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Heavy Metals Contaminations and Ecological Risk Assessment in Soils, Mining Wastes and Sediments of the Ngoura Gold Mining Area, Eastern Cameroon

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Abstract

To assess contamination levels, 14 samples were taken from mining sites in the Ngoura gold mining area, to determine the possible ecological hazards of heavy metals (Al, Mn, As, Ba, V, Cr, Ag, Pb, Hg, Y, Th and U). Physico-chemical parameters (pH, OM, CEC, Available P, and EC) were analysed. Using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), heavy metals were identified. The contaminations were estimated using the following methods: enrichment factor (EF), contamination factor (CF), mean contamination index (Im), pollution load index (PLI), geo-accumulation index (I-Geo), and ecological risk index (Ri). Findings indicated that mining materials exhibit acidic to highly alkaline pH (5.2 to 9.8), are non-saline (EC < 250 µS/cm), with low to very high OM (1.20 to 6.51), moderate to very high CEC (14.11 to 45 meq/100g), and very low to medium available phosphorus (7 to 34.34 mg/kg). Heavy metal analysis revealed concentrations (mg/kg) exceeding UCC values: soils near mines: Hg (24.81), Pb (18.99), Th (8.46) mining wastes: Y (97.66), Hg (26.96), Pb (25.85), Th (169.96), U (9.8) residues: Hg (19.49), Pb (30.25), Th (21.12), U (16.5) sediments: Ba (682.75), Y (65.75), Hg (4.2), Pb (26.93), Th (236.65), U (16.15). Contamination indices (EF, I-Geo, CF, Im, PLI) revealed contamination by Hg, Y, Pb, Th, and U, with extreme enrichment of Hg across all materials. I-Geo indicated extreme Hg contamination, while Im confirmed contamination in most samples. Hg posed a very high ecological risk, making it the principal contaminant in the Ngoura mining area. Phytoremediation can help to reduce the contaminations in this study area.

Keywords

Ngoura, Mining Sites, Contaminations, Heavy Metals, Ecological Risks

1. Introduction

In many African nations, mining has grown to be a significant economic activity, providing as a significant source of income for large segments of the population and raising hopes for development. The enactment of new mining laws in the late 1980s throughout most countries fostered private sector investment in this industry (Lamine, 2011). Cameroon is among the countries in sub-Saharan Africa with an abundant subsurface resource base. The development of its mineral resources could play a pivotal role in its economy and overall development, helping it achieve emerging market status by 2035 (Friedrich-ebert-stiftung, 2015). Over the past few years, environmental contaminations caused by trace metals has become a global concern. Their toxicity, biodegradation resistance, and propensity to enter the food supply chain are the causes of this problem (Kinimo et al., 2018; Ouattara et al., 2020). Mining, agriculture, industry, and household waste are only a few of the natural and man-made processes that release trace metals into the environment (N'guessan et al., 2009; Du et al., 2013). The entrance of contaminants into the soil is made worse by human activity and urbanization, which can eventually damage natural resources by causing deterioration and loss of soil function (Soro et al., 2009). Significant health risks can arise from high concentrations of heavy metals in soils (Alloway, 1995), as humans may be exposed through ingestion, direct touch, or inhalation of airborne particles. For example, lead (Pb) and arsenic (As) are known to cause cancer (Jaishankar et al., 2014). Rahman et al. (2014) state that certain metals, such as copper (Cu) and zinc (Zn), are essential elements for human health but are toxic in large concentrations. Methyl and elemental mercury (Hg) are especially harmful to the central and peripheral neurological systems. Inhaling mercury vapor can also damage the immunological, digestive, and neurological systems, the kidneys as well and lungs. It can also be lethal (WHO, 2016). Mental retardation, convulsions, and vision impairment are examples of neurological symptoms and hearing impairments, developmental delays, speech illnesses as well as memory loss. In children, chronic mercury exposure can cause acrodynia, a condition characterized by red and painful extremities (WHO, 2016). Mining activities, including excavation and pre-treatment processes (crushing and grinding), release significant amounts of metal-laden wastes into the surroundings. While gold mining, tonnes of solid waste are generated and stored as spoil heaps. These untreated mining wastes, when exposed to climatic conditions such as wind and rainfall, present environmental threats to nearby water, soil, and vegetation due to trace metals (ETM) and cyanide (Ibrahim et al., 2019). Gold mining activities in Betaré-Oya, a site close to the Ngoura study area, frequently cause environmental problems (Tehna et al., 2015; Pahimi et al., 2015; Rakotondrabe et al., 2017). Research has confirmed the presence of heavy metals in the water, sediments, and soils of some active mining areas. The simple fact that heavy metals are present in an environment does not, however, imply contaminations or pollutions (Ekoa Bessa et al., 2018). For instance, Chabukdhara et al. (2017) in Ghana reported that harmful metals such as Cu, Zn, Cd, and Hg in the lower Pra Basin originate from anthropogenic activities related to mining. Similarly, in Ngoura, traditional gold mining has been practiced for decades using harmful substances like mercury and cyanide. Despite existing pollution assessments of certain Cameroonian mining sites (Tehna et al., 2019; Elvine Paternie et al., 2023; Tonang et al., 2022; Danala et al., 2024), little research has focused on the Ngoura mining area. The current investigation seeks to determine the levels of metalloids and heavy metals, in addition to the physico-chemical parameters (pH, OM, CEC, available phosphorus, and CE), in soils around the mines, mining waste, and sediments from the Colomine, Camp Bleu, Bemdere, Malewa, Danko, and Ngongowe sites (all within Ngoura municipality). The degree of contamination (DC), mean contamination index (Im), pollutant load index (PLI), enrichment factor (EF), contamination factor (CF), geo-accumulation index (I-Geo), and ecological risk index (Ri) are also used to evaluate the degrees of contamination.

2. Materials and Procedures

2.1. Research Space

Between latitudes 4˚50'02" and 5˚03'33"N and longitudes 14˚08'23" and 14˚25'02"E is the district of Ngoura. It is situated in the Lom and Djerem department in the Eastern Cameroon region (**Figure 1**).

With an estimated 42,103 residents, it occupies an area of 7000 km^2. The Congo forest has a significant impact on the humid, subequatorial climate in this area (Tsaléfac, 2007). Two seasons define the climate (Olivry, 1986; Suchel, 1987): a brief dry season (November-March) and a substantial rainy season (April-October). The Ngoura-Colomines region is part of the South Cameroonian plateau, which has elevations ranging from 550 to 850 meters. The Oudou River, the principal water tributary of the Kadey watershed, drains Ngoura-Colomines. Together with the Ngoko basin (which is composed of the Dja and the Boumba), it forms the Congo's vast hydrographic basin (Olivry, 1986). Three primary soil types comprise the study area's soil cover: hydromorphic or yellowish clayey sandy soils in the lowlands, red or yellow ferralitic soils in the upstream portion of the slopes, and poorly evolved soils on mountain reliefs (Bilong et al., 1992; Bitom & Volkoff, 1995, Kamgang Kabeyene Beyala, 1998). The Central-Cameroon domain, which is a crucial component of the Pan-African Chain of Central Africa, includes the research region. The two types of formations found in this domain are magmatic formations, which are primarily granitic and the most characteristic of our study region, and metamorphic formations, which are composed of orthogneisses, migmatites, schists, and quartzites (Nzenti et al., 1994; Tanko Njiosseu et al., 2005).

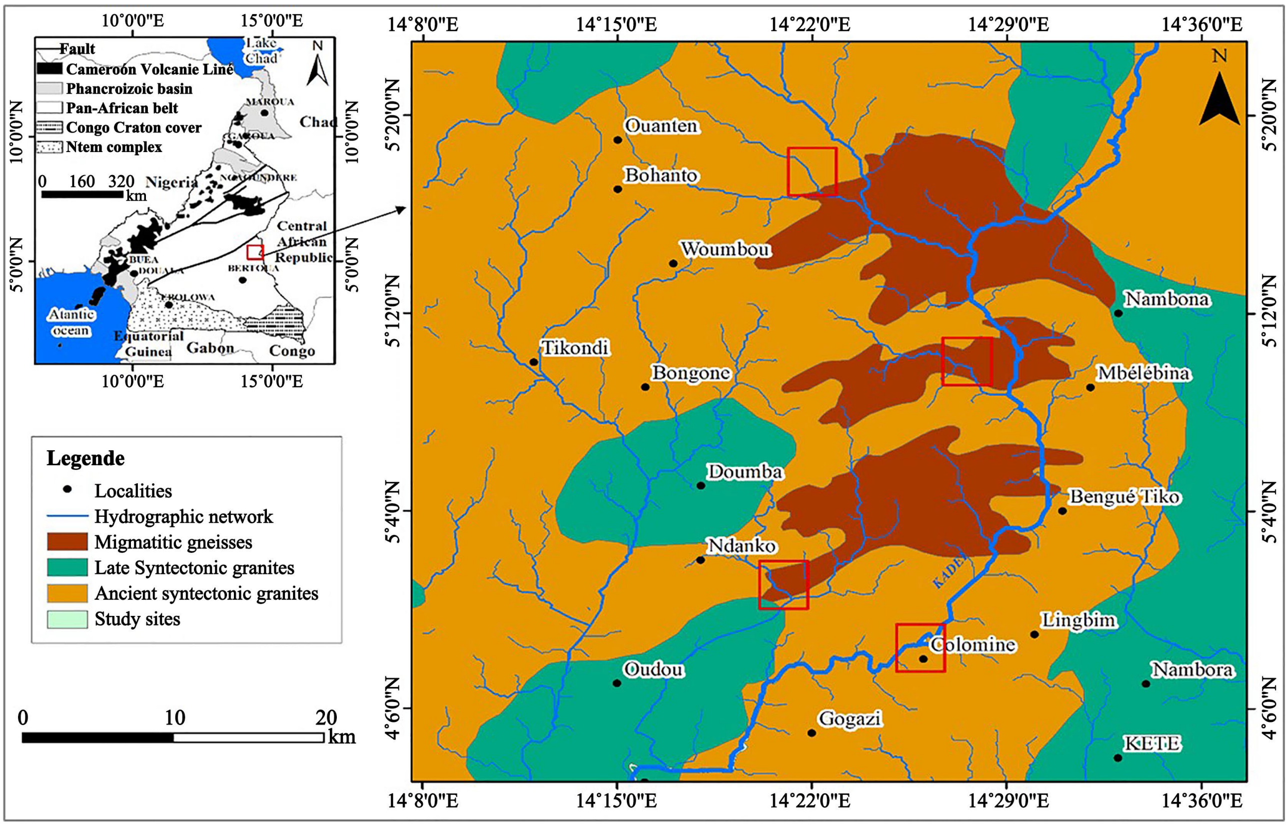

Figure 1. Location map of the study area (source: Champrtier & Aubegue, 1956).

