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Assessment of Trace Metal Soil Pollution Level and Remediation: The Case of the Penga-Penga District in the City of Lubumbashi, Haut-Katanga Province in the Democratic Republic of Congo

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Abstract
This research work focuses on the assessment of urban soil pollution and remediation methods, focusing on trace metal elements as the main pollutants. The study was carried out on the Gécamines site in Penga-Penga, analyzing pollution by trace metal elements. Soil samples were taken in three areas of Penga-Penga and two other districts (Kasapa and Gambela2) as control soils, confirming pollution by trace metal elements. Simple extraction tests at different pH showed significant results: acetic acid extracted 25 % of the copper and 29 % of the lead, caustic soda extracted 55 % of the cobalt and 47 % of the zinc, while distilled water extracted 81 % of cadmium. Phytoremediation with amaranthus viridis and brassica chinesis was carried out, showing specific plant affinities for certain metals: brassica chinesis extracted 62 % of the copper and 97 % of the cobalt, while amaranthus viridis extracted 93 % of the cadmium and 38 % of the lead. This study proposes phytoremediation as a remediation solution for the risks linked to metallic trace elements, offering a less expensive alternative and a precautionary measure. This approach makes it possible to consider other options in the future depending on the evolution of the local context and the metal market, highlighting its effectiveness in the rehabilitation of soils contaminated by trace metal elements.

Keywords: Soil pollution, Trace metal elements, Phytoremediation.

1. Introduction

Resulting of complex interactions between climate, geology, vegetation, biological activity, weather, and land use, the soil is a non-renewable resource. It is a soft surface layer of the earth's crust of variable thickness which results from the alteration of the underlying rocks (source rock) and the degradation of

organic matter, under the influence of biological agents (vegetation, soil fauna, etc.), chemical and physical (precipitation, temperature variation, etc.) [1,2].

The soil is made up of solid constituents (minerals and organisms) and pores containing liquid and gaseous constituents. The mineral constituents come from the degradation of the parent rock, plants, and contributions by man. The organic constituents are generally in very low proportion (around 5 %). They come from organisms present in the soil or brought to the soil by plants and animals [3]. In addition to its food function, the soil can also constitute an effective environmental filter by purifying the water that passes through it of various pollutants that can contaminate the food chain and groundwater [4,5,6]. However, industrialization, agriculture, and urbanization can pollute soils when not well managed.

Soil is considered polluted when the degradation of its quality by the anthropic contribution of toxic elements can harm human health or the environment. The presence of a pollutant in the soil is not in itself a danger. The risk appears as soon as this pollutant can be mobilized and acts on the environment (fauna, flora) or on humans [7]. There are several soil pollutants: hydrocarbons, polymers, heavy metals commonly called trace metal elements, etc. In themselves, pollutants are biological, physical, or chemical alterations, beyond a certain threshold, and sometimes under certain conditions, develop negative impacts on all or part of an ecosystem or the environment in general [8].

Consequently, we witness soil pollution when there is dispersion of these pollutants from one compartment to another. Therefore, the problem of polluted sites and soils is often associated with industrial activity. Indeed, the nature of the products handled, the quantities present on the site, and the intensity of the operations mean that industrial activities are the cause of more frequent incidents and with greater consequences for the soil. Soil alteration and humification are processes conditioned by a set of environmental factors such as the regional climate, the nature of the parent rock, its topography, living organisms, and time [9].

The Gécamines Penga-Penga site is located northeast of the Lubumbashi factories and the Lubumbashi slag heap processing company, in the Mampala district of the commune of Lubumbashi, in the city of Lubumbashi. This site has been the subject of several investigations into soil quality in recent years [10]. It is to deepen the research already carried out by other scholars [9,10]. That we carried out this study. The objective of this study is to highlight the quality of the soil of this site by analyzing the physicochemical and elemental parameters of the soil to evaluate the concentration of heavy metals in this soil.

2 Material and methods

2.1 Study area

The Gecamines Penga-Penga site is in the city of Lubumbashi in the Democratic Republic of Congo. It is located precisely in the North-East of the Lubumbashi plants and the Lubumbashi slag heap company (STL) in the Mampala district. Figure 1 gives the geolocation of the Penga-Penga site**.**

Figure 1: Location of Gecamines Penga-Penga site

Tables 1, 2, and 3 show the geographical coordinates of the different sampling sites that were used for the completion of this study (site 1, site 2, and 3). Site 1 extends from the Joseph Kabila stadium, Maendeleo Elementary School, and Avenue de la Mission. Site 2 runs from the bridge to the avenue leading to Tshondo on National Highway no. 1. And site 3 runs from Avenue Kakanda to Avenue Kambove on Avenue Musonoie.

Table 1: Geographical coordinates of site 1

Sample coding (E)	Geographical coordinates	
	Latitude	Longitude
E1	S11°40'34.3"	E27°27'43.3"
E2	S11°40'34.8"	E27°27'44.0"
E3	S11°40'34.5"	E27°27'44.4"
E4	S11°40'34.9"	E27°27'44.9"
E5	S11°40'36.3"	E27°27'44.7"
E6	S11°40'36.2"	E27°27'45.4"
E7	S11°40'35.7"	E27°27'45.8"
E8	S11°40'35.4"	E27°27'46.5"
E9	S11°40'34.6"	E27°27'47.7"
E10	S11°40'34.5"	E27°27'48.6"
E11	S11°40'34.0"	E27°27'47.8"
E12	S11°40'33.2"	E27°27'33.2"
E13	S11°40'32.0"	E27°27'46.5"
E14	S11°40'32.1"	E27°27'47.3"
E15	S11°40'33.2"	E27°27'48.3"
E16	S11°40'34.7"	E27°27'49.2"

