

Assessment of Soil Pollution by Heavy Metals at the Daniela Oil Site in the Bongor Basin of Southern Chad

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Abstract

This study evaluates heavy metal pollution in soils from the Daniela oil sites located in the Kouno sub-prefecture, Loug-Chari Department. The primary objective is to determine the extent of heavy metal contamination in the Daniela area. At the Raphia site, the metal concentration order is Cu > Mn > Fe > Cd > Pb, while at the Lanéa 1 and Lanéa 2 sites, it is Cu > Fe > Mn > Cd > Pb. Contamination factors (CF) for Mn, Fe, and Pb are very low (< 1), indicating no pollution from these metals. However, the contamination factors for Cd and Cu are significantly high according to the AFNOR standard. Additionally, the average contamination index across all three sites exceeds 2, confirming soil pollution by Cd and Cu at the sampled locations.

Keywords

Soil Pollution, Heavy Metals, Oil Site, Daniela

1. Introduction

Soil is the natural support of plant and animal life on earth. It is in the soil that plants sink their roots and draw the water and nutrients that they need to thrive [1]. At the surface of the lithosphere, soils form a thin film of varying thickness and composition, depending in particular on climate and the nature of the parent materials.

Soil is also a vital and fundamental element for mankind. It is therefore essential for life and part of people's daily lives. Soil supplies nutrients, water and minerals

to plants and trees, stores carbon and is home to billions of insects, small