Gathering Samples

The Ngoura mining sites are the compartments under study number of elements, including sediments, mining waste (waste rock and residues), and soils surrounding the mines. Aluminum (Al), manganese (Mn), arsenic (As), barium (Ba), vanadium (V), chromium (Cr), silver (Ag), lead (Pb), yridium (Y), mercury (Hg), thorium (Th), and uranium (U) are the metallic trace elements (heavy metals) that are the subject of this study. Several sample collection campaigns were conducted for the goal of gathering data from the previously listed metallic trace elements. Soil and mining waste samples were collected using a mechanic auger from a depth of 0 to 30 cm. To prevent contamination, surface sediments were gathered using a stainless-steel spoon along the streams where mining occurs. A composite sample (0.5 - 1 kilogram) is drawn from five elementary samples at each location. These samples come in a sterile, easily identifiable plastic bag. Three composite samples were created for the soil surrounding the mines, three for waste rock, four for tailings, and four for sediments, giving a total of fourteen composite samples.

2.2. Analysis of Samples

2.2.1. Chemical and Physical Analysis

Following a minute of stirring with a magnetic stirrer and two hours of rest, the pH of the samples are determined in the supernatant of a mixture of 10 g of sample and 25 ml of distilled water. A Crison BASIC 20+ brand pH meter is used to measure the pH in accordance with the NFT 90-008 standard, and a Knick Portamess type multi-parameter is used to calculate the electrical conductivity (EC) in accordance with standard NF EN 27888. The AFNOR NF X31-130 standard's Metson method was used to quantify the cation exchange capacity (CEC) (Saragoni et al., 1992). In accordance with the international standard NF ISO 11263, assailable phosphorus (Pass) was calculated (Webster, 2011). Additionally, loss on ignition was used to determine the samples' organic matter (OM) concentration (Allen, 1974).

2.2.2. Analysis of Chemicals

Using a combination of HF/HNO_3 concentrates, heavy metals (Al, Mn, Ba, V, Cr, Pb, As, Ag, Y, Hg, Th, and U) were examined by acid digestion. The ALS lab in Vancouver, Canada, then used ICP-MS (inductively coupled plasma mass spectrometry) measure the quantities of heavy metals.

2.3. Determining the Level of Contaminations

The degree of contamination of materials (soils surrounding mines, waste rock, residues, and sediments) in trace elements was evaluated using the following metrics: the enrichment factor (FE), the geo-accumulation index (Igéo), the contamination factors (CF), the degree of contamination (DC), the average contamination index (Im), the pollution load index (PLI), and the ecological risk index (Ri).

2.3.1. Factor of Enrichment (EF)

To differentiate human contributions from natural resources and assess the level of contamination, the enrichment factor (EF) has been proposed (Reimann & de Caritat, 2005). The EF was calculated by comparing the concentration of a relatively immobile component in the sample with the amount of a contaminating component present in the sample. This ratio was then compared to the material reference concentration, which is globally recognized as the reference concentration for uncontaminated areas (Turekian & Wedepohl, 1961; Martínez et al., 2007). Aluminum (Al) was selected as the reference element for this calculation since it is a fundamental immobile element. In this study, aluminium (Al) was chosen as the normalizing element because it is a rather conservative element, a major constituent of clays, with a very significant correlation with most of the trace metal elements studied, and it comes mainly from natural sources (Roussiez et al., 2005).

The EF is calculated using the relationship below (Zoller et al., 1974; Elvine Paternie et al., 2023).

$$EF = \frac{\left([M][Al]\right)\text{sample}}{\left([M][Al]\right)\text{background}}$$

Five categories are used to group the EF values: According to Yongming et al. (2006), EF ≤ 1 indicates minimal to no enrichment, 1 < EF ≤ 3 indicates low enrichment, 3 < EF ≤ 5 indicates moderate enrichment, 5 < EF ≤ 10 indicates moderate to high enrichment, $10 < EF \le 25$ indicates significant enrichment, $10 < EF \le 25$ strong enrichments, $25 < EF \le 50$ very enriching, and $EF > 50$ indicates extremely high enrichment.

2.3.2. Index of Geo-Accumulation (I-Geo)

Müller (1969) claims that this indicator compares a value thought to reflect the geochemical background with a particular concentration of a sediment. The geochemical background noise in this study is defined by the mean values of the continental crust as established by Rudnick and Gao (Rudnick & Gao, 2004). The following formula was used to determine the geo-accumulation index:

$$\mathrm{I}_{\mathrm{geo}} = \log 2\left(\frac{Cn}{1.5Bn}\right)$$

where C is the concentration observed in the sample, B is the geochemical background, I-geo is the geo-accumulation index, log2 is the base-2 logarithm, n is the element taken into consideration, and 1.5 is the factor normalizing its natural fluctuations. According to Müller (1969), the findings are interpreted as follows: Class (0), I-geo < 0: uncontaminated; 0 - 1 (1): free from mild contamination; Light to moderate contamination is represented by I-geo 1 - 2 (2), moderate contamination by 2 - 3 (3), medium to severe contamination by 3 - 4 (4), strong contamination by 4 - 5 (5), and extreme contamination by I-geo > 5 (6).

2.3.3. Pollution Load Index (PLI), Average Contamination Index (Im), Degree of Contamination (DC), and Contamination Factor (CF)

The contamination factor is determined by the following formula:

$$\mathrm{CF} = \frac{Cx}{Bgx}$$

Bgx: backdrop for a metallic element x; Cx: measured content for an element x. The Canadian pollution limits for trace elements in sediment, which are included in **Table 1** (CCME, 2001), serve as the reference concentrations. Hakanson (1980) provided the following interpretation for the CF values: $CF \le 1$ denotes mild contamination, $1 \le CF \le 3$ denotes moderate contamination, $3 \le CF \le 6$ denotes considerable contamination, and $CF > 6$ denotes very strong contamination.

The following formula was used to determine the average contamination index (Im).

$$\mathrm{Im} = \frac{1}{n}\sum \mathrm{CF}$$

where CF represents the contamination factor and n corresponds to the number of elements examined. Im > 2 is the source of the contamination (Nadem et al., 2015).

The root number (n) times the contamination factor (CF) values, which are represented by the following formula are equal to the pollutant load index (PLI) of a single site.

$$\mathrm{PLI} = \sqrt[n]{\mathrm{CF}_1 \times \mathrm{CF}_2 \times \mathrm{CF}_3 \times \cdots \times \mathrm{CF}_n}$$

PLI results are interpreted as follows: PLI < 0 shows pure sediments; PLI = 0 denotes excellence; PLI = 1 simply indicates baseline levels of pollution; and PLI > 1 (Harikumar et al., 2009; Seshan et al., 2010), where n indicates the total number of metals and CF portrays the contamination factor.

2.3.4. Ecological Risk Index (Ri)

Ecological risk Index was established by Hakanson (1980). Sediments' ecological danger is evaluated using this measure. Other writers utilize it to evaluate the ecological risk of pollutants like metals in sediments and soil (Yi et al., 2011).

$$\mathrm{Er} = \mathrm{Tr} \times \mathrm{CF}$$

$$\mathrm{Ri} = \sum_{1}^{n} \mathrm{Er}$$

where each metal's potential ecological risk is depicted by Er, the ecological risk index by Ri, the toxic response factor by Tr, and the contamination factor by CF. The trace elements that were examined (V, Mn, Cr, As, Hg, and Pb) had toxic reaction factors (Tr) of 2; 1; 2; 30; 40; and 5, respectively, according to Hilton et al. (1985). As outlined by Hakanson (1980), the following table presents the assessment of the ecological risk levels of sediments:

Potential ecological risk (Er) and ecological risk index (Ri) characteristics Er's Value Possible threat to the environment the value of Ri indicator of ecological risk Er (**Table 1**).

Table 1. Interpretations of potential ecological factor (Er) and ecological risk index (Ri).

Value of Er	Potential ecological risk	Value of Ri	Ecological risk index
Er < 40	Low	Ri < 95	Low
40 ≤ Er < 80	Moderate	95 ≤ Ri	Moderate
80 ≤ Er < 160	Considerable	190 ≤ Ri < 380	Considerable
160 ≤ Er < 320	High	380 ≥ Ri	Very high
320 ≥ Er	Very high		

3. Findings

3.1. Physico-Chemical Parameters

Table 2 presents findings from the physico-chemical parameters in soils around the mines, waste rock, residues and sediments.

According to these findings, the pH is moderately acidic to slightly acidic (5.6 to 6.1) in the soils around the mines; acidic to slightly acidic (5.2 to 6.3) in waste rock; slightly acidic to very alkaline (6.6 to 9.8) in tailings and slightly alkaline (7.1 to 7.8) in sediments. Organic matter (OM) is average to high (3.07 to 6.51) in the soils around the mines, Additionally, in the waste rock (3.70 to 4.94); it is low to medium (1.30 to 3.90) in the residues, on the other hand in the sediments it is low to high (1.20 to 4.74). Assailable phosphorus varies from 5.07 to 34.34 mg/kg in the soils around the mines, from 22.38 to 33.06 mg/kg in the waste rock, from

22.19 to 33.61 mg/kg in residues and 21.46 to 31.58 mg/kg in sediments; assailable phosphorus is t almost average in the materials used except in the sample (E25BE) of soils around mines, where it is low with a value less than 7 mg/kg. The cation exchange capacity (CEC) is moderate to high in soils around mines, tailings and sediments (between 14.11 and 35.34 meq/100g), conversely, in waste rock it is moderate to very high (19.13 to 45 meq/100g). The electrical conductivity (EC) of all samples is less than 250 (µs/cm), therefore all these materials are non-saline.

Table 2. Physico-chemical parameters of study site materials.