E17	S11°40'35.0"	E27°27'50.3"
E18	S11°40'35.7"	E27°27'49.9"
E19	S11°40'35.8"	E27°27'51.0"
E20	S11°40'30.9"	E27°27'49.3"

Table 2: Geographical coordinates of site 2

Sample coding (E)	Geographical coordinates	
	Latitude	**Longitude**
E21	S11°40'29.3"	E27°28'06.6"
E22	S11°40'29.9"	E27°28'06.3"
E23	S11°40'30.0"	E27°28'06.4"
E24	S11°40'30.4"	E27°28'06.4"
E25	S11°40'30.4"	E27°28'06.8"
E26	S11°40'30.2"	E27°28'07.8"
E27	S11°40'31.1"	E27°28'06.3"
E28	S11°40'31.7"	E27°28'05.5"
E29	S11°40'32.9"	E27°28'04.9"
E30	S11°40'32.2"	E27°28'04.2"
E31	S11°40'34.5"	E27°28'04.6"
E32	S11°40'34.2"	E27°28'05.3"
E33	S11°40'33.3"	E27°28'05.7"
E34	S11°40'32.6"	E27°28'06.2"
E35	S11°40'31.2"	E27°28'07.3"
E36	S11°40'30.7"	E27°28'08.2"
E37	S11°40'30.7"	E27°28'08.2"
E38	S11°40'29.0"	E27°28'10.3"
E39	S11°40'29.5"	E27°28'10.4"
E40	S11°40'29.1"	E27°28'09.8"

Table 3: Geographical coordinates of site 3

Sample coding (E)	Geographical coordinates	
	Latitude	**Longitude**
E41	S11°41'06.0"	E27°27'35.1"
E42	S11°41'06.30"	E27°27'35.18"
E43	S11°41'06.0"	E27°27'36.0"
E44	S11°41'05.6"	E27°27'36.6"
E45	S11°41'05.1"	E27°27'37.4"
E46	S11°41'04.9"	E27°27'37.7"
E47	S11°41'04.7"	E27°27'38.2"

E48	S11°41'03.4"	E27°27'40.2"
E49	S11°41'02.8"	E27°27'41.1"
E50	S11°41'02.6"	E27°27'41.6"
E51	S11°41'02.0"	E27°27'41.3"
E52	S11°41'02.7"	E27°27'40.1"
E53	S11°41'03.4"	E27°27'38.8"
E54	S11°41'03.0"	E27°27'39.3"
E55	S11°41'04.1"	E27°27'37.9"
E56	S11°41'05.2"	E27°27'36.8"
E57	S11°41'05.5"	E27°27'36.1"
E58	S11°41'05.8"	E27°27'35.1"
E59	S11°41'05.7"	E27°27'35.4"
E60	S11°41'06.0"	E27°27'35.1"

Aerial views of these three sites are shown in Figures 2, 3 and 4.

Figure 2: Representation of site 1

Figure 3: Representation of site 2

Figure 4: Representation of site 3

The three sites that make up the study area are shown in Figure 5.

Figure 5: Representation of the sampling site

2.2 Sampling

The sampling strategy, defining the layout of the observation points in the study area, was based on a statistical approach, i.e. random sampling [11]. With sampling point holes ranging from 20 to 30 cm deep, samples were taken on roadsides and in plots. We subdivided the study area into three sites: S1, S2, and S3. In each site, we took 20 samples (E1 to E20 for the first site) to form a composite sample per site (E61, E62, and E63 for the three sites).

The following equipment was used for sample collection: GARMIN-type GPS for site geo-colocalization, a complete set of ergonomic augers used for sampling heterogeneous soils, plastic packaging, and a notepad. Samples were taken during one day between 9:00 am and 3:00 pm on 13 April 2019. As soon as they were taken, the sixty samples were stored in plastic bags, and labeled. Once in the laboratory, they were mixed to form composite samples and then quartered to obtain representative samples. The resulting samples were then placed in plastic bags and labeled for preservation.

Sample E61 is made up of twenty samples: E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E11, E12, E13, E14, E15, E16, E17, E18, E19 and E20. Sample E62 is also made up of twenty samples, including: E21, E22, E23, E24, E25, E26, E27, E28, E29, E30, E31, E32, E33, E34, E35, E36, E37, E38, E39 and E40. Sample E63 is also made up of twenty samples like the other two: E41, E42, E43, E44, E45, E46, E47, E48, E49, E50, E51, E52, E53, E54, E55, E56, E57, E58, E59 and E60.

2.3 Moisture, organic matter, and pH

The moisture content was determined by drying the material at a temperature of around 105°C for 24 hours. The material is considered dry when the weight difference between two weighings at different times becomes zero or very negligible [9]. The organic matter content was assessed by calcination and was determined by loss on ignition on a previously dried sample. To determine the hydrogen potential of soils, we used a Hanna HI 99121 pH meter, the characteristics of which are given in Table 4.

Table 4: Features of the HI 9921 pH meter

Mesure	Range	Resolution	Precision
pH	-2 à +16	0,01	±0,02
Temperature	-5 à +105 °C	0.1 °C	±0.5°C (up to 60°C); ±1°C (outside)

2.4 Chemical analysis of trace metals in soils

The method used here is the Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). This technique involves vaporizing the sample in a high-temperature plasma (over 800 K). The ions formed are then excited to produce a light emission. This spectrometer can be used to measure almost all the elements simultaneously (the analysis takes just a few minutes, apart from sample preparation). The chemical analyses focused on copper, cobalt, lead, cadmium, and zinc. The concentrations measured are total levels.

