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Risks of chemical pollution on the environment by solid mine waste at the semi-industrial iron mining site in Bandjeli, Togo

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Abstract

The abandoned Bandjeli iron mining site in Bassar district in northern Togo has huge impacts on natural resources and the biodiversity. The diagnosis of the current state of the environment was carried out on the river which received the water from the washing of the ore and the leaching water from the waste rock and ore stockpiles that are abandoned without protection. The traces metallic elements (TME) proportions of these wastes were determined to evaluate the chemical contamination of water, soil, sediments and air from these wastes. The samples of sediment, waste rock piles, raw and semi-washed ores were taken from the site. Analysis of these samples shows the following results: All of these samples contain Pb, Cd, As, Mn and Fe with respective average values: 52, 4 mg/kg, 34.8 mg/Kg, 53.68 mg/Kg, 2503.6 mg/Kg and 383742 mg/Kg. The sediments samples were also taken along the river. The analysis highlighted the strong sediments pollution by Pb (lead), Cd (calcium), Mn (manganese) and Fe (iron) with respective average values 112.75 mg/kg, 5.75 mg/kg, 2991.75 mg/kg and 177133 mg/kg. These values are extensively high to the reference values of TME in the continental crust. High levels of trace metallic elements in stream sediments are a source of contaminations in stream waters and pose a risk of public health since water from the streams is used for human and animal consumption during periods of rain.

1. Introduction

African countries like other countries in the world have always used natural resources in different area for their development. Since the colonial period, African countries have always supplied mineral resources to industries in developed countries [1]. Africa is a major producer of mining raw materials [2]. The Democratic Republic of Congo was a major supplier of copper. African countries supply almost all-natural rubber [3] and Togo ranked fifth in the world in phosphate production [4]. More and more African states are basing their hopes on natural resources in general and mining resources in particular to boost their economic. They intend to seize the opportunity to increase export earnings, stimulate growth, create jobs and fight poverty [5]. Nigeria and Ghana achieved cumulative exports of mineral resources in 1980 to around 98% of primary commodities. Likewise, Zambia's Copper export is estimated at 90%. Togo has distinguished itself in the exploitation of phosphates, limestone, marble and iron. Today, Togo has launched the mining sector in its poverty reduction strategy. Several companies have obtained certificates of environmental compliance for the exploitation of manganese ores, precious stones, gravel, sand, migmatite, gold, gneiss, iron, marble, Ilmenite, granulite and limestone [6]. In 2010, Togo's national report for the18th session of the United Nations Sustainable Development Commission established clinker and cement as Togo's first export products [7]. According to the Extractive Industries Transparency Initiative (EITI) report in 2017, the revenues generated by the mining sector amounted to 16,261 billion Fcfa for the year 2017.

This hope that mineral resources arouse for the economy of Togo leads to an intensification of mining methods [3]. This massive exploitation of mineral resources is accompanied by environmental degradation, particularly chemical pollution. The production of industrial waste is increasing at an alarming rate worldwide [8] and in particular mining waste at operating or abandoned sites. Mining is one of the most important sources of heavy metals in the environment [9].The mines are sources of chemical contamination of the environment for three reasons [10]. At first, the mineral deposits contain large quantities of substances with no economic value, and as a result, mining opens up routes for water circulation in areas that are not cracked and exposes them to pollutants such as heavy metals, finally, mining produces huge masses of waste rock.

The problems of environmental chemical pollution by mining activities in Africa as in the whole world are no longer to be demonstrated. This pollution is dangerous for human health and the survival of ecosystems as a result of chronic exposure and accumulations [11, 4]. The main pollutants typically are copper (Cu), nickel (Ni), zinc (Zn), lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr) and some other metals, whose high contents could pose risks for human and environment [12, 13, 14, 15, 16]. Arsenic (As) and selenium (Se), which are only trace elements and not metals, should be added to this list [17, 18]. In the Hahotoe-Kpogame phosphate mining area, the contamination of surface and groundwater by trace metallic elements was reported, in particular by lead (258.9µg/l) and cadmium (24.74µg/l) [19]. Like any extractive company, the exploitation of Bandjeli iron in the prefecture of Bassar is probably a source of chemical pollution.