	Samples	pH-eau	MO (%)	CEC (méq/100g)	P assim (mg/kg)	CE (µs/cm)
Ground mining	E065CB	6.1	5.99	19.28	34.34	100
	E16EM	6.1	6.51	35.34	20.54	50
	E25BE	5.6	3.07	15.54	5.07	20
Steriles	E165CB	5.6	3.70	21.00	22.38	10
	E17EM	6.3	3.90	45.00	33.06	10
	E77DA	5.2	4.94	19.13	32.13	20
Tailings	E67CB	7.1	3.17	24.72	33.61	80
	E89KO	6.6	2.34	14.11	22.56	40
	E84LT	9.8	3.90	19.97	24.77	120
	E85LT	8.8	1.30	32.95	22.19	180
Sediments	E80SK	7.7	2.86	23.19	24.22	50
	E81SK	7.5	1.20	18.39	31.58	20
	E71SCM	7.8	3.38	33.12	23.11	30
	E72SCM	7.1	4.94	19.32	21.46	40

3.2. Heavy Metal Concentrations

The MTE contents (Al, Ba, Mn, Cr, V, Y, Ag, Hg, Pb, Th and U) are presented in Table 3.

The materials from mining sites have contents sometimes exceeding UCC's values (Rudnick & Gao, 2004) for certain MTEs. The values in MTE (mg/kg) in the soils around the mines vary for Al from 9600 to 18300; Ba from 166 to 287; for V from 22 to 102; Cr from 30.9 to 68 Mn from 95 to 564; for Y from 11 to 18; Ag starting at 0.019 to 0.028; for Hg 3.29 to 50; for As from 0.1 to 1.1; for Pb from 14.17 to 28.04; for Th from 3.5 to 13.8 and for U from 1.2 to 3.5. Consequently, the decreasing order abundance of ETMs in the soils around the mines is the following: Ag > As > U > Th > Y > Pb > Hg > Cr > V > Ba > Mn > Al.

In the waste rock the MTE contents vary as follows: Al from 1300 to 14800; Ba from 167 to 373; V from 13 to 50; Cr 8.5 to 31.7; Mn 38 to 673; Y from 14 to 262; Ag 0.02 to 85.26; Hg from 0.35 to 50; As from 0.1 to 2.9; Pb 5.93 to 39.24; Th from 11.3 to 476.3 and U from 2.3 to 19.6. The abundant order of MTE in waste rock is: As > U > Cr> Pb > Hg > Ag > V > Y > Th > Ba > Mn > Al.

Table 3. MTEs concentrations in soils around mines, waste rock, residues and sediments at Ngoura.

		Al	Ba	V	Cr	Mn	Y	Ag	Hg	As	Pb	Th	U
	L.D.	0.01	0.5	1	0.5	1	3	2	5	0.1		0.1	0.1
Ground mining	E065CB	11,100	212	22	42.9	514	11	0.019	21.14	0.4	28.04	8.3	3.5
	E16EM	9900	287	35	30.9	564	18	0.028	50	0.1	14.75	3.3	1.2
	E25BE	18,300	166	102	68	95	17	0.021	3.294	1.1	14.18	13.8	1.9
Sterile	E165CB	14,800	373	35	26.8	312	14	0.025	29.732	0.2	32.39	11.3	7.5
	E17EM	1300	227	50	31.7	673	262	85.267	50	2.9	39.24	476.3	19.6
	E77DA	7600	167	13	8.5	38	17	0.02	0.355	0.1	5.93	22.3	2.3
Tailings	E67CB	3000	507	17	26.2	1283	35	1.124	50	0.1	33.57	29.1	20.4
	E89KO	3200	75	10	10.3	222	5	0.004	9.445	0.3	9.28	9.8	1.5
	E84LT	5200	319	29	43	442	12	0.579	10.137	3	40.4	22.1	25
	E85LT	5100	417	28	39.1	901	9	0.245	8.39	2	36.85	23.5	19.1
Sediments	E80SK	1800	671	7	18.7	35	21	0.059	0.005	2	19.05	1	0.2
	E81SK	4400	250	16	7.7	194	223	0.021	1.641	1.2	40.73	875.9	60.3
	E71SCM	9200	152	84	105.4	402	11	0.054	8.575	0.4	39.8	44.2	3.1
	E72SCM	11,000	1658	50	63.8	119	8	0.029	6.643	1.4	8.14	25.5	1
	Max	**18,300**	**1658**	**102**	**105.4**	**1283**	**262**	**85.267**	**50**	**3**	**40.73**	**875.9**	**60.3**
	Min	**1300**	**75**	**7**	**7.7**	**35**	**5**	**0.004**	**0.005**	**0.1**	**5.93**	**1**	**0.2**
	UCC	**81,500**	**628**	**97**	**92**	**800**	**21**	**53**	**0.05**	**4.8**	**17**	**3.8**	**2.7**

In the residues the MTE contents vary: Al from 3000 to 5200; Ba from 75 to 507; V from 10 to 29; Cr from 10.3 to 43; Mn from 222 to 128 3; Y from 5 to 35; Ag 0.04 to 1.12; Hg 8.39 to 50; Ace from 0.1 to 3; Pb from 9.28 to 40.4; Th from 9.8 to 29.1 and U from 1.5 to 25. The order of abundance of ETMs in the residues is as follows: Ag > As > Y > U > Hg > V > Th > Cr > Pb > Ba > Mn > Al.

In sediments, MTE contents (mg/kg) vary as follows: Al from 1800 to 11,000; Ba from 152 to 1658; V from 7 to 84; Cr from 7.7 to 105.4; Mn from 35 to 402; Y from 8 to 223; Ag 0.021 to 0.059; Hg from 0.005 to 8.57; Aces from 0.4 to 2; Pb from 8.14 to 40.73; Th from 1 to 875.9 and U from 0.2 to 60.3. The order of abundance of ETMs in sediments is as follows: Ag > As > Hg > U > Pb > V > Cr > Y > Mn > Th > Ba > Al.

3.3. Estimation of Contamination

3.3.1. Enrichment Factor (EF)

The enrichment factor (EF) is widely used method for evaluating the extent of enrichment. Additionally, it is generally useful for comparing the level of contamination in different environmental biota. The enrichment factors (EF) of MTEs in soils around mines, waste rock, tailings and sediments are indicated in **Table 4**.

Table 4. Enrichment factor (EF) for heavy metal soils around mines, waste rock, residues and sediments.

EF		Ba	V	Cr	Mn	Y	Ag	Hg	As	Pb	Th	U
Ground minig	E065CB	2.48	1.67	3.42	4.72	3.85	0.00	3104.34	0.61	12.11	16.04	9.52
	E16EM	3.76	2.97	2.76	5.80	7.06	0.00	8232.32	0.17	7.14	7.15	3.66
	E25BE	1.18	4.68	3.29	0.53	3.61	0.00	293.40	1.02	3.71	16.17	3.13
Sterile	E165CB	3.27	1.99	1.60	2.15	3.67	0.00	3274.54	0.23	10.49	16.38	15.30
	E17EM	22.66	32.32	21.60	52.74	782.16	100.86	62692.31	37.88	144.71	7857.99	455.10
	E77DA	2.85	1.44	0.99	0.51	8.68	0.00	76.14	0.22	3.74	62.93	9.13
Tailings	E67CB	21.93	4.76	7.74	43.57	45.28	0.58	27166.67	0.57	53.65	208.04	205.26
	E89KO	3.04	2.63	2.85	7.07	6.06	0.00	4811.05	1.59	13.90	65.68	14.15
	E84LT	7.96	4.69	7.33	8.66	8.96	0.17	3177.56	9.80	37.25	91.15	145.12
	E85LT	10.61	4.61	6.79	18.00	6.85	0.07	2681.51	6.66	34.64	98.83	113.05
Sediments	E80SK	48.38	3.27	9.20	1.98	45.28	0.05	4.53	18.87	50.74	11.92	3.35
	E81SK	7.37	3.06	1.55	4.49	196.69	0.01	607.92	4.63	44.38	4269.49	413.67
	E71SCM	2.14	7.67	10.15	4.45	4.64	0.01	1519.27	0.74	20.74	103.04	10.17
	E72SCM	19.56	3.82	5.14	1.10	2.82	0.00	984.37	2.16	3.55	49.72	2.74
	Max	**48.38**	**32.32**	**21.60**	**52.74**	**782.16**	**100.86**	**62692.31**	**37.88**	**144.71**	**7857.99**	**455.10**
	Min	**1.18**	**1.44**	**0.99**	**0.51**	**2.82**	**0.00**	**4.53**	**0.17**	**3.55**	**7.15**	**2.74**

In the soils around the mines there are zero enrichments in As and Ag; Ba shows weak enrichment; V, Cr, Mn and Y show moderate enrichments; U and Pb indicate moderate to strong enrichments; Th illustrates strong enrichment and at the end Hg shows extreme enrichment. Depending on the average values of EF in the soils around the mines, enrichment order is respectively: Ag (0) > As (0.6) > Ba (2.47) V > (3.10) > Cr > (3.15) > Mn (3.68) > Y (4.84) > U (5.43) > Pb (7 .65) > Th > (13,12) > Hg (3876.68).

In the waste rocks the enrichment factor differs from that of the soils around the mines, thus Cr and Ba show moderate to strong enrichment; V, As and Mn illustrate strong enrichments; Ag shows very strong enrichment; while Pb, U, Y, Th and Hg illustrate extreme enrichments. The order of enrichment in the waste is as follows: Cr (8.06) > Ba (9.59) > V (11.91) > As (12.77) > Mn (18.46) > Ag (33.62) > Pb (52.98) > U (159.84) > Y (264.83) > Th (2645.76) Hg > (22014.33).