2.5 Simple extraction and phytoremediation

For simple extraction, the method used was the extraction of trace metal elements from soils. This method involved stirring the soil sample (with a liquid/solid weight ratio of 10) in a reagent for two hours, then filtering. Phytoremediation involves the extraction of trace metals by plants. In our case, we used cabbage and amaranth. Samples were placed in plastic bags and then, after conditioning, seeded. After 30 days, the samples and the plants were taken to the laboratory for chemical analysis of the trace metals.

3. Results and discussion

3.1 Chemical characterization of trace metals

Trace metals are a group of elements with metallic behaviour that are difficult to degrade and which release into the environment must be strictly controlled because of their toxicity, sometimes at very low concentrations [12,13,14]. The results of the chemical characterization for the three sampling zones are presented in Tables 5, 6, and 7, and illustrated in Figures 6, 7, and 8.

Table 5: Trace metal content in soil samples from Site 1

N°	Sample coding (E)	Trace metal content in soil (ppm)				
		Cu	Co	Zn	Cd	Pb
1	**E1**	3951	349.2	1090	37.15	464,5
2	**E2**	5857	254.4	1320	11	560.3
3	**E3**	6720	796.4	2560	0.58	324.4
4	**E4**	7489	1498	2900	21.02	860.9
5	**E5**	9178	1010	3970	24.84	891.7
6	**E6**	7202	787.1	2540	14.8	683.4
7	**E7**	7480	287.7	1960	29.62	388.7
8	**E8**	7109	166.8	1850	33	723.9
9	**E9**	8290	446.5	1590	6	586.6
10	**E10**	5224	118.2	1360	19.75	358.3
11	**E11**	7897	1185	7090	6	889
12	**E12**	7444	675.4	2490	17.29	696.7

13	**E13**	6925	488.6	2100	19.17	466.1
14	**E14**	9682	546	2380	20.14	759
15	**E15**	8640	569.6	2240	39.41	1636
16	**E16**	3699	866.5	1320	18.05	80.28
17	**E17**	6081	473.2	3640	26.21	366.6
18	**E18**	6771	986.8	6240	4	432.1
19	**E19**	6386	455.4	2280	34.97	417.9
20	**E20**	5190	438.2	1580	12	453.1
Average		6860,75	619.95	2625	19.73	601.97
Minimum		3699	118.2	1090	0.58	80.28
Maximum		9682	1498	7090	39.41	1636
Reference value AFNOR NF U 44-041		100	30	300	2	100

Figure 6: Concentrations of trace metals in soil at Site 1

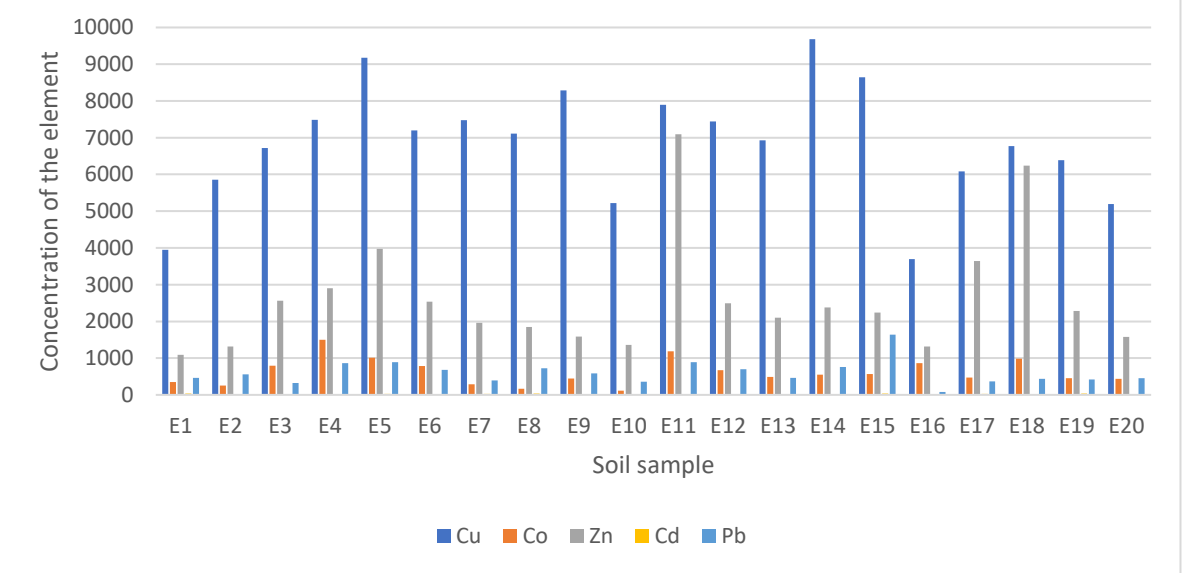


Table 6: Trace metal content in soil samples from Site 2

N°	Sample coding (E)	Trace metal content in soil (ppm)				
		Cu	**Co**	**Zn**	**Cd**	**Pb**
1	**E21**	8202	757.1	4340	18.8	683.4
2	**E22**	8400	247.7	2960	29.62	318.7
3	**E23**	8109	166.8	2850	38	711.9
4	**E24**	9290	146.5	2590	4	406.6
5	**E25**	6424	18.21	2360	19.73	312.1
6	**E26**	7897	1085	8290	4	889
7	**E27**	6044	425.4	4590	18.27	596.9
8	**E28**	7748	408.5	3100	23.57	467.1