The overall objective of this study is to contribute to controlling the environmental problems raised by abandoned mining sites in Togo. More specifically, the study aims at carrying out the physico-chemical characterization of the residues stored on the site, then determining the polluting capacity of these residues by measuring the trace metallic elements and finally determining the environmental impacts of these residues.

2. Methodology

2.1 Presentation of the study area

The prefecture of Bassar is located in the northwest of Togo precisely in the southwest of Kara region. It covers a surface area of 3620 km^2 and is located between 09°9°30´North latitude and 0° 35° 50´ East longitude. Bandjéli is a township in the prefecture of Bassar and located about 36 km west of the town of Bassar and borders Ghana. It is located between 09°42°19´ North latitude and 0°62°43´ East Longitude (figure 1). The iron mining area consists of the quarry and direct influenced localities such as Bandjeli, Byakpambé, Bakpyabé, Bytakpambé, Bissibé, Koutangbaw, Milé-Milé, Nantchamba, Pikabombé, Tabalé and others indirectly.

Bandjeli iron mining is operated by MM Mining SA on the basis of an investment agreement of 7 August 2006 with the Togolese State. The mining activities could cover an area of about 3708 km² in the structural unit of Buem and about 11621 km² in the structural unit of Atakora.

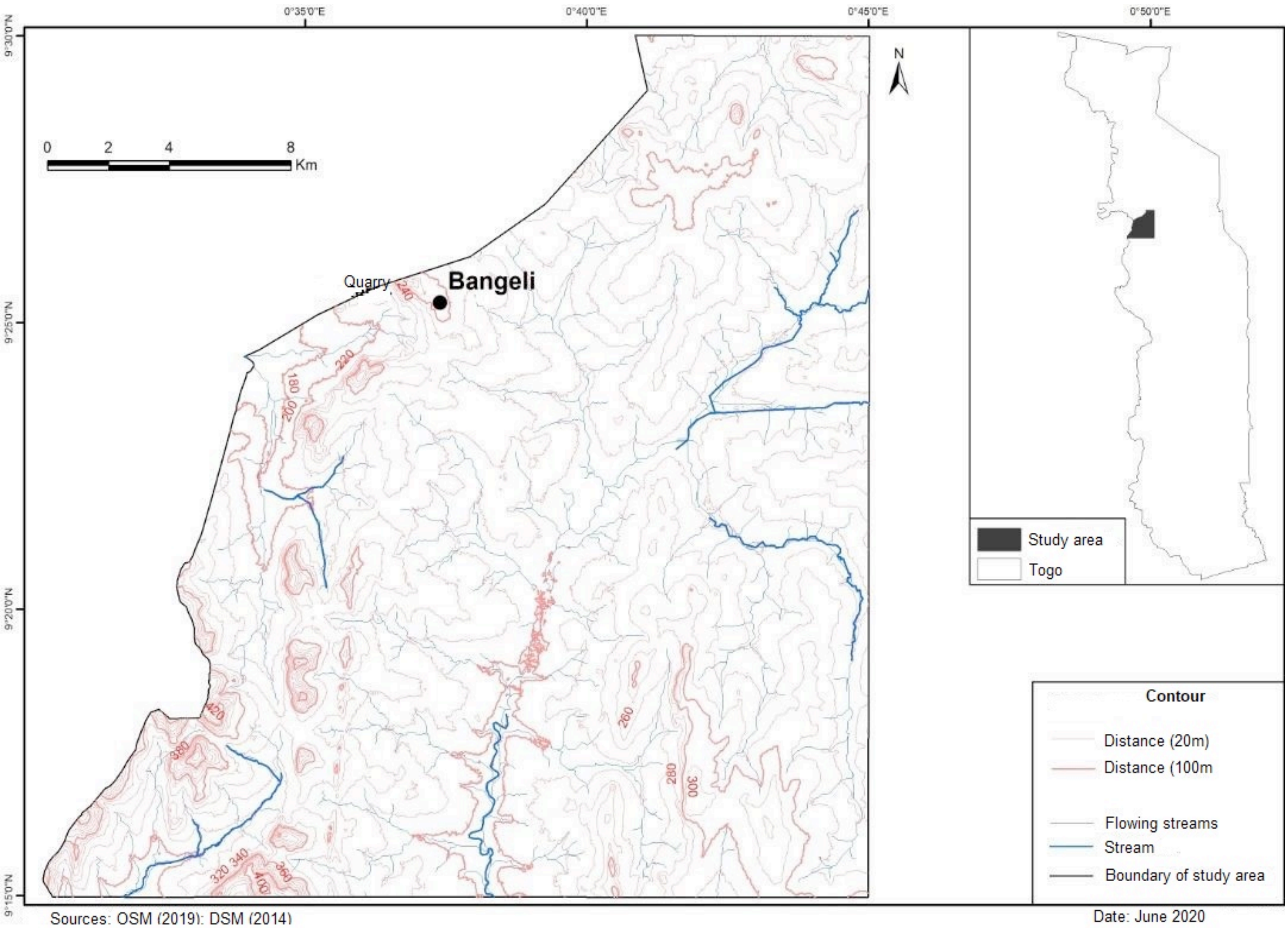

Figure 1: Geographic area of study

The reserve is estimated at 500 million tons and is located in depth of about 10 to 30 meters from the ground surface. The iron ore is mainly concentrated over a length of 50 km at the level of the hill of Bandjéli (figure 2) with iron proportions varying between 35 and 55%. The ore appears as hematite (Fe_2O_3) with traces of titanium (Ti), aluminum, manganese (Mn) and water (H_2O).

The area is built on the Precambrian meta-sedimentary and is characterized by large annual amounts of precipitation (1277.2 mm), varied and diversified soils [20], a Guinean Sudanese-type climate [21] and a hydrographic composed of creeks, marigots, standing waters and thalwegs. The wind velocity varies between 01 and 02 meters per second. These characteristics of the study area influence the mobility of chemical elements and other environmental components.