In the residues, the enrichment factor shows results contrary to that of the waste rock, it is thus observed that Ag shows zero enrichment; V and As show moderate enrichments; Cr illustrates moderate to strong enrichment; Ba, Y and Mn show strong enrichments; Pb shows very high enrichment; Th, U and Hg show extreme enrichments. The order of enrichment in the residues is presented as follows: Ag (0.20) > V (4.17) > As (4.65) > Cr (6.17) > Ba (10.88) > Y (16.78) > Mn (19.32) > Pb (34.86) > Th (115.92) > U (119.39) > Hg (9459.19). In sediments the enrichment factor varies thus, Ag shows zero enrichment; Mn and V show moderate enrichments; Cr and As show enrichments moderates to strong; Ba illustrates strong enrichment; Pb shows very strong enrichment; Y, U, Hg and Th present extreme enrichments. The order of enrichment in sediment is presented as follows: Ag (0.01) > Mn (3.01) > V (4.45) > Cr (6.51) > As (6.6) > Ba (19 ,36) > Pb (29.85) > Y (62.35) > U (107.48) > Hg (779.02) > Th (1108.54).

3.3.2. Geo-accumulation Index (I-geo)

Values of geo-accumulation index (I-geo) of MTEs are recorded in the table and presented in Table 5.

Table 5. Geo-accumulation index (I-geo) of heavy metals for soils around mines, waste rock, residues and sediments of selected sites of Ngoura.

I-geo		Al	Ba	V	Cr	Mn	Y	Ag	Hg	As	Pb	Th	U
Ground minig	E065CB	−3.46	−2.15	−2.73	−1.69	−1.22	−1.52	−12.03	8.14	−4.17	0.14	0.54	−0.21
	E16EM	−3.63	−1.71	−2.06	−2.16	−1.09	−0.81	−11.47	9.38	−6.17	−0.79	−0.79	−1.75
	E25BE	−2.74	−2.50	−0.51	−1.02	−3.66	−0.89	−11.89	5.46	−2.71	−0.85	1.28	−1.09
Sterile	E165CB	−3.05	−1.34	−2.06	−2.36	−1.94	−1.17	−11.63	8.63	−5.17	0.35	0.99	0.89
	E17EM	−6.56	−2.05	−1.54	−2.12	−0.83	3.06	0.10	9.38	−1.31	0.62	6.38	2.27
	E77DA	−4.01	−2.50	−3.48	−4.02	−4.98	−0.89	−11.96	2.24	−6.17	−2.10	1.97	−0.82
Tailings	E67CB	−5.35	−0.89	−3.10	−2.40	0.10	0.15	−6.14	9.38	−6.17	0.40	2.35	2.33
	E89KO	−5.26	−3.65	−3.86	−3.74	−2.43	−2.66	−14.28	6.98	−4.58	−1.46	0.78	−1.43
	E84LT	−4.56	−1.56	−2.33	−1.68	−1.44	−1.39	−7.10	7.08	−1.26	0.66	1.96	2.63
	E85LT	−4.58	−1.18	−2.38	−1.82	−0.41	−1.81	−8.34	6.81	−1.85	0.53	2.04	2.24
Sediments	E80SK	−6.09	−0.49	−4.38	−2.88	−5.10	−0.58	−10.40	−3.91	−1.85	−0.42	−2.51	−4.34
	E81SK	−4.80	−1.91	−3.18	−4.16	−2.63	2.82	−11.89	4.45	−2.58	0.68	7.26	3.90
	E71SCM	−3.73	−2.63	−0.79	−0.39	−1.58	−1.52	−10.52	6.84	−4.17	0.64	2.96	−0.39
	E72SCM	−3.47	0.82	−1.54	−1.11	−3.33	−1.98	−11.42	6.47	−2.36	−1.65	2.16	−2.02
	Max	**−2.74**	**0.82**	**−0.51**	**−0.39**	**0.10**	**3.06**	**0.10**	**9.38**	**−1.26**	**0.68**	**7.26**	**3.90**
	Min	**−6.56**	**−3.65**	**−4.38**	**−4.16**	**−5.10**	**−2.66**	**−14.28**	**−3.91**	**−6.17**	**−2.10**	**−2.51**	**−4.34**

The variation of Igeo in tailings, waste rock, soils and sediments presented in Figure 2. The Igeo values in the tailings, waste rock, and soils surrounding the mines as well as in the sediments for Ag, Al, As, Ba, V, Cr and Mn are less than 0 indicating the character non-contaminating of these materials for these elements. As for Pb, its Igeo values are lower than zero as well in all materials except in the residues where its value medium indicates that it is without contamination to slight contamination (0 ≤ Igeo < 1). The soils surrounding the mines also exhibit no contamination to mild contamination. However, in the waste rock and sediments Th exhibits moderate to strong contamination (2 ≤ Igeo < 3), while Th and U exhibit moderate contamination (1 ≤ Igeo < 2). In the soils surrounding the mines and mining waste, mercury exhibits extreme pollution (Igeo < 5); yet, in the sediments of, mercury exhibits strong contamination (3 ≤ Igeo < 4).

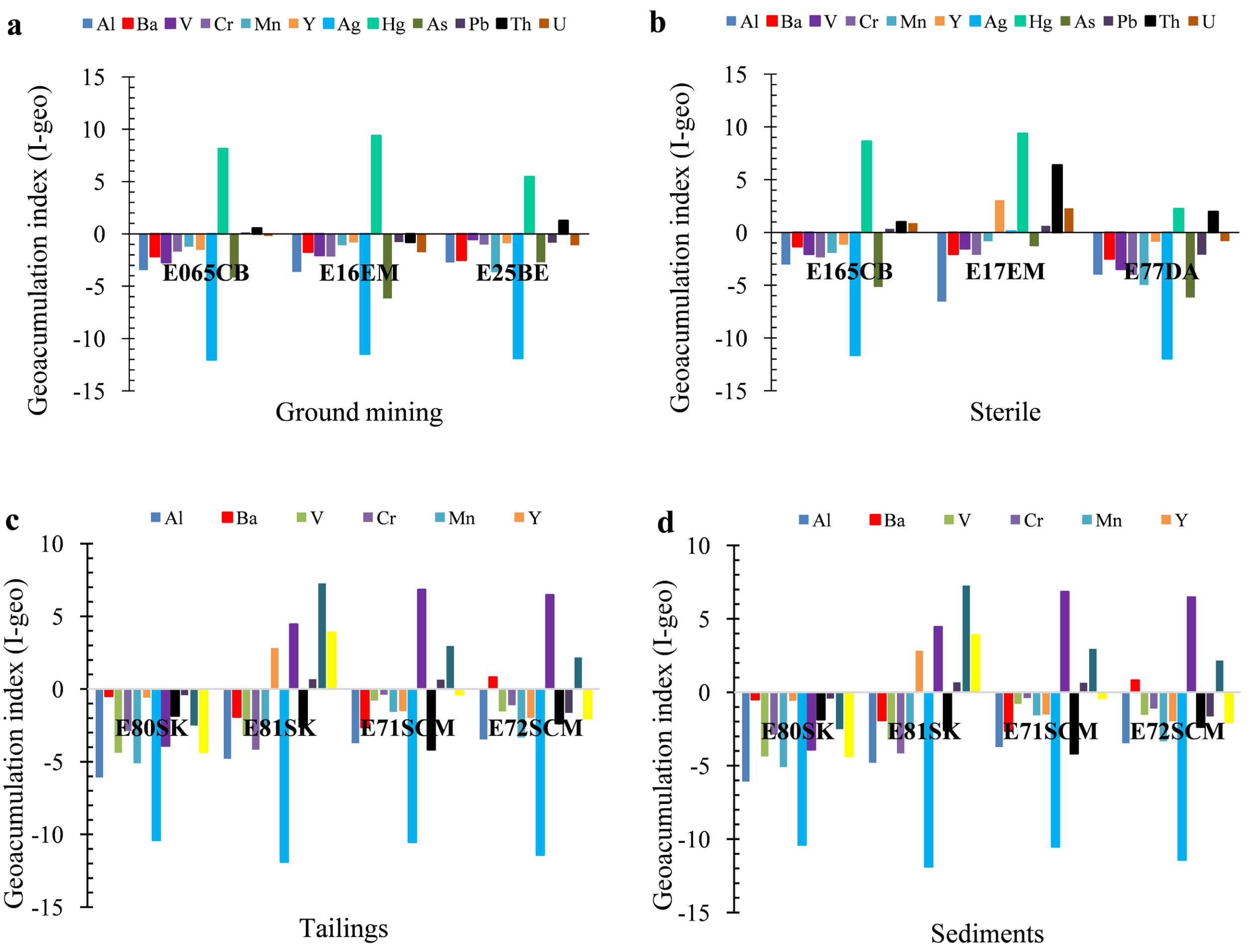

Figure 2. Geo-accumulation index (I-geo) variations: (a) Soils and mines; (b) Waste rock; (c) residues; (d) Sediments.

3.3.3. Pollution Load Index (PLI), Contamination Index Average (Im), and Contamination Factor (CF)

Table 6 displays the outcomes of the CF, Im, and PLI calculations. For the contamination factor, it is observed around the mines in the soils absent to low contamination for Ag, As, Al, Ba, Mn, Cr, Y and U (CF < 1); moderate contaminations for Pb and Th (1 ≤ CF < 3) and very strong contamination for Hg (6 ≤ CF). In the waste rock, Al, As, Cr, V, Ba, Mn and Ag present absent to low contamination; Pb shows moderate contamination; U and Y indicate considerable contaminations (3 ≤ CF < 6); Th and Hg illustrate very strong contaminations. In residues; Ag, Al, V, As, Cr, Ba, Y and Mn show absent at low contaminations, Pb indicates moderate contamination, Th shows considerable contamination, U and Hg show extremely high levels of pollution. Ba and Pb exhibit moderate contaminations, U and Y present significant contaminations, Th and Hg indicate very strong contaminations, while Al, Mn, As, V, Cr and Ag suggest absent at low contaminations in the sediments.

The pollutant load index (PLI) calculated from the contamination's values factor (CF) shows that all samples have a PLI < 1, except the waste rock sample E17EM which has a PLI of 2.30; translating thus that all samples are unpolluted, except sample E17EM, (PLI > 1), is interpreted as being a very strong pollution. However, the calculation of the Im shows that all the samples are contaminated (Im > 2) with the exception of samples E77DA (1.30) and E80SK (0.37) of waste rock and sediment respectively.

Table 6. Contamination factor (CF), Pollution Load Index (PLI) and average contamination index (Im) in soils around mines, waste rock, residues and sediments.