9	**E29**	9542	346	3380	16.04	655
10	**E30**	10880	766.5	5441	37.05	1439
11	**E31**	7699	266.5	3368	22.09	90.28
12	**E32**	5165	413.2	7041	24.11	386.6
13	**E33**	6746	566.7	7620	5	419.2
14	**E34**	6310	254.5	3285	34.97	417.7
15	**E35**	5886	318.6	2580	8	356.1
16	**E36**	5757	248.9	2210	9	760.3
17	**E37**	9250	311.4	2158	29	663.8
18	**E38**	6069	216.5	892	17.79	700.7
19	**E39**	5320	214	710	2.47	509
20	**E40**	5092	191	2160	8	699.1
Average		7291,5	368.45	3596,25	18.47	574.12
Minimum		5092	18.21	710	2.47	90.28
Maximum		10880	1085	8290	38	1439
Reference value AFNOR NF U 44-041		100	30	300	2	100

Figure 7: Concentrations of trace metals in soil at Site 2

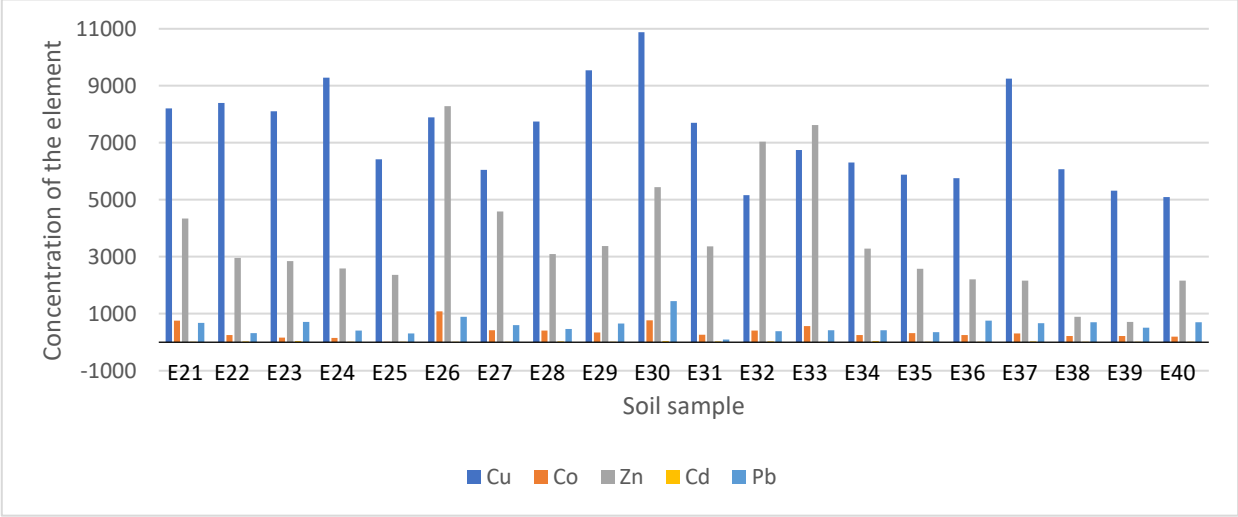
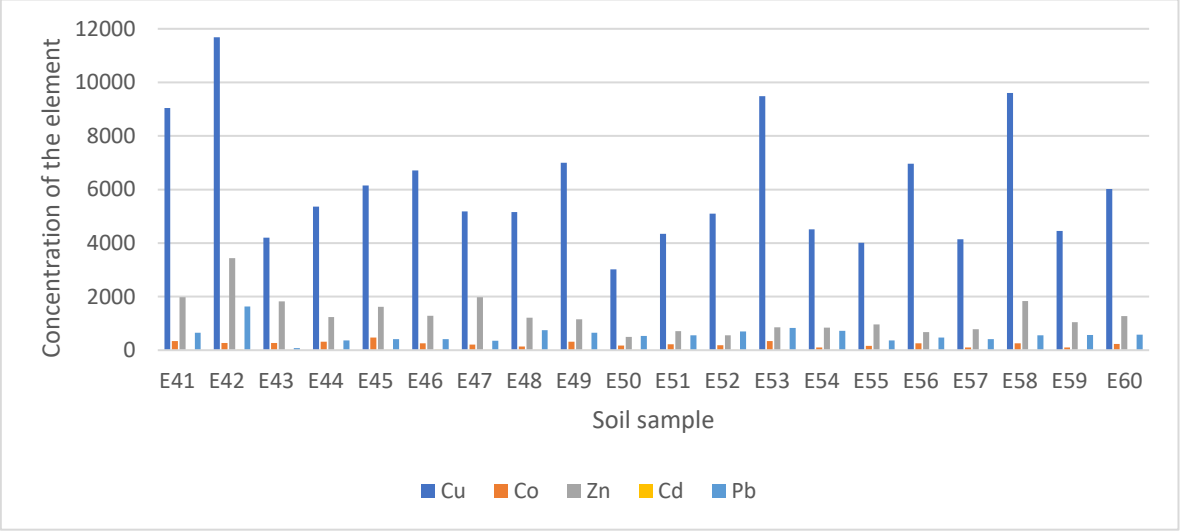


Table 7: Trace metal content in soil samples from Site 3

N°	Sample coding (E)	Trace metal content in soil (ppm)				
		Cu	Co	Zn	Cd	Pb
1	**E41**	9040	346	1980	6.04	655
2	**E42**	11680	266.6	3440	15.61	1636
3	**E43**	4201	266.5	1820	11.05	80.28
4	**E44**	5365	313.2	1240	4.11	366.6
5	**E45**	6146	466.8	1620	4	409.2