The iron mining of Bandjeli began in 2010 and stopped in 2016 leaving open-pit solid mine waste on the site on the side of a steep mountain. In order to access the iron layer, the company cleans the surface by raising all the vegetation and then the dead earth that covers the iron layer. Crude iron ore blocks are extracted by drilling and blasting the iron layer. These blocks are then crushed and separated from their clay gangue and washed. The wash water is stored in a drain and the sludge is deposited by settling. The overflow of this drain is discharged directly into a stream (river) that discharges into the other down streams. Soil cleaning products, dead land, processed and unprocessed iron ore are stored on site. In this study, solid mine waste residues consists of waste rock piles, stored ore piles and drain sediments abandoned at the Bandjeli Iron Mine Site.

Figure 2: Map showing the study area with some sampling points

2.2. Material and Method of Residue Analysis

A preliminary field prospection was carried out in June and July 2017 to identify the zones and points of sampling of sediment, sterile soil and stored ore. The drain sediment samples were collected by diving, using a manual corer consisting of tubes of 40 cm long and 7 cm in diameter driven vertically into the sediment. These samples were taken from plastic bowls of 02.5 kg and then transported to the laboratory for analysis. The samples from the waste rock piles and the raw and semi washed ore in the plastic bowls of 02.5g were collected using a small plastic shovel. The sediment of river receiving the wastewater from the drain was also sampled in the same condition. The different treatments of the sediment samples consist in drying in ambient air around 40 °C to constant mass, followed by a reduction of the clods and sieving through a 2 mm "Nylon" type sieve. Analytical work took place in two laboratories. The Laboratory of Applied Hydrology and the Environment of the University of Lomé served as a framework for physico-chemical analysis as well as the preliminary treatment of samples for the determination of heavy metals in the “laboratory of Faso” in Burkina Faso. The “Laboratory of Faso” is specialized in physico-chemical and microbiological analyses of water and laboratory study on decontamination of mining site. The physicochemical parameters determined are: pH, organic matter, residual humidity and electrical conductivity. Calcium, magnesium, silica, sodium, potassium and phosphorus concentrations are measured. The particles size of the residues was carried out on filters of 500 µm, 250 µm, 100 µm, 75 µm and less than 75µm to determine the size of the different particles. The sieves (AFNOR standard) were used to determine the particles size.