CF		Al	Ba	V	Cr	Mn	Y	Ag	Hg	As	Pb	Th	U	PLI	Im
Ground minig	E065CB	0.14	0.34	0.23	0.47	0.64	0.52	0.00	422.80	0.08	1.65	2.18	1.30	0.46	35.86
	E16EM	0.12	0.46	0.36	0.34	0.71	0.86	0.00	1000.00	0.02	0.87	0.87	0.44	0.40	83.75
	E25BE	0.22	0.26	1.05	0.74	0.12	0.81	0.00	65.88	0.23	0.83	3.63	0.70	0.44	6.21
Sterile	E165CB	0.18	0.59	0.36	0.29	0.39	0.67	0.00	594.64	0.04	1.91	2.97	2.78	0.53	50.40
	E17EM	0.02	0.36	0.52	0.34	0.84	12.48	1.61	1000.00	0.60	2.31	125.34	7.26	2.30	95.97
	E77DA	0.09	0.27	0.13	0.09	0.05	0.81	0.00	7.10	0.02	0.35	5.87	0.85	0.18	1.30
Tailings	E67CB	0.04	0.81	0.18	0.28	1.60	1.67	0.02	1000.00	0.02	1.97	7.66	7.56	0.87	85.15
	E89KO	0.04	0.12	0.10	0.11	0.28	0.24	0.00	188.90	0.06	0.55	2.58	0.56	0.19	16.13
	E84LT	0.06	0.51	0.30	0.47	0.55	0.57	0.01	202.74	0.63	2.38	5.82	9.26	0.89	18.61
	E85LT	0.06	0.66	0.29	0.43	1.13	0.43	0.00	167.80	0.42	2.17	6.18	7.07	0.81	15.55
Sediments	E80SK	0.02	1.07	0.07	0.20	0.04	1.00	0.00	0.10	0.42	1.12	0.26	0.07	0.13	0.37
	E81SK	0.05	0.40	0.16	0.08	0.24	10.62	0.00	32.82	0.25	2.40	230.50	22.33	0.75	24.99
	E71SCM	0.11	0.24	0.87	1.15	0.50	0.52	0.00	171.50	0.08	2.34	11.63	1.15	0.62	15.84
	E72SCM	0.13	2.64	0.52	0.69	0.15	0.38	0.00	132.86	0.29	0.48	6.71	0.37	0.49	12.10
	Max	**0.22**	**2.64**	**1.05**	**1.15**	**1.60**	**12.48**	**1.61**	**1000.00**	**0.63**	**2.40**	**230.50**	**22.33**	**2.30**	**106.38**
	Min	**0.02**	**0.12**	**0.07**	**0.08**	**0.04**	**0.24**	**0.00**	**0.10**	**0.02**	**0.35**	**0.26**	**0.07**	**0.13**	**0.12**

3.3.4. Index of Ecological Risk (Ri)

Table 7 records the ecological risk index and possible risk factors (Er) of sediment trace elements. The results of the risk index assessment ecological in relation to contamination materials in trace elements show the potential's values risk factors (Er) which vary from the lowest value (0.04) for Mn to the highest value (40,000) for Hg. Values of V vary from 0.14 to 2.10 with the greatest value in mining soils. Like V, Cr values are between 0.17 and 2.29 but with a maximum in sediments. Potential risk factors for Mn are very low, with a maximum value observed in wash residues. The As values of 0.63 - 18.75 and Pb (1.74 - 11.98) indicate low Er with maximum values respectively in washing residues and sediments. The Er values of Hg (4 - 40,000) are very high in all materials (Table). The potential risk factors show ecological risks very high in the majority of samples, except sample E77DA of waste rock and E80SK of sediment.

3.4. Statistics Analysis

The statistical analysis methods listed and used in this work are the Pearson correlation matrix and principal component analysis.

Table 7. Potential ecological factor (Er) and ecological risk index (Ri) in in soils around mines, waste rock, residues and sediments.

Er		V	Cr	Mn	Hg	As	Pb	RI
Ground minig	E065CB	0.45	0.93	0.64	16912.00	2.50	8.25	16924.78
	E16EM	0.72	0.67	0.71	40000.00	0.63	4.34	40007.06
	E25BE	2.10	1.48	0.12	2635.20	6.88	4.17	2649.95
Sterile	E165CB	0.72	0.58	0.39	23785.60	1.25	9.53	23798.07
	E17EM	1.03	0.69	0.84	40000.00	18.13	11.54	40032.23
	E77DA	0.27	0.18	0.05	284.00	0.63	1.74	286.87
Tailings	E67CB	0.35	0.57	1.60	40000.00	0.63	9.87	40013.02
	E89KO	0.21	0.22	0.28	7556.00	1.88	2.73	7561.31
	E84LT	0.60	0.93	0.55	8109.60	18.75	11.88	8142.32
	E85LT	0.58	0.85	1.13	6712.00	12.50	10.84	6737.89
Sediments	E80SK	0.14	0.41	0.04	4.00	12.50	5.60	22.70
	E81SK	0.33	0.17	0.24	1312.80	7.50	11.98	1333.02
	E71SCM	1.73	2.29	0.50	6860.00	2.50	11.71	6878.73
	E72SCM	1.03	1.39	0.15	5314.40	8.75	2.39	5328.11
	Max	**2.10**	**2.29**	**1.60**	**40000.00**	**18.75**	**11.98**	**40032.23**
	Min	**0.14**	**0.17**	***0.04**	**4.00**	**0.63**	**1.74**	**22.70**

Table 8. Pearson correlation matrix between physico-chemical parameters and heavy metals in this study.

Variables	Al	Ba	V	Cr	Mn	Y	Ag	Hg	As	Pb	Th	U	pH-eau	MO	CEC	P assim	CE
Al	**1**	0.05	**0.63**	0.48	−0.32	−0.42	−0.36	−0.12	−0.39	−0.28	−0.34	−0.39	−0.47	0.36	−0.32	**−0.62**	−0.23
Ba	0.05	**1**	−0.01	0.17	−0.10	−0.17	−0.12	−0.10	0.18	−0.27	−0.15	−0.15	0.17	0.15	−0.10	−0.08	0.05
V	**0.63**	−0.01	**1**	**0.84**	−0.12	−0.03	0.15	−0.03	0.06	0.05	−0.09	−0.24	−0.13	0.07	0.19	**−0.65**	−0.27
Cr	0.48	0.17	**0.84**	**1**	0.01	−0.28	−0.06	−0.11	0.05	0.17	−0.29	−0.32	0.19	0.14	0.20	−0.44	0.04
Mn	−0.32	−0.10	−0.12	0.01	**1**	0.09	0.22	**0.69**	0.01	0.52	−0.05	0.22	0.26	−0.06	0.51	0.36	**0.54**
Y	−0.42	−0.17	−0.03	−0.28	0.09	**1**	**0.74**	0.26	0.40	0.45	**0.91**	**0.68**	−0.05	−0.26	0.41	0.42	−0.35
Ag	−0.36	−0.12	0.15	−0.06	0.22	**0.74**	**1**	0.49	0.50	0.29	0.41	0.14	−0.14	0.04	**0.67**	0.30	−0.26
Hg	−0.12	−0.10	−0.03	−0.11	**0.69**	0.26	0.49	**1**	−0.13	0.24	0.01	−0.01	−0.25	0.39	**0.60**	0.30	−0.05
As	−0.39	0.18	0.06	0.05	0.01	0.40	0.50	−0.13	**1**	0.39	0.27	0.33	**0.61**	−0.28	0.30	−0.02	0.30
Pb	−0.28	−0.27	0.05	0.17	0.52	0.45	0.29	0.24	0.39	**1**	0.45	**0.65**	**0.54**	−0.38	0.43	0.35	0.30
Th	−0.34	−0.15	−0.09	−0.29	−0.05	**0.91**	0.41	0.01	0.27	0.45	**1**	**0.84**	0.06	−0.40	0.16	0.37	−0.31
U	−0.39	−0.15	−0.24	−0.32	0.22	**0.68**	0.14	−0.01	0.33	**0.65**	**0.84**	**1**	0.40	**−0.54**	0.03	0.38	0.10
pH-eau	−0.47	0.17	−0.13	0.19	0.26	−0.05	−0.14	−0.25	**0.61**	**0.54**	0.06	0.40	**1**	−0.43	0.11	0.04	**0.66**
MO	0.36	0.15	0.07	0.14	−0.06	−0.26	0.04	0.39	−0.28	−0.38	−0.40	**−0.54**	−0.43	**1**	0.12	0.11	−0.14
CEC	−0.32	−0.10	0.19	0.20	0.51	0.41	**0.67**	**0.60**	0.30	0.43	0.16	0.03	0.11	0.12	**1**	0.21	0.08
P assim	**−0.62**	−0.08	**−0.65**	−0.44	0.36	0.42	0.30	0.30	−0.02	0.35	0.37	0.38	0.04	0.11	0.21	**1**	0.08
CE	−0.23	0.05	−0.27	0.04	**0.54**	−0.35	−0.26	−0.05	0.30	0.30	−0.31	0.10	**0.66**	−0.14	0.08	0.08	**1**

3.4.1. Pearson Matrix of Correlation

The Pearson correlation matrix between heavy metals and physico-chemical parameters (**Table 8**) show substantial positive relationships between V/Cr and Al/V. The values of these correlations are among others rAl-V = 0.63; rCr-V = 0.84. Significant correlations are also observed between Mn and Hg, with a value rMn-Hg = 0.69. Ag, Th and U show strong correlations with Y, and with each other, with corresponding rAg-Y = 0.74; rTh-Y = 0.91, rU-Y= 0.68 and rTh-U = 0.84. A considerable correlation is noticed between Pb and U, this correlation presents the value of r = 0.65. Positive correlations are observed between heavy metals and physico-chemical parameters, including Mn/CE (r = 0.54), Ag/CEC (r = 0.67), Hg/CEC (r = 0.60), As/pH (r = 0.61), Pb/pH (r = 0.54). A significant and negative correlation is noted between U/MO (r = −0.54). The physicochemical parameters present a single significant and favorable relationship between EC and pH (r = 0.66).

3.4.2. Principal Component Analyzes

Principal component analysis is an effective method for examining and comprehending data. According to the statistical analysis of heavy metals conducted as part of this work, variables F1 and F2 have a percentage of 76.07 (**Table 9**). 26.37% of the variables are explained by the factor axis F2, while 49.70% of the variables

Table 9. Results of principal component analysis (PCA): percentage of variance for each component and correlation coefficient of each variable with the components. In bold: correlation coefficient > 0.5).