6	**E46**	6710	254.5	1280	13.9	417.9
7	**E47**	5186	208.6	1980	1.2	352.1
8	**E48**	5157	142.9	1211	2.1	750.5
9	**E49**	7000	313.4	1155	3.3	653.8
10	**E50**	3023	170.7	492	7.79	530.7
11	**E51**	4341	216	710	0.18	559
12	**E52**	5092	191.03	560	1.3	697.2
13	**E53**	9481	337.1	850	0.1	830.5
14	**E54**	4516	105.9	848	3.1	720
15	**E55**	4006	166.8	961	5.25	366.8
16	**E56**	6964	251.9	680	4.2	470.9
17	**E57**	4139	102.2	786	3.1	410.6
18	**E58**	9604	253.9	1840	9	551.5
19	**E59**	4453	96.78	1044	3.9	562.1
20	**E60**	6017	230.2	1277	5.27	574.6
Average		6106,05	235.05	1288.7	5.225	579.76
Minimum		3023	96.78	492	0.1	80.28
Maximum		11680	466.8	3440	15.61	1636
Reference value AFNOR NF U 44-041		100	30	300	2	100

Figure 8: Concentrations of trace metals in soil at Site 3



In the absence of legislation on soil pollution in the Democratic Republic of Congo (DRC), the evaluation of trace metal elements in the soil of the study area was carried out by comparing the results obtained with the reference values of the french association for standardization (AFNOR NF U 44-041) [15]. The chemical analysis revealed the presence of heavy metals at all three sites. At site 1, copper (Cu) levels ranged from 3951 ppm to 9682 ppm, zinc (Zn) from 1090 ppm to 7090 ppm, cobalt (Co) from 118.2 ppm to 1498 ppm, lead (Pb) from 80.28 ppm to 891.7 ppm, and cadmium (Cd) from 0.58 ppm to 39.41 ppm.

As we can notice, the concentrations of all these elements in the soils exceed the acceptable values published by AFNOR standards [15]. This indicates that the three sites are severely polluted with heavy metals.

Concentrations of trace metals at the second site were similar to those at the first, with metal levels also exceeding the reference values. Site 3 has slightly lower pollution levels than sites 1 and 2. Here, the concentrations of copper (Cu), cobalt (Co), zinc (Zn), cadmium (Cd), and lead (Pb) vary respectively between 3023 ppm and 11680 ppm (Cu), 1678 ppm and 466.8 ppm (Co), 492 ppm and 3440 ppm (Zn), 0.1 ppm and 15.61 ppm (Cd), and 80.28 ppm and 1636 ppm (Pb). The results show that all three sites suffer from severe heavy metal pollution. This can be explained by the proximity of the study area to the old Lubumbashi factories and the installations of the slag heap processing company (S.T.L).

In general, industrial activities generate pollutants that depend on the nature of the activities carried out. Nevertheless, many hydro-metallurgical plants and foundries in Lubumbashi discharge effluents containing by-products rich in zinc, lead, arsenic, cadmium, or sulfur compounds into the environment [16]. These toxic substances pollute the environment. This can be seen in Table 8 and Figure 9, which show the average concentrations of trace metals (TME) in the three composite samples from the study area.

Table 8: Average trace metals in soil in the study area

Sites	**Trace metal content in soil (ppm)**				
	Cu	**Co**	**Zn**	**Cd**	**Pb**
Site 1	6865.00	621.00	2625.00	19.80	602.00
Site 2	7295.00	370.00	3596.00	19.50	574.10
Site 3	6019.00	231.20	1277.00	5.30	574.60
Reference value AFNOR NF U 44-041	100	30	300	2	100

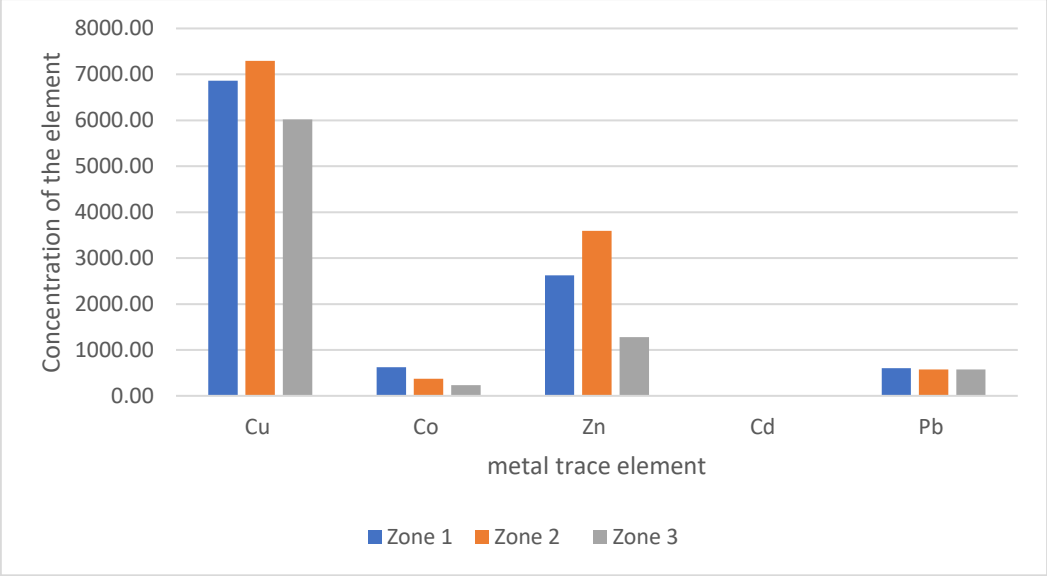
Figure 9 shows an overview of the concentrations of trace metals in the study area. As can be seen, the levels of copper (Cu), cobalt (Co), zinc (Zn), cadmium (Cd), and lead (Pb) are respectively sixty-seven, fourteen, eight, seven, and six times higher than the reference values. They are a danger to humans, animals, and plants. However, the copper levels are in line with the results published by other researchers [17, 18]. These authors reported a high concentration of copper in soil polluted by mining activities in the Boumerzoug basin in Algeria and Lagos state in Nigeria. Similar concentrations to ours were also reported by Banza's research team in Lubumbashi [19]. The authors investigated chemical pollution in Tshamilemba and Kabecha neighborhoods in the city of Lubumbashi in 2012. They reported average copper concentrations of 1036 ppm ten times higher than the reference value (100 ppm). The same trends were published by Mpundu's research team [20]. In a study, entitled Statistical synthesis of soil properties taken from vegetable gardens in the Lubumbashi area, Mpundu and his team found maximum copper concentrations of 11388.4 ppm in the soils of certain vegetable gardens in Lubumbashi.