2.3 Traces metallic elements analysis

In order to determine the polluting capacity of the solid mine waste, the study proceeded to the dosage of some heavy metals (traces metallic elements). The chemical treatment consisted of dissolving the residue samples using aqua regia [22, 23]. The method consists in subjecting the sample to the action of aqua regia (mixture of pure nitric acid (15.8 M) and pure hydrochloric acid (12 M) by microwave). The extract is then filtered and adjusted to volume with nitric acid. For the analysis TME, the MP-AES 4200 (microwave plasma atomic emission spectrometer) was used.

3. Results and Discussion

3.1. Residue Characterization

To understand mobility and chemical reactivity, the particle size and some physicochemical parameters were determined.

3.1.1. Different Particles and their size

Size distribution allows determining sand, clay and silting composition in the residue. The knowledge of these constituents contributes in knowing their mobility. The finer constituents are easily carried by wind and run-off. The results (Figure 3) show that the sterile soil, the drain sediment, the untreated ores and the processed minerals respectively consist of 67.34%, 45.51%, 16.08% and 4.06% of particle size less than 500 µm. The sterile soil even contains 47.96% of the particles which size is less than 75 µm (Figure 4). The ore extracted is an aggregate of rock and the washing rids it of the finest particles. The fine particles resulting from this washing settle and pile up in the drain the unproductive soil is a vegetative soil rich in fine particles. Sterile soil, drain sediment, unwashed and semi-washed ore (solid mine waste) consists of fine particles including trace metallic elements. The washing and leaching of this solid mine waste removes these trace metallic elements toward the drain and other environmental components where they deposit and accumulate. These fine particles can be sent far into nature by winds and rainwater.

