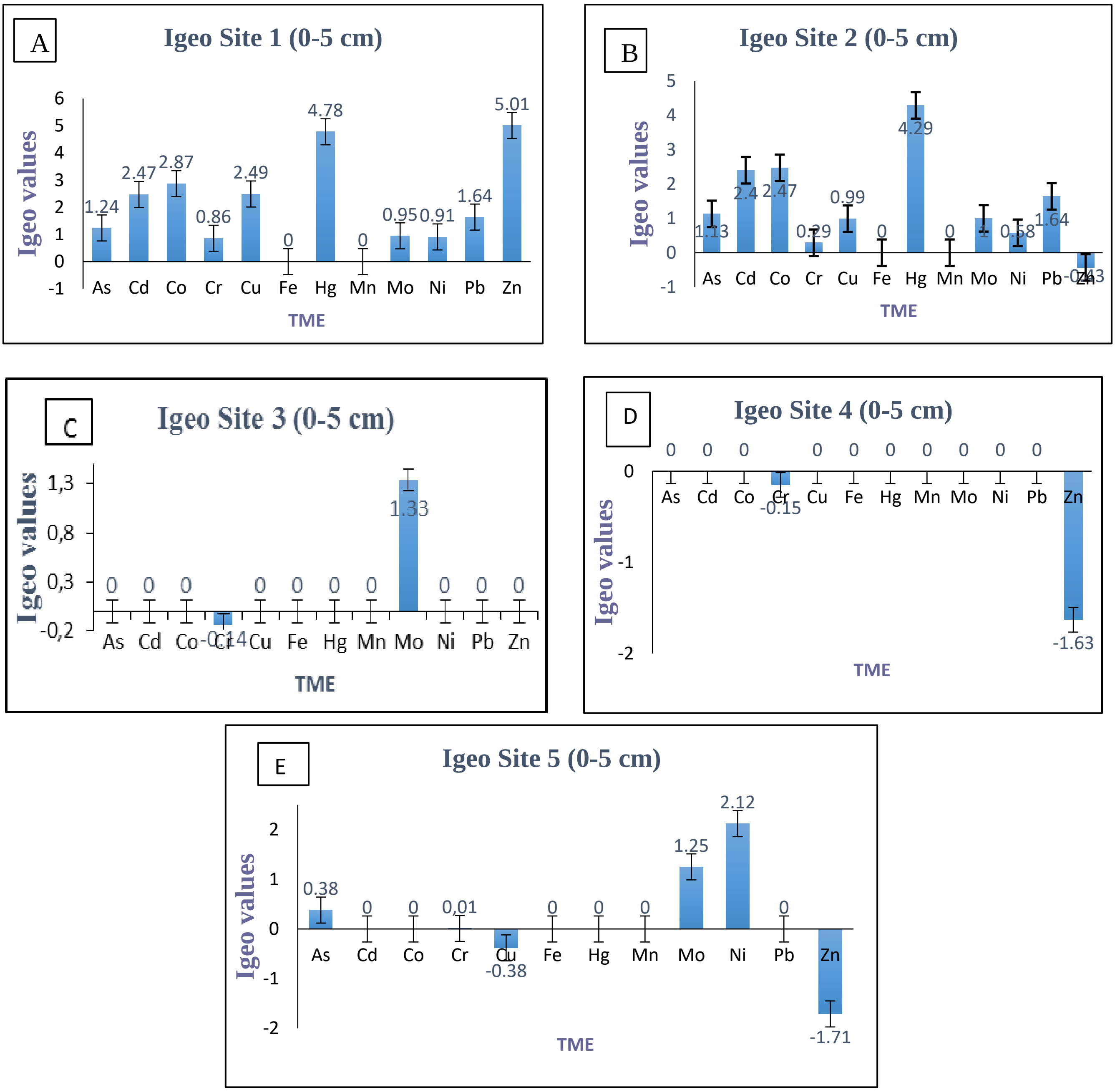

Figure 3. Geo-accumulation indices of the 5 sites.

The Igeo values show that the soils at this site are highly to extremely contaminated with Zn (5.1) and Hg (4.78), moderately to highly contaminated with Co (2.87), Cd (2.47) and Cu (2.49) and moderately contaminated with Cr (0.86), Mo (0.95) and Ni (0.91). This contamination is closely linked to the use and discharge of chemicals without prior treatment and confirms the results of the pollution parameters. These results are close to those obtained at the Asmakum landfill in Koumassi (Ghana) with Igeo values of 2.07; 1 to 2.62 and 0.2 to 3.37 respectively for Cu, Pb and As. However, the Igeo of Zn (0.58 to 1.59) was lower [14]. **Figure 3B** shows soil at site S2 moderately contaminated with As and Pb (Igeo = 1.13 and 1.64), moderately to heavily contaminated with Cd and Co (Igeo = 2.4 and 2.47) and heavily to extremely contaminated with Hg (Igeo = 4.29). Contamination by the other elements is moderate overall. However, the results in **figures 3C** and **3D** for the two peripheral sites show moderate contamination only in Mo (Igeo = 1.33) at site 3 and an unpolluted site 4. **Figure 3E** shows that the soil at site 5 is moderately to heavily contaminated with As, Mo and Ni with Igeo values of 0.38; 1.25 and 2.12 respectively.