On the other hand, the cobalt concentration values published by Haichan's team [20] are much lower than ours. For zinc, our values are higher than those obtained by Ilonga's team [21]. The soil in the Penga-Penga neighborhood contains a high concentration of lead, ranging from 574.10 ppm to 602.00 ppm. These

values are higher than the data obtained by other authors [22,23]. When they investigated the impact of soils polluted by industrial and mining activity.

A composite soil sample was taken at Gécamines Penga-Penga and analysed on an ICP-OES spectrometer. The results are shown in Figure 9.

Figure 9: Average content of trace metals in composite samples from the study area

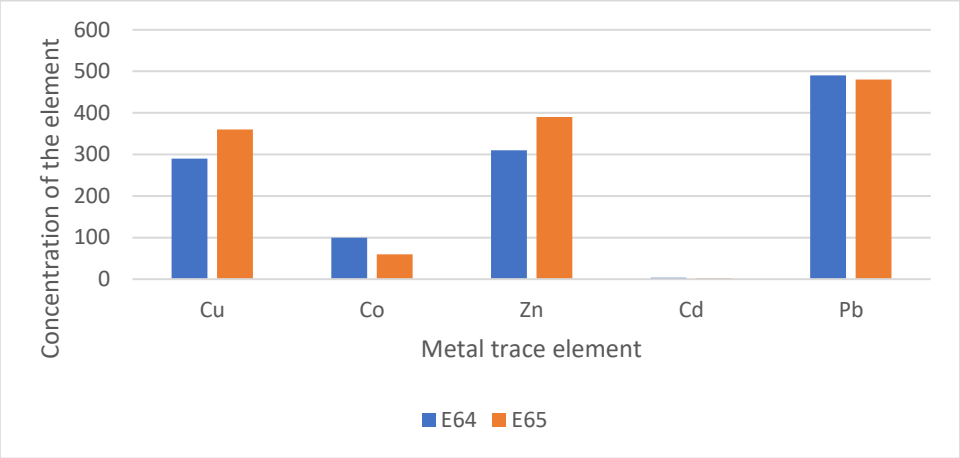


Comparing copper concentrations at the three sites investigated, we found that copper levels are very high at site 2. This is because this site is closer to the Lubumbashi factories and the Société des Terrils de Lubumbashi (STL) than the other two sites (sites 1 and 3). Unlike copper, cobalt values are higher at site 1. This can be explained by the passage of run-off water and the presence of plant cover, which fixes the available cobalt, particularly at high pH and in well-drained soils [24]. Cadmium and lead are no exception to the rule. Table 9 and Figure 10 show the results for the control soil samples.

Table 9: Trace metal content in control soil samples

Sample coding (E)	**Trace metals content in soil (ppm)**				
	Cu	**Co**	**Zn**	**Cd**	**Pb**
E64	290	100	310	3.5	490
E65	360	60	390	2.9	480
Reference value AFNOR NF U 44-041	100	30	300	2	100

Figure 10: Representation of trace metal levels in control soil samples



We took a control soil sample to assess the average levels of trace metals in Lubumbashi. Two soil samples were taken in the Gambela 2 neighborhood, and the results of the analysis are shown in Figure 10. The trace metal content of the control samples is well below the levels in the study area for all elements. Although the two samples contained copper, cobalt, zinc, cadmium, and lead levels above the standard (100 ppm, 300 ppm, 300 ppm, 2 ppm, and 100 ppm respectively), their values were well below those observed in the soils of the study area (Penga-Penga site). Tables 10 and 11 illustrate the results of the control soils after treatment.

Table 10: Trace metal levels in control soil samples after remediation with cabbage

Sample coding	Periode of remediation	Trace metal content in soil (ppm)				
		Cu	Co	Zn	Cd	Pb
E64C	Before	290	100	310	3.5	490
	After	80	70	110	1.3	143
E65C	Before	360	60	390	2.9	480
	After	110	20	178	0.8	30

Except for cadmium, the concentrations of the trace metals (Cu, Co, etc.) in the control soil sample exceeded the reference values before and even after planting the cabbage for E64C. Table 11 shows the trace metal values in the control soil sample after phytoremediation using amaranths.

Table 11: Trace metal levels in control soil samples after remediation with amaranth

Sample coding (E)	Remediation period	Trace metal content in soil (ppm)				
		Cu	Co	Zn	Cd	Pb
E64A	Before	290	100	310	3.5	490
	After	60	60	95	0.9	110
E65A	Before	360	60	390	2.9	480
	After	90	15	165	0.5	90

Based on the data displayed in Table 11, we can say that amaranths absorb more heavy metals than cabbage.

3.2 Extraction of trace metals

Tables 12, 13, and 14 show the evolution of heavy metals (copper, cobalt, zinc, cadmium, and lead) after extraction with distilled water, acetic acid, and caustic soda.

Table 12: Results of extraction of the three composite samples with distilled water.