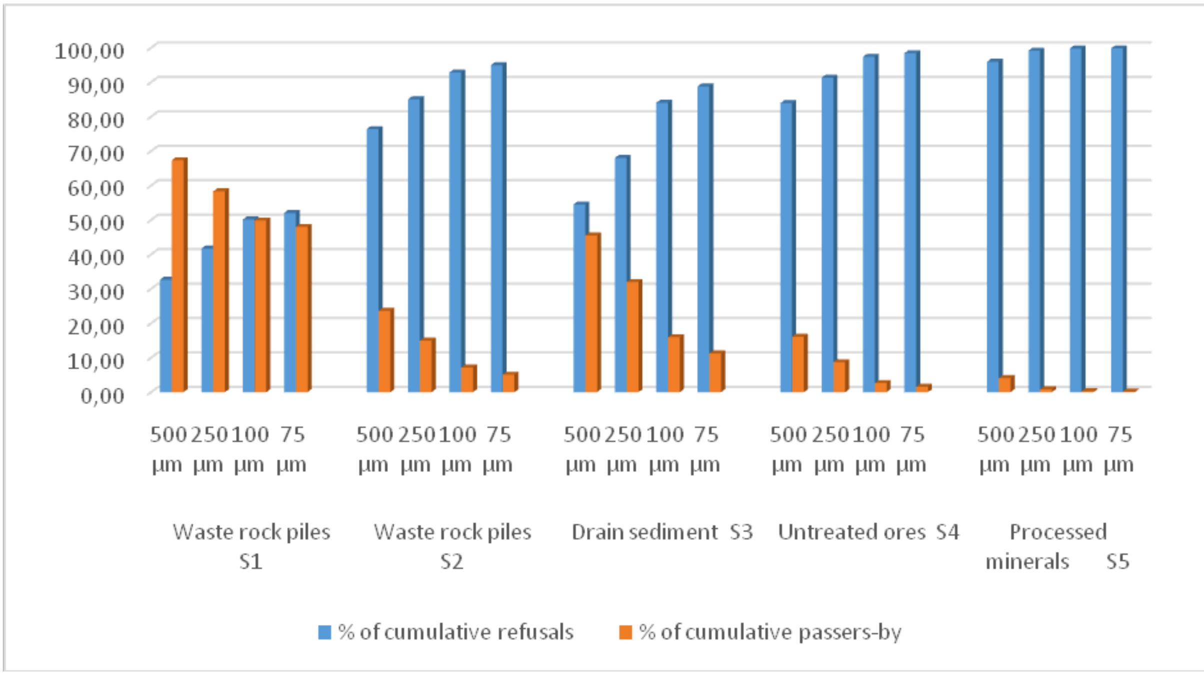

Figure 3: Particles size distribution in the residue

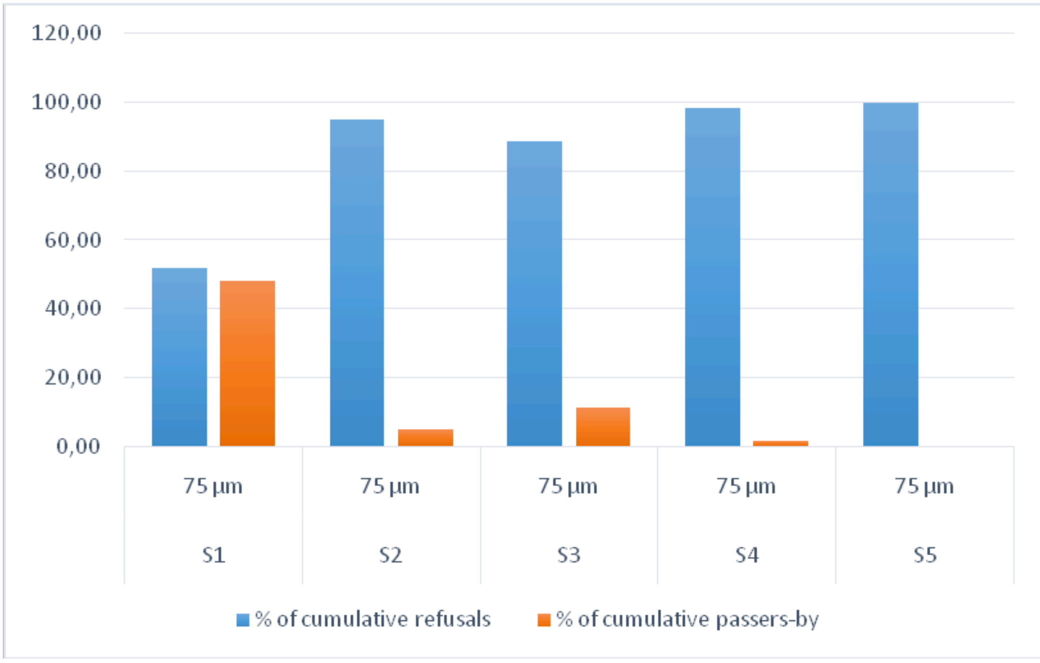

Figure 4: Particles less than 75 µm in size

3.1.2. Physicochemical Parameter and Trace Metallic Elements of residues

The physico-chemical parameters and Trace Metal Elements of residues were determined and presented in table 1, table 2, table 3, table 4, table 5 and table 6.

3.1.2.1. Physicochemical Parameters

The results of the general parameters measured in the residues and the sediment of the river are presented in Tables 1 and 2.

Table 1: Physicochemical parameters of the residues

Paramètres généraux	Drain sediment S3	Waste rock piles S1 et S2	Untreated ores S4	Processed minerals S5	Average value	minimum value	maximum value
pH	7.14	6.67	6.65	6.69	6.79	6.65	7.14
Cond (µS/cm)	18.4	10.2	10.5	10.1	12.3	10.1	18.4
Organic Matter (OM) (%)	5.511	2.738	2.134	1.643	3.0065	1.643	5.511
$CaCO_3$ (%)	0.8	1.6	2	0.8	1.3	0.8	2

The physico-chemical parameters of residues are characterized by a weakly acid pH and close to neutral pH. The average pH is 6.79 with a maximum pH (7.14) in the drain sediment and a minimum pH (6.65) in the untreated ore. The electrical conductivity is also low and varies between 10.1 µS,/cm to 18.4 µS/cm with an average of 12.3 µS/cm. This conductivity is characteristic of poor environment in anions and cations as shown in Table 2. The residues contain low organic matter and carbonates. The organic matter (OM) concentration varies between 1.643% (washed ore) and 5.511% (drain sediment) with an average of about 3.01%. The greatest concentration of carbonates (2%) is found in unwashed ore.