	F1	F2	F3	F4	F5
Al	**0.55**	0.05	0.03	0.09	0.09
Ba	0.04	0.03	0.01	0.00	**0.44**
V	0.12	0.13	0.35	**0.37**	0.02
Cr	0.12	0.01	**0.59**	0.12	0.00
Mn	0.23	0.01	0.23	**0.32**	0.09
Y	**0.64**	0.14	0.05	0.15	0.00
Ag	0.35	**0.38**	0.02	0.02	0.12
Hg	0.10	**0.43**	0.06	0.25	0.01
As	0.27	0.06	0.12	0.11	**0.30**
Pb	**0.52**	0.01	0.18	0.01	0.13
Th	**0.52**	0.01	0.12	0.24	0.01
U	**0.60**	0.07	0.04	0.08	0.08
pH-eau	0.16	**0.53**	0.21	0.00	0.02
MO	0.17	**0.28**	0.00	0.17	0.06
CEC	0.25	0.24	**0.28**	0.02	0.02
P assim	**0.39**	0.01	0.10	0.22	0.00
CE	0.03	**0.39**	0.22	0.21	0.00

are indicated by the factor axis F1. Heavy metals including Al, Y, Pb, Th, and U exhibit strong relationships with the F1 axis Al, Y, Pb, and Th have the corresponding correlation coefficients of 0.55, 0.64, 0.52, and 0.60 for this axis. Ag, Hg, pH, MO, and CE all show moderate correlations on the F2 axis, with corresponding coefficient values of 0.38, 0.43, 0.53, 0.28, and 0.39 for Ag, Hg, pH, and CE, respectively.

4. Discussion

4.1. Physico-Chemical Parameters

The pH varies in the materials analyzed, ranging from acidic to very alkaline (5.2 to 9.8) in the samples, the smallest value is located in the waste rock sample E77DA and the largest value is observed in the sample E84LT of tailings. pH results are almost comparable to those documented (5.01 to 8.34) on soils and sediments from artisanal gold sites of Betaré-oya (Elvine Paternie et al., 2023). The acidity of the waste rock can be deduced from the nature of the parent rock and the alkalinity is surely due to the use of chemical substances such as cyanide and mercury.

Organic matter (OM) varies from low to very high (1.20 to 6.51) in the studied materials. Organic matter plays an important contributing factor to the dispersion of MTEs between soil solution and MTE, and therefore in controlling their availability. Organic compounds generally have a high affinity for EFAs, as a result of the presence of carboxylic, phenolic or alcoholic groups or ligands (Alloway, 1995).

4.2. Heavy Metals

1) Al

The average content (mg/kg) in Al of the soils surrounding the mines (13,100) is higher, waste rock (7900), tailings (4125) and sediments (6600), yet below the reference value (81,500) of the UCC. In contrast to the abandoned artisanal gold mining sites of Betarè-oya, where the average Al contents in the soils and sediments were 88,000 and 95,200 mg/kg, respectively, the average Al contents in the soils surrounding the mines are lower (Elvine Paternie et al., 2023). The average Al content in our sediments is lower than those of the sediments (9590.01) of the Abieté-Toko gold zone, in southern Cameroon (Mandeng et al., 2019). The Al in this study contents represent the highest concentrations compared to other metals. Al is an abundant element in the earth, but its concentration can vary according to geological and environmental conditions. The low Al values observed in soils around mines, waste rock, tailings and sediments. The UCC is contrast value may be due to either leaching, fixation or dilution (Alloway, 2013). Indeed, Al can be leached or diluted in mines and soils, tailings by runoff and especially the washing operations observed during ore processing. The correlation between Al and V mineralogical explanations of association: these metals can be associated with similar minerals such as silicates or iron oxides, which are commonly present in mining soils and sediments.

2) Ba

The average contents (mg/kg) of Ba around the mines in the soils (221.66), in the waste rock (255.66), in the residues (329.5) are lower than those of the sediments (662.75) which is higher than the benchmark value (628) of the UCC. The average Ba values of our mining waste are lower (578.95) than those of mining waste from the Bétaré-oya gold district (Manga et al., 2017). The average Ba content obtained significantly more in the study's sediments than the 43.25 mg/kg found in Boyo sediments in the Betaré-oya district (Ndema et al., 2021). The average Ba content observed on our soils around the mines is lower than the value of 382.27 mg/kg which represents the average concentration on the soils surrounding the mines in the northwest of Ivory Coast, from Gbétogo to Séguéla (Yao et al., 2020). It is believed that low Ba values are caused by the condition of H, which is either basic or acidic in the media leading to reduced solubility (Kabata-Pendias & Pendias, 2011).

3) Mn

In comparison to the soils surrounding the mines (391), waste rock (341), tailings (712), and the UCC reference value (800), the average content (mg/kg) of Mn in the sediments (187.5) is lower. The highest value (1283) in Mn is found in sample E67CB of residues obtained after treatment of gold mineralized gravels. The manganese provenance of the analyzed components is geogenic, as it moves from damaged rocks when an oxidative process takes place in the soil, and changes into manganese oxides. It could constitute a relevant indicator in the quest for gold (Ntiamoah-Agyakwa, 1979). Although manganese ore comes from geological processes, it could also come from mining actions. Generally, heavy metals are found naturally in the soil. However, mining increases the potential for exposure through excavation, crushing, management and removal of mining waste from the area. The low Mn content is thought to be linked either to leaching processes (ore processing methods: washings), or to complexation processes with organic and inorganic ligands in water, which could lead to its solubilization and leaching loss into watercourses (Luoma & Rainbow, 2005). Correlations between Mn and Th are notable. Due to Mn association with mineral phases rich in oxides and hydroxides, Th has strong affinities with the same mineral phases as Mn, and is most often absorbed by oxy-hydroxides.

4) Y

Sediment (65.75) and waste rock (97.66) have greater average Y contents (mg/kg) than the UCC reference value (21). The average Y concentration found in waste rock is more than the value found in Betaré-oya waste rock (39.35) (Manga et al., 2017). This study's Y concentration is below the average of 85.37 mg/kg found in the Boyo sediments at Betaré-oya (Ndema et al., 2021). Our study's Y levels vary from 14 to 262 mg/kg in waste rock and from 8 to 223 mg/kg in sediments. These are greater than the 15.8 to 26.3 mg/kg found at the Betaré-oya gold location (Blanchard et al., 2018). Since significant levels of Y ranging from 16 to 82 mg/kg have been found in the Betaré-oya mining sites, it is believed that the nature of the parent rock and mining activity are the causes of the high levels of Y in our materials (Manga et al., 2017). Compared to sediments from the Eséka stream, which had an average Y value of 6.5 mg/kg, the sediments from this study had a greater Y value (Sababa et al., 2021). Y and Ag and Th and U were found to be positively correlated. Granitic rocks are believed to be associated with the occurrence of yttrium in the sediments of the investigated area (Gao & Zhou, 2016).

Despite being mislabeled as a heavy metal; yttrium is actually a rare earth that has some toxicity. When its concentration in the human body exceeds safe thresholds, it may be harmful to the liver (He, 2013). As consequence, residents and crafts people may be at risk of Y contamination.

5) V

The average concentrations (mg/kg) of V in the tailings (21), waste rock (32.66), sediments (39.25), and soil surrounding the mines (53) are all below the UCC reference limit (97). The E25BE soil sample at the mining tower has the highest value (102) in V; this value is higher than the UCC value. The average V concentrations in soils and mine waste in the Betare-oya mining region at the vicinity to the study area are 83.75 and 125.25, respectively (Tehna et al., 2019); these values are greater than those registered in this study for the same materials. The V concentration in the soils surrounding the Gbétogo mines in Séguéla, northwest Ivory coast, ranges from 323.28 to 509.18 mg/kg (Yao et al., 2020). These values exceed those of the soils surrounding the mines in this study (22 to 102) and the Bengote mine (East-Cameroon) (Tehna et al., 2023). The low V values found in this study could be the consequence of physical or chemical changes that lower the concentration of V, or they could have been leached off during the washing process of ore processing. V and Cr were found to display a positive correlation, which can be explained by the fact that these two metals have a common geological origin that allows them to be linked to similar iron, titanium, or chromite minerals that are typically found in mining sites (Alloway, 2013).

6) Cr

The average Cr contents (mg/kg) in the waste rock (22.33), tailings (29.65), and soils surrounding the mines (47.26) are lower than those in the mines (47.26) and sediments (48.2), but the latter are higher than the UCC reference value (92). According to Léopold et al. (2016), the mean Cr concentration in the soils (47.26) is higher than that of the exploited soils of Fel (22.1) and slightly lower than that of the Wantia exploited soils (50.9). Our tailings' average Cr concentration (29.65) is less than that of the tailings in the Betare-oya mine area (152.5) (Tehna et al., 2019). According the average Cr concentration in the sediments is 48.2, which exceeds the value of 35 mg/kg in the continental crust (Wedepohl, 1995). The fallout of air particles and the leaching of chromium-containing particles account for the existence of Cr in sediments (Kotas & Stasicka, 2000). Since Cr was only detected in trace amounts (around 22 mg/kg) in the mozogranite of the study site, the low Cr concentrations found in the study highlights a geological fact (Lemdjou et al., 2022). The toxicity of these metals, which is based on the number of oxidations and their extremely low content in the water network such as gravel treatment (washing) systems mineralized that use large amounts of water sometimes in a closed vacuum (for example during cyanidation or artisanal washing), is what makes chromium (Cr) speciation important. Trivalent Cr(III) and hexavalent Cr(VI) are the two valence states of chromium that are most prevalent in the environment. The body requires chromium (III) as a micronutrient, whereas chromium Cr(VI) is very hazardous and carcinogenic (Wiryawan et al., 2018).