3.4.3. Contamination factor of the different sites

The contamination factors of the different soils at the depth of 0-5 cm with TMEs were calculated from **Eqn. 3**. The results obtained are reported in **Table 5**. The results in **Table 5** show high values of contamination factors for the soil of site 1, particularly for Cd (17.79), Co (26.60), Cu (18.12), Hg (179.50), Pb (7.80) and Zn (226.28), as well as for the soil of site 2, particularly for Cd (16.69), Co (17.76) and Hg (110.33), thus indicating a very high level of contamination of these cyanidation sites by TMEs. The latter could come from the chemicals used during the processing of gold ores, or from certain products such as paints and cosmetics that contain metals and are present on these sites. For the peripheral (S3 and S4) and mining (S5) sites, the contamination is globally moderate for the TMEs detected on these sites. Although both Cu and Zn are essential elements that act as micronutrients to maintain normal body functioning, their high presence at site 1 could pollute the surrounding crops and watercourses [10].

Table 5. Contamination factors for the different sites studied at the 0-5 cm depth

Metals	**Contamination factors**				
	Site 1	**Site 2**	**Site 3**	**Site 4**	**Site 5**
As	5.20	4.65	-	-	2.19
Cd	17.79	16.69	-	-	-
Co	26.60	17.76	-	-	-
Cr	3.56	2.01	1.29	1.29	1.53
Cu	18.12	4.06	-	-	1.02
Hg	179.50	110.33	-	-	-
Mo	3.88	4.08	5.72	-	5.26
Ni	3.75	2.69	-	-	3.18
Pb	7.80	2.13	-	-	-
Zn	226.28	0.97	-	0.29	0.27

3.4.4. Potential Ecological Risk Index of individual sites

To further assess the ecological risk from heavy metal pollution, the Potential Ecological Risk Index (PERI) was calculated from **Eqn. 4** and the results are shown in **Table 6**. The PERI values for the cyanidation sites indicate an overall metal pollution that results in a low to very high risk in the order: Cr < Ni < Pb < As < Cu < Co < Zn < Cd < Hg for site 1 and Zn < Cr < Pb < Ni < Cu < As < Co < Cd < Hg for site 2. For the peripheral sites (Sites 3 and 4), the overall ecological risk for metals is low, indicating that these sites are not polluted by TMEs [20]. In addition, Site 5 has a very low ecological risk with PERI values of 21.9 for As, 3.06 for Cr, 5.1 for Cu, 19.08 for Ni and 0.27 for Zn all below 40. Currently, regional ecological risk assessments and the safe utilization of cultivated land are of increasing public concern; and provide pertinent information for zoning risk assessments and controlling heavy metal pollution in agricultural areas [39-41].

Table 6. Potential Ecological Risk Index of the different sites on the 0-5 cm depth

Metals	**Potential Ecological Risk Index**				
	Site 1	**Site 2**	**Site 3**	**Site 4**	**Site 5**
As	52	46.5	-	-	21.9
Cd	533.7	500.7	-	-	-
Co	133	88.8	-	-	-
Cr	7.12	4.02	2.58	2.58	3.06
Cu	90.6	20.3	-	-	5.1
Hg	7180	4413.2	-	-	-
Ni	22.5	16.14	-	-	19.08
Pb	39	10.65	-	-	-
Zn	226.28	0.97	-	0.29	0.27

Conclusion

This study aimed to assess the levels of pollution, depending on the depth of sampling, of the soils in the mining areas of Komabangou in Niger. At the end of this work, the soils studied are contaminated with arsenic, cadmium, chromium, copper, lead, mercury, nickel and zinc. In most cases, the recorded TME contents decrease in the soils from the cyanidation sites to the sites outside the mining area, via the peripheral sites where chemicals are not used. The sub-surface part (0-5 cm) of the cyanidation sites are heavily polluted with As, Cd, Cu, Co, Hg, Mn and Zn. The pollution indexes as well as the geo-accumulation and contamination indexes indicated high pollution by Cd, Co, Cu, Hg and Zn in the mining area. The potential ecological risk indexes indicate overall pollution, a potential source of toxicity for flora, fauna and inhabitants.

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