Table2: Physico-chemical parameters of sediments samples

Physico-chemical Para - meters	composite sediment between 50 and 100m (1)	composite sediments at approximate-ly 1 km (2)	Composite sediments at approximately 1.5 km (3)	Composite sediments at approximate-ly 2.2 km (4)	Average value	minimum value	maximum value
pH	7.57	6.86	6.60	7.56	6.86	6.60	7.57
Cond (µS/cm)	72.7	65.7	48 .2	19.3	51.475	19.3	72.7
MO (%)	2.926	10.236	11.734	1.752	6.662	1.752	11.734
$CaCO_3$ (%)	1.2	0.4	2	1.6	1.3	1.2	2

The pH in the sediment is between 6.60 and 7.57 with an average of 6.86. This is a pH almost neutral like that of residues. The conductivity and organic matter are respectively low in average at 51.48 µS/cm and 6.662%. Carbonates are also little present in the samples and are evaluated at 1.30%.

3.1.2.2. Major elements Content of Residues and sediment of the river

Table 3 and 4 show the percentages of the major elements (Mg, Ca, Na, K, Si, Al, Fe, Ti, P, Mn and Cr) of the residues and the sediments of the river. The analysis of Table 3 shows low contents of major elements in the analyzed residues except the iron proportion which vary between 15.86% in the sediment of the drain and 51.55% in the washed ore. The average iron proportion in residues is 23.95%. The average of the other major elements is between 0% and 0.57%. All residue samples are mainly composed of iron.

Table 3: Percentages of major elements in residues

Major Elements (%)	Drain sediment S3	Waste rock piles S2 et S2	Untreated ores S4	Processed mineralsS5	Average value	minimum value	maximum value
Ca	0.01	0.01	0.00	0.01	0.01	0.00	0.01
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.01	0.01	0.01	0.02	0.01	0.01	0.02
Na	0.03	0.02	0.04	0.02	0.03	0.02	0.04
PT	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Silice	0.29	0.21	0.22	0.21	0.23	0.21	0.29
Fe	15.86	41.57	48.12	51.55	23.95	15.86	51.55
Mn	0.17	0.23	0.37	0.28	0.16	0.17	0.37
Cr	0.01	0.01	0.01	0.01	0.00	0.01	0.01
Al	1.04	1.21	0.78	0.67	0.57	0.67	1.21
Ti	0.03	0.05	0.04	0.03	0.02	0.03	0.05
Total	**17.46**	**43.34**	**49.61**	**52.81**	**25.01**	**16.99**	**53.57**

Table 4 shows that the proportion of all the major elements in sediments of the river receiving the wastewater of mining, is less than 1% except iron which ratio varies between 15.978% and 19.191%.

The average concentration of major elements per sample is 19.75% and is mainly composed of 17.713% iron. These soils are poor in nutrient probably due to leaching phenomenon during rainy season where water flows permanently in the stream.

Table 4: Percentages of major elements in sediments of the river

Major elements (%)	composite sediment between 50 and 100m (1)	composite sediments at approximately 1 km (2)	Composite sediments at approximately 1.5 km (3)	Composite sediments at approximately 2.2 km (4)	Average value	minimum value	maximum value
Tca	0.01	0.02	0.02	0.00	0.01	0.00	0.02
Tmg	0.00	0.00	0.00	0.01	0.00	0.00	0.01
K	0.05	0.05	0.04	0.03	0.04	0.03	0.05
Na	0.04	0.05	0.05	0.04	0.05	0.04	0.05
PT	0.01	0.03	0.02	0.02	0.02	0.01	0.03
Silice	0.39	0.11	0.36	0.29	0.29	0.11	0.39
Fe	19.19	17.91	17.77	15.98	17.71	15.98	19.19
Mn	0.26	0.39	0.39	0.02	0.27	0.02	0.39
Cr	0.00	0.01	0.01	0.00	0.00	0.00	0.01
Al	0.87	1.43	1.41	1.59	1.33	0.87	1.59
Ti	0.04	0.04	0.04	0.02	0.03	0.02	0.04
Total	**20.87**	**20.04**	**20.11**	**17.99**	**19.75**	**17.99**	**20.87**

3.2. Residue Mobility and Polluting Capacity

3.2.1. Trace Metallic Elements in the Residues

The analysis results of trace metallic elements in the residues are presented in Table 5. The concentrations of Se, Sb, Ag, Co and Ni are below the analytical system detection limit of 0.1 µg/mg. The drain sediment has zero proportion of As. All others samples contain Pb, Cd, As, Mn, Cr, Cu, Fe, Al, Ti and Zn at various concentrations. Some elements such as Ti, Zn, Al, Cr and Cu are found in a trace state in the samples with concentrations lower than those of the geochemical background [25, 26]. Le Pb, Cd, As, Mn and Fe are present in all samples for content above the geochemical background limit values.