Sample	Remediation time	Trace metal content in soil (ppm)				
		Cu	Co	Zn	Cd	Pb
E61	Before	6865	621	2625	19.8	602
	After	5092	357.2	1160	6.4	560.3
E62	Before	7295	370	3596	19.5	574.1
	After	5657	191.0	2290	4.96	464.5
E63	Before	6019	231.2	1277	5.3	574.6
	After	4516	105.5	847	0.07	324.4

Table 13: Results of the acetic acid extraction of the three composite samples

Sample	Remediation period	Trace metal content in soil (ppm)				
		Cu	Co	Zn	Cd	Pb
E61	Before	6856	621	2625	19.8	602
	After	4008	352	962	10.35	460.9
E62	Before	7295	370	3596	19.5	574.1
	After	4925	166.8	1580	9.25	410.5
E63	Before	6019	231.2	1277	5.3	574.6
	After	4139	102.2	786	2.15	365.8

Table 14: Results of extraction of the three composite samples with caustic soda

Sample	Remediation period	Trace metal content in soil (ppm)				
		Cu	Co	Zn	Cd	Pb
E61	Before	6865	621	2625	19,8	602
	After	5024	353.4	1040	17.52	563.1
E62	Before	7295	370	3596	19.5	574.1
	After	7295	370	3596	19.5	574.1
E63	Before	5455	133.1	1880	13.7	550.9
	After	6019	231.2	1277	5.3	574.6

Tables 9, 10, and 11 show that acetic acid has greater extracting power than distilled water and caustic soda. Copper reacts with iron, causing iron deficiency in the plant (chlorosis: the brownish chlorination of the leaves) and the excess copper in the soil reduces the root growth, leading to stunted growth. Copper

has a bactericidal effect which reduces microbial activity in the soil. Copper ions flood the cell, damaging the DNA and rupturing the cell membrane. This causes the cell to lose nutrients and die [25].

3.3. Phytoremediation

Tables 15 and 16 show the results of Brassica chinesis and amaranthus viridis extraction.

Table 15: Results of heavy metal concentration in the soil after remediation with Brassica chinesis

Sample	Remediation period	Trace metal content in soil (ppm)				
		Cu	Co	Zn	Cd	Pb
E61	**Before**	6865	621	2625	19.8	602
E66C	**After 1**	4690	210	1320	10	350
E69C	**After 2**	1977	20	311	2.2	161
E62	**Before**	7295	370	3596	19.5	574.12
E67C	**After 1**	5200	130	2230	9	278.9
E70C	**After 2**	2586	10	1708	1.6	221
E63	**Before**	6019	231.2	1277	5.3	574.6
E68C	**After 1**	4680	110	920	0.53	180
E71C	**After 2**	3008	5	357	0.4	116

Table 16: Results of trace metal levels in soil samples after remediation with amaranthus viridis

Sample	Remediation period	Trace metal content in soil (ppm)				
		Cu	Co	Zn	Cd	Pb
E61	**Before**	6865	621	2625	19.8	602
E66A	**After**	5560	250	1540	1.8	550
E69A	**After**	3934	28	320	0.9	470
E62	**Before**	7295	370	3596	19.5	574.1
E67A	**After**	5810	150	2340	1.9	490
E70A	**After**	3588	10	456	0.9	364
E63	**Before**	6019	231.2	1277	5.3	574.6
E68	**After**	4360	90	420	1.3	450
E71A	**After**	1874	5	20	0.6	264

The global trend that we can pick up from these results is a reduction of the heavy metal concentrations in the soil after remediation, although some values are still higher than the reference standards. For copper, the remediation with Brassica chinesis produced very good results in zones 1 and 2, reducing copper (Cu) concentrations by up to 25 % and 34 % respectively. However, amaranthus viridis were more effective in zone 3, reducing copper concentrations by up to 31 %. For cobalt, Brassica chinesis remediation produced outstanding results, reducing soil concentrations of the metal by 66 %, 33 %, and 17 % respectively.
amaranthus viridis proved to be more efficient than Brassica chinesis for the remediation of soils polluted with zinc. It reduced the concentrations of zin in the soil samples to 12 % and 13 % respectively. The same trend was observed for cadmium, with a successful reduction of the zinc concentration by amaranths for all three samples. However, Brassica chinesis slightly exceeded the reference value for the first sample

(E61). Even though lead (Pb) concentrations were also reduced, the three samples (E61, E62, and E63) showed zinc (Zn) values above the standards. Brassica chinesis showed a greater affinity for lead absorption than amaranthus viridis ;it reduced zinc content up to 27 %, 38 %, and 20 % respectively. In short, although reductions in concentrations were observed for several heavy metals, their concentrations often remained above the reference standards.

3.4 Mobility Influencing Factors

Le Table 17 presents the mobility factors of the three composite samples (E61, E62, and E63) before remediation (pH, moisture, and organic matter).

Table 17: Mobility influencing factors for composite samples

N°	Remediation period	Moisture (%)	pH	MO (%)
1	**E61**	13.54	6.12	17.86
2	**E62**	1104	7.75	13.33
3	**E63**	11,03	7.2	16.84
Average		11.87	7.02	16.01

Moisture levels varied between 11.03 % and 13.54 %, with an average of 11.87 %. These contents are high, which can be explained by the fact that the samples were taken during the rainy season. The moisture content of the composite samples after the first Brassica chinesis remediation averaged 5.85 % and 10.64 % for the second Brassica chinesis treatment. As with the amaranth treatment, the average moisture content after the second treatment was 10.56%.

Cu has a minimum solubility of between pH 6 and 8. At pH less than 6, it is mainly in ion form (Cu^{2+}), and above pH 8 copper forms a complex with dissolved organic matter (DOM). The concentration of Cu in solution increases sharply at pH < 5 [26]. The highest proportion of Cu is fixed by HA in the pH 4 - 5 range, and by FA in the pH 6 - 7 range [27]. In neutral to alkaline soils, Cd mobility and bioavailability are low, and at pH 7, Cd can co-precipitate with $CaCO_3$ or precipitate as $CdCO_3$ or Cd phosphates [28]. Tables 18 and 19 show the mobility factors for the different samples treated with cabbage and amaranth, respectively.