7) Hg

The average Hg level (mg/kg) in the sediments (4.21) is lower than that of the tailings (19.49), waste rock (26.69), and soils surrounding the mines. However, these values are remarkably higher than the 0.05 UCC reference value. Only the sediment sample E80SK has a concentration (0.005) below the UCC reference value among all the samples examined. The Hg concentration in the soils surrounding the mines (24.81 mg/kg) is also higher than the value (0.03) often reported in the soils (Lindsay, 1979; Murthy, 2008). According to Ngounouno et al. (2021), the Hg contents in the sediments of the present study varies from 0.005 to 8.57 mg/kg, which is lower than the values found in the sediments of the Lom River in Wakaso (Adamawa, Cameroon). Our mining discharges had Hg concentrations ranging from 0.35 to 50 mg/kg, which is significantly higher than the 0.005 to 0.032 mg/kg found in the Betare-oya mining discharges (Tehna et al., 2019). The greatest Hg level in Iran's gold mine tailings is 100 mg/kg (Rafiei et al., 2010), which is greater than the study's maximum estimate of 50 mg/kg. The use of mercury for ore processing is undoubtedly the cause of the presence of mercury in the several compartments under study. Actually, gold is typically amalgamated with mercury to create a mercury-gold amalgam, which is subsequently heated to extract the mercury from the gold (WHO, 2016; Stoffersen et al., 2019). The creation of Hg-Mn complexes in mine site materials may be the cause of the observed positive association between Hg and Mn, which could affect the materials' mobility and availability.

8) As

The average As content (mg/kg) in soils around the mines (0.53) is lower than in waste rock (1.06), tailings (1.35) and sediments (1.25). The UCC is below all of these values reference (4.8). The maximum values recorded in our materials are below the maximum As value permitted in soils, which is 12 mg/kg (CCME, 1999). Elvine Paternie et al. (2023), almost found an average As concentration in sediments slightly higher than ours, with an exact value of 1.82 mg/kg. The low As levels recorded in this study may be due either to mineral fixation or leaching. Indeed, As can be fixed in soil on iron and other minerals, oxides or silicates, making it difficult to be extracted and measured. Despite arsenic levels below the WHO limit, continued exposure has adverse health effects. As per the WHO, the prolonged exposure has detrimental consequences for people's health. Inorganic As(III) and arsenate As(III) present the highest degree of toxicity. Inorganic As(III) and arsenate As(V) are predominant in mining waste. Indeed, The extraction procedure ore from the ground, and crushing and processing rock, produces vast volumes of waste containing sulfide minerals, which leach large volumes of metals such as arsenic (Fashola et al., 2016). pH influence on the availability of As explains the positive association between As and pH that was reported. Accordingly, an acidic pH (below 6) might enhance the availability of As and encourage its release from minerals (Alloway, 2013).

9) Pb

Waste rock (25.85), tailings (30.02), and sediments (26.93) had higher average Pb contents (mg/kg) than the soils surrounding the mines (18.81). However, the UCC (Rudnick & Gao, 2004) reference value (17) is significantly lower than these values. The mean Pb levels in the soils and sediments in this investigation are greater than the mean values found in the exploited soils (8.84) and sediments (24.2) of Betare-oya (Elvine Paternie et al., 2023). Mining discharges (waste rock and residues) have higher average Pb contents than waste from Kombo-laka mining sites (23) (Danala et al., 2024). The average lead concentration in the earth's crust is 16 $mg \cdot kg^{-1}$, according to Kabata-Pendias & Pendias (2010). However, the average lead concentrations in this study are greater at this number. The lead concentation in the mining processing discharges from the antimony mines of Tourtit and Ichoumellal (central Morocco) have been reported to be extremely high, ranging from 155.38 to 27594.60 mg/kg (Ahmedat et al., 2018). This is higher than the levels found in our rejects, which range from 5.93 to 39.24 in the waste rock and 9.28 to 40.4 in detergent residues. Lead is a chalcophile element whose primary mineralogical form found in the terrestrial environment is galena (PbS). The presence of lead in the different materials under study may be caused by mining in the study region or by the nature of the parent bed rock (Matocha et al., 2001). Both atmospheric fallout and contaminated waste that has been deposited on the ground, such as fuel and oil motor discharge from mining machinery and motor pumps, can contribute to the buildup of lead (Raskin & Ensley, 2000; Elvine Paternie et al., 2023) in mining sites. The study's Pb, U, and pH correlations can be explained by a number of factors, most notably mineralogical association and the influence of pH on the availability of Pb and U. Similar minerals like sulfides and oxides, which are typically found in soils, tailings, and sediments from mining sites, can be linked to these two elements. Accordingly, an acidic pH can enhance the availability of minerals and encourage the release of Pb and U (Kabata-Pendias & Pendias, 2011).

10) Th

The average concentrations of thorium (mg/kg) in tailings (21.12), waste rock (169.96), sediments (236.65), and soils surrounding mines (8.46) are significantly higher than the UCC reference value (3.8). Sediments from the Vale Abrutiga uranium mine (Pinto et al., 2004) and Th concentrations (15.19) in Nyambaka stream samples collected by Edima Yana et al. (2021) have lower mean Th values than the sediments (236.65). Rock weathering, leaching, and transport may liberate Th and other metals, increasing their concentration in waste rock and sediments, which might explain the elevated Th levels in these materials (Bradl, 2005). Mineralogical relationship explains Th's very high positive correlations with U and Y.

11) U

In soils surrounding mines, the average uranium content (mg/kg) is 2.2, which is lower than the UCC reference value (2.7) for waste rock (9.8), tailings (16.5), and sediments (16.15). In comparison to Tehna et al. (2019), who reported U values of 1.53 and 3.41 mg/kg for Betaré-oya soils and mine tailings, respectively, the average U contents in the soils surrounding the mines and in mine tailings are greater. This study's mean U content in the sediments (16.15) is significantly above 0.78 mg/kg found in the Abiete-Toko sediments (Mandeng et al., 2019). According to Liu et al. (2015), however, extremely high U concentrations of up to 537 mg/kg had been documented in sediments from the uranium mine in southern China. The presence of U in Ngoura mining materials is due to the nature of the parent rock. Pb and Th and U and Y have substantial positive correlations, which suggests that these elements share a common source.

4.3. Contaminations Estimates

4.3.1. Enrichment Factor

The calculation of the enrichment factor (EF) is an essential parameter to show whether heavy metals are of human or natural origin, as stated by Franco-Uría et al. (2009), and EF < 2 stipulates natural enrichment and a EF of 5 indicates anthropic enrichment. Therefore, according to this study (**Table 4**), Y, Hg, Pb, Th, and U are of anthropogenic origin, while Al, Ba, Mn, V, Cr, Ag, and As can be regarded as having a natural origin. The extreme enrichment observed for certain metals, such as Hg, are due to the varied ore processing methods which use mercury to amalgamate gold. For the different materials studied the order of decreasing enrichment is as follows: sediments soils around the mine residues sterile. The locality's gold mining sites contain materials that are rich in heavy metals, including Y, Hg, Pb, Th, and U.

4.3.2. Geo-accumulation Index

The geo-accumulation index makes it possible to emphasize contamination linked to anthropogenic activities (Zhang et al., 2022). In this study, it is used to assess the level of heavy metal pollution in the soil surrounding mines, waste rock, residues, and sediments. The geo-accumulation indices in the various materials under study are displayed in **Figure 2**, it is observed that Hg shows extreme contaminations in all materials, with in particular I-geo of classes 6 for the soils around the mines, the waste rock and residues, then the sediments indicate an I-geo class 4. These results are slightly similar to those of Fodoué et al. (2022), who also showed that Hg presents very strong contaminations in the Pawara gold sites. It is also observed that Th and U show strong contaminations, with Igeo ranging from class 2 to 3.

4.3.3. Pollution Load Index (PLI), Average Contamination Index (Im), and Contamination Factor (CF)

Calculation of the contamination factor (**Figure 3**) shows a very strong contamination of Hg in all the materials used except in the sample of sediment E80SK which presents no contamination to low. These results are in agreement with those of Igeo, the high Hg contaminations reported in our materials are due to the usage of mercury in gold mining (Fodoué et al., 2022).

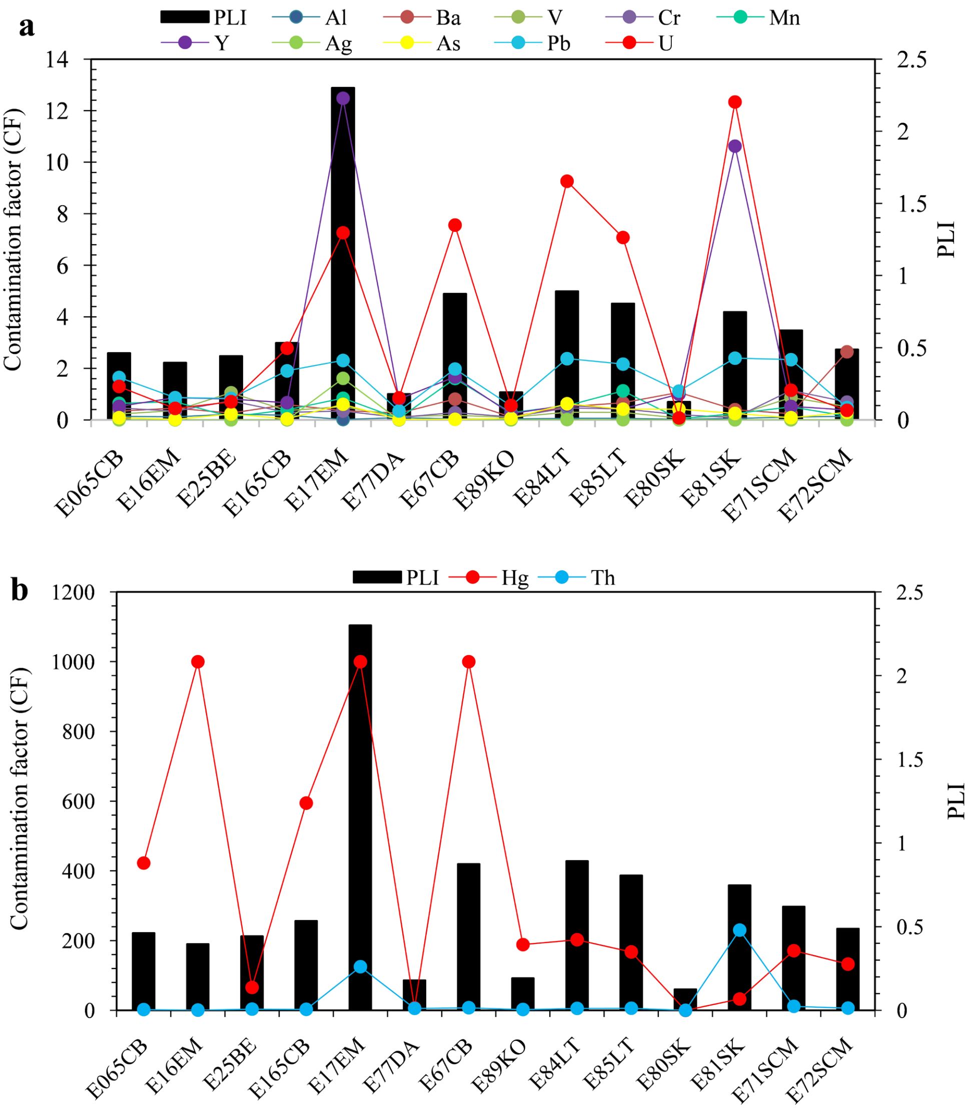

Figure 3. Variations in contamination factor (CF) and pollutant load index (PLI): (a) Low levels: CF (Al, Ba, V, Cr, Mn, Y, Ag, As, Pb, U) and PLI; (b) High levels: CF (Hg, Th) and PLI.