The contents of Pb, As, Cd, As, Mn and Fe exceed those refer to the continental layer. Therefore, these residues contain TMEs with concentrations higher than those of the geochemical background. These high levels of TME could be the result of anthropogenic pollution, geology or the soil environment of the ore. Indeed, Bandjeli's iron ore is a hematite which is a mineral species composed of iron oxide (Fe_2O_3) with traces of Titanium (Ti), Aluminum, Manganese (Mn) and Water (H_2O). It is an Alpha polymorph of Fe_2O_3 [24]. The other metallic elements can come from the ore of bauxite and their related metals present in the structural unit of Atacora and the structural unit of Buem such as arsenopyrite (FeAsS) often associated with the presence of gold [24]. As the environment is practically very mountainous and unsuitable for agricultural activities, the sources of contamination related to human activities can be neglected.

Table 5: Results of trace metallic elements in the residues (mg/Kg)

Residues	Pb	Cd	As	Ni	Co	Mn	Cr	Cu	Ag	Fe	Al	Se	Ti	Zn	Sb
Drain sediment	48	5	17	< 1	< 1	1657	51	14	< 1	158626	10429	< 1	334	15	< 1
Waste rock piles	39	40	60	< 1	< 1	2284	71	10	< 1	415740	12066	< 1	549	18	< 1
Waste rock piles	44	36	54	< 1	< 1	2029	64	10	< 1	347570	9354	< 1	525	15	< 1
Untreated ores	77	46	67	< 1	< 1	3730	78	13	< 1	481249	7809	< 1	394	25	< 1
Processed minerals	54	47	70	< 1	< 1	2818	63	10	< 1	515523	6723	< 1	337	24	< 1
Average value	52.4	34.8	53.68	< 1	< 1	2503.6	65.4	11.4	< 1	383742	9276.2	< 1	427.8	19.4	< 1
Geo-chemical back-ground	***17***	***0.09***	***1.5***	***44***	***17***	***600***	***83***	***25***	***0,051***	***35000***	***80400***	***-***	***3000***	***71***	***0,2***

Legend

- (red) Trace Metallic Elements content higher than geochemical background
- (yellow) Trace Metallic Elements content lower than geochemical background
- (green) Trace Metallic Elements content below detection limit

3.2.2. Trace Metallic Elements in Stream Bed Sediments

Table 6 presents the results of the metallic elements in the sediments samples taken from the bed of the river which received the ore washing water and the leaching water from the ores and earth piles stored and abandoned on the site. The results show that all the samples contain higher content of Pb, Cd, Mn and Fe than the reference values of TME in the continental layer [25, 26] which are respectively 17 mg/g, 0.09 mg/g, 600 mg/g and 35000 mg/g. Only the sediment sample taken from the bed at 2.2 km from the drain contains chromium (216 mg/kg) and copper (39 mg/kg) which values exceed those of reference in the continental layer respectively 83 mg/kg and 25 mg/kg. If the contents of Arsenic, Nickel, Cobalt, Silver, Selenium and Antimony are almost zero, the content of Aluminum, Titanium, Zinc are all lower in all the samples than those of the reference of the continental layer.

These results confirm studies by the Academy of Sciences [27] who found heavy metals in riparian soils at mine sites. These mining residues abandoned in open-cast mine constitute a TME reservoir. They contain metals at higher ratio than that in the continental crust [25, 26]. Sediment samples from the stream bed show an increase in TME levels as you move away from the site. This increase can be explained by the fact that the stored waste and drain are on top of the mountain and the water from the drain and tailings leaching into the stream has little time to stay in the bed of the river at the flank level. The flow rate of water decreases in the plain allowing deposition of sediments that contain TME. As the consequence, the Bandjéli River, the source that can supply the population with drinking water is polluted by the Trace Metallic Elements as reported by the NGO Solidarity and Action for a Sustainable Development (SADD) at a press conference on March 20, 2014 [28].