Table 18: Physico-chemical parameters of composite samples after cabb sanitation

Species	N°	Samples	Moisture (%)	pH	MO (%)
Cabbage	**1**	E66C	5.85	7.6	9.67
	2	E67C	4.96	7.79	3.31
	3	E68C	16.85	7.37	5.55
		Average	9.22	7.59	6.18
Cabbage	**1**	E69C	10.52	7.6	6.15
	2	E70C	11.25	7.64	4.91
	3	E71C	10.14	7.78	5.55
		Average	10.64	7.67	5.54

Table 19: Physico-chemical parameters of composite samples after amaranth remediation

Species	N°	Samples	Moisture (%)	pH	MO (%)
Amaranth	1	E66A	1.18	7.17	4.58
	2	E67A	2.91	7.39	4.13
	3	E68A	2.61	6.93	12.07
		Average	2.23	7.16	6.93
Amaranth	1	E69A	9.67	7.56	6.02
	2	E70A	11.58	7.62	5
	3	E71A	10.43	7.72	5.33
		Average	10.56	7.63	5.45

In general, complexes between trace metals and inorganic ligands are more stable than those formed by organic ligands. Some authors have shown that the extent of complexation of trace metals by mineral surfaces in the presence of organic matter increases at low pH, but decreases at high pH [29].

However, some researchers have shown that the complexation of Cu^{2+} and Pb^{2+} by different inorganic ligands in the presence of organic matter decreases and that this decrease cannot be attributed solely to the complexation of trace metal elements by organic compounds in solution but also to the presence of organic matter coatings on the surface of minerals. Researchers [30] found that the increase in dissolved organic matter concentrations induced by roots led to a decrease in the concentration of Cu^{2+} which was complex not only by dissolved organic matter but also adsorbed by the other solid phases of the soil. These authors also reported an increase in the ability of the dissolved organic matter Cu complex in the rhizospheric solution.

Moisture encourages biological activity in the soil, and therefore the production of acidic or complex substances resulting from the biodegradation of organic matter. It also has a direct effect on the precipitation and solubilization process. Excessive humidity can also lead to poor soil aeration. The mobility parameters for trace metals were also analyzed for the control soils and are presented in table 20.

Table 20: Résultats des analyses physico-chimique des sols témoins

Species	N°	Sample coding (E)	Moisture (%)	pH	MO (%)
Cabbage	1	E64C	12.17	7.78	5.45
	2	E65C	9.37	7.62	2.38
		Average	10.77	7.7	3.915
Amaranth	1	E66A	3.11	7.54	6.44
	2	E65A	12.02	7.56	7.41
		Average	7.565	7.55	6.925

The results in Table 20 show an average moisture content of 10.77 % for the control soil samples E65C and E64C treated with cabbage, and an average of 7.57 % for the samples E64A and E65A treated with amaranth. The pH ranged from 7.62 to 7.78 for the cabbage-treated E65C and E64C samples, and from

7.54 to 7.56 for the amaranth-treated E64A and E65A samples. The organic matter values are 5.45 % and 2.38 % respectively for samples E65C and E64C treated with cabbage, while samples E64A and E65A, treated with amaranth, show organic matter levels of 6.44 % and 7.41 %. Overall, the trace metal values for the Gécamines Penga-Penga site are extremely high compared with the values for the control soils. This can be explained by the industrial activities taking place on the site. Phytoremediation is therefore a simple and effective extraction technique for improving the quality and repairing soil polluted by trace metals.

Conclusion

This work aimed to assess the quality of the soil at the Gécamines Penga-Penga site and to identify the source of the pollution in this neighborhood located to the north-east of the Lubumbashi factories and the Lubumbashi slag heap company (STL). To do this, we carried out random soil sampling at three sites to provide a representative sample of the soil in the study area.

The samples were physico-chemically characterized to determine moisture, organic matter, and pH. The results show a variation in moisture from 11.03 % to 13.54 % for samples E63 and E61, a pH ranging from 6.12 to 6.75, and an organic matter content ranging from 13.33% to 17.86%. After treatment with cabbage and amaranth, the moisture content fell to 5.85% and 10.64% respectively, the pH rose to 7.59 and 7.67 (for the cabbage treatment) and 7.16 and 7.63 (for the amaranth treatment), and the organic matter content fell to 6.18 % and 5.54 % (for the cabbage-treated soils), and 6.93 and 5.45 % (for the amaranth-treated soils).

It should be noted that copper is mainly soluble between pH 6 and 8, while cadmium shows low mobility in neutral to alkaline soils and can precipitate at pH 7. This leads us to deduce that the pH of sample E66c at 7.6 reduces the mobility of metallic trace elements.

Elemental chemical analysis revealed high concentrations of trace metals (TME) such as copper, cobalt, zinc, cadmium, and lead in Gécamines Penga-Penga soils, exceeding reference values by up to sixty-seven times. Compared with the control soil samples, we found that the soils in the neighborhoods far from the industrial zones had much lower concentrations of TME than those in the study area. This high level of TMEs in the soils of the study area represents a risk to human, animal, and plant health. Heavy metals were extracted using distilled water, acetic acid, and caustic soda, demonstrating that their affinity depends on the nature of the heavy metals present in the soil.

To remediate soil pollution at Gécamines Penga-Penga, we turned to phytoremediation (using cabbage and amaranth) as a remedial technique. The results of phytoremediation using cabbage and amaranth were conclusive, showing a reduction in copper content in most treated samples, while cobalt and cadmium levels were regulated in all the composite samples studied. Despite the drop in TME concentrations in the treated samples, copper and lead levels remained higher than the reference values in the sites studied.

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