4.4. Risk to the environment

The Er and IR of the heavy metals in the various samples are shown in **Figure 4**. Practically in every sample, Hg displays the highest Er level. In fact, the possible ecological risk level for mercury is quite high in all samples, with values much above 320, except for two samples (E77DA and E80SK). V, Cr, Mn, As, and Pb have a low potential ecological risk, as indicated by the fact that their sum of potential ecological risk is less than 40. In the materials under study, the ecological risk result is extremely high, especially for mercury. Thus, the substantial risk of mercury pollution in the Ngoura mining area is confirmed by the prospective ecological index that was developed.

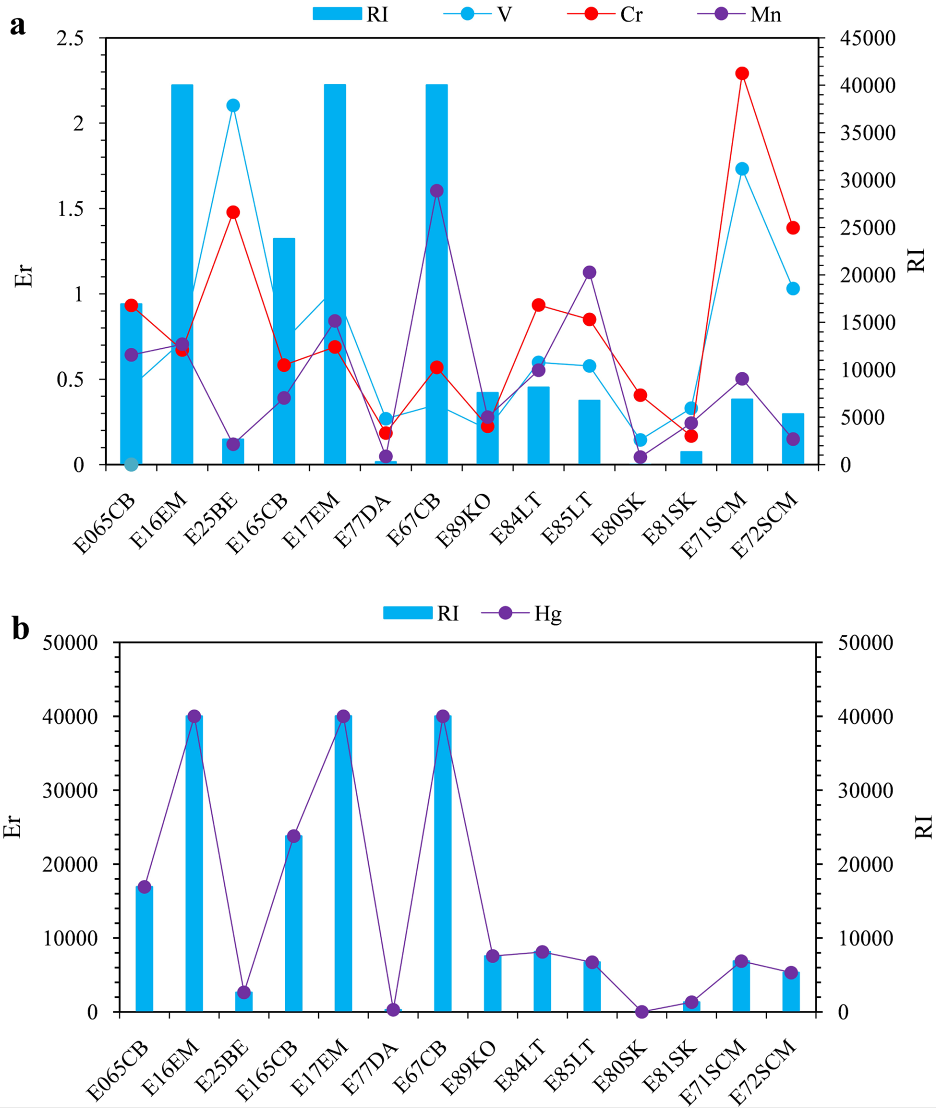

Figure 4. Variations potential ecological factor (Er) and ecological risk index (Ri) in in soils around mines, waste rock, residues and sediments: (a) Low levels (V, Cr, Mn, As, Pb); (b) High levels (Hg).

The average ecological risk index value is 14265.43, which is greater than the values recorded on sediments in two watersheds in the southern Cameroonian Abiete-Toko gold district (1311.38) (Mandeng et al., 2019). The similarly, a high value (6084) for possible ecological danger in mercury has been found in soils from the Pawara gold mining region in eastern Cameroon (Fodoué et al., 2022).

The different correlations observed between the elements studied are illustrated in **Figure 5**. The positive and significant correlations observed between most of the metals studied could be explained by a possible common origin or having the same chemical properties; on the other hand, the negative correlations could evoke either different origins between these elements or the fact that an increase in the concentration of one element could lead to a decrease in the concentration of the other.

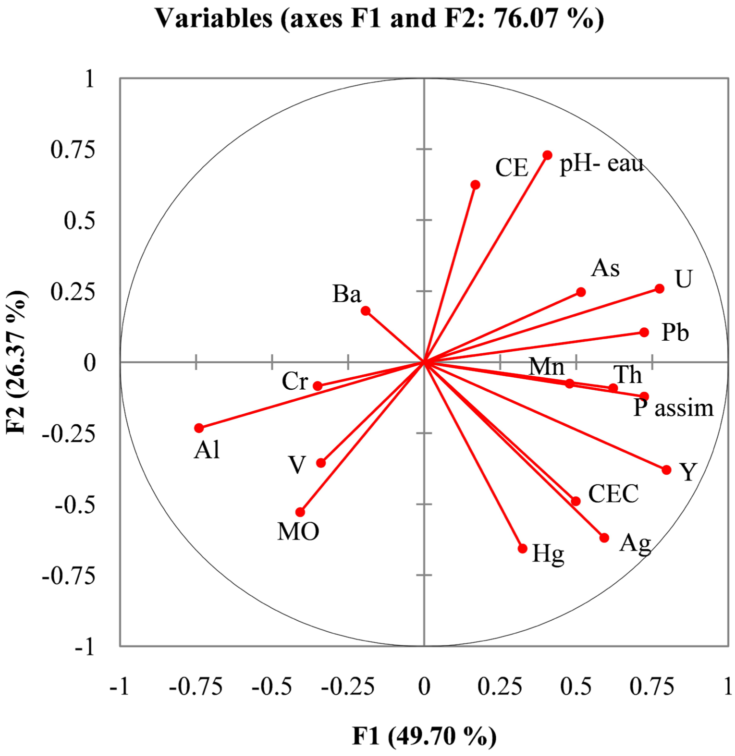

Figure 5. Principal component analysis (PCA).

5. Conclusion and Recommendations

5.1. Conclusion

By assessing the concentrations of heavy metals (Al, Ba, V, Cr, Mn, Ag, Pb, As Y, Hg, U, and Th) in the materials under investigation (soils surrounding the mines, waste rock, tailings, and sediments), this study sought to investigate the chemical effects of gold extraction activities in the Ngoura area. To achieve this, these materials were sampled and analyzed. The results showed materials with acidic to very alkaline pH and are non-saline, with low to very high OM, moderate to very high CEC, very low assailable phosphorus (Pass) to medium. Variable and high contents (mg/kg) were recorded in the materials studied including 1300 to 18,300 for Al, 75 to 1658 for Ba, 7 to 102 for V; 7.7 to 92 for Cr, 35 to 1283 for Mn, 5 to 262 for Y; 0.004 to 85.26 for Ag; 0.005 to 50 for Hg; As 0.1 to 3; Pb ranges from 5.93 to 40.73, Th ranges from 1 to 875.9, and U ranges from 0.2 to 60.3. Calculations of the contamination indices (EF, Igeo, CF, Im, PLI and Ri) showed polymetallic contamination of substances investigated in heavy metals, specifically Hg, Y, Pb, Th, and U. Furthermore, the ecological risk (Ri) which englobes toxicity, it can be seen that the materials from the mining sites in the locality of Ngoura indicate an ecological risk (Ri > 380) which is very high, due to Hg which shows a very high potential ecological risk (Er > 320). In fact, mercury is generally used in mining, these processes generate risks of contamination of ecosystems and local populations hence the need to offer reliable solutions to these problems.

5.2. Recommendations

1) There are many potential remediation strategies for mitigating heavy metal pollution, including phytoremediation, bioremediation, chemical remediation, physical remediation and electrochemical remediation. But in our context, phytoremediation could be the most suitable way of limiting contamination in the study area.

2) Prevention and reduction at source: Use alternative extraction methods to mercury and cyanide, such as gravimetry or leaching with thiosulphate.

3) Supervision of artisanal mining activities: Train miners in good practice and regulate the use of toxic products.

4) Mine waste management: store mine waste (waste rock and tailings) in appropriate infrastructure to prevent seepage.

5) Opt for revegetation of degraded and contaminated sites by planting local species to stabilise the soil and limit erosion.

Conflicts of Interest

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

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