Table 6: The results of trace metallic elements in the sediment in mg/Kg

Residues	Pb	Cd	As	Ni	Co	Mn	Cr	Cu	Ag	Fe	Al	Se	Ti	Zn	Sb
Composite sediments at approximately 2.2 km	173	5	< 10	< 1	< 1	1525	216	39	< 1	159782	15934	< 1	155	25	< 1
Composite sediments at approximately 1.5 km	193	6	< 10	< 1	< 1	3939	45	17	< 1	177713	14132	< 1	401	26	< 1
Composite sediments at approximately 1 km	54	6	< 10	< 1	< 1	3929	46	17	< 1	179126	14293	< 1	416	27	< 1
Composite sediment between 50 and 100m	31	6	< 10	< 1	< 1	2574	44	10	< 1	191912	8663	< 1	392	14	< 1
Average value	113	6	< 10	< 1	< 1	2992	88	21	< 1	177133	13256	< 1	341	23	< 1
Geochemical background	**17**	**0.09**	**1.5**	**44**	**17**	**600**	**83**	**25**	**0.051**	**35000**	**80400**	**-**	**3000**	**71**	**0,2**

Legend

Red: Metal trace element content higher than geochemical background

Yellow: Metal trace element content lower than geochemical background

Green: Metal trace element content below detection limit

3.2.3. Influence of Physico-chemical Parameters

Analysis of the physico-chemical parameters in the residues shows that the pH is slightly acid. This pH acid is linked to the low content of $CaCO_3$ (1.3%) which plays a buffer role [29] in the residues and silica amount around zero (0.23%). The low content of organic matter and nutrients (phosphorus, potassium) in the waste dumps can be a limiting factor for the growth of the vegetation. The electrical conductivity of the samples is dominated by iron and has an average of 12.2 (µS/cm). The concentrations of calcium, magnesium, potassium, sodium, phosphorus, silica, manganese, chromium, aluminum and titanium are less than 1% in these residues.

The slight acid pH (6.79), the low proportion of carbonates (1.3%), organic matter (3%) and silica (0.23%) in the residues are the factors that will lead the remobilization TMEs [30] which can be driven by run-off and wind towards soils, water resources and the atmosphere.

Indeed, the residues have a low adsorption capacity and a high mobility of TMEs due to the low organic matter and an acid pH. Organic matter in sediments can efficiently chemisorb metal ions with a high degree of selectivity [31]. Carbonates and silica can incorporate or adsorb metal cations in their crystalline mesh [32] while they are in a very low average quantity. On the other hand, this mobility of metals in the residues can be reduced by the presence of major elements in the form of their oxide and hydroxide, including iron (23.95%), aluminum (0.57%), manganese (0.16%) which play an important role in the retention of metal ions [33]. The total average of these major elements is

25.01%. The stabilization of TMEs is related to the change in pH [34, 35]. The mobility of these ETMs in the soil is then clearly influenced by its physico-chemical parameters [36].

Conclusion

It appears from this study that the open-air deposits of the waste rock piles, washed and unwashed ore and drain sediments from the Iron mining site in Bandjeli/Bassar are characterized by a slightly acid pH, a low conductivity, low content of organic matter and carbonates. The analysis of the sediment from the stream receiving drain water and run-off water also shows that these sediments have low acid pH, low conductivity, organic matter and carbonate content. The results of TMEs in these sediments, confirm the presence of Pb, Cd, Mn, Cr, Cu and Fe with an average high than the reference values of TME in the continental crust. This contamination would come from residues which also contain these TMEs with proportion above the reference. In addition to Pb, Cd, Mn, Cr, Cu and Fe, these residues sampled in mining area contain As, Al, Ti and Zn in lower proportion than the TME reference in the continental crust. However, the accumulation of theses TMEs can be source of environment contamination. These residues constitute a TMEs reservoir and expose the soil, water and air of the locality. Contamination of these environmental components exposes the population who consumes water from the polluted river and agricultural products from contaminated sediments [37]. Additional studies (environmental, epidemiological and clinical) will better help to specify the environmental impacts and the biological consequences [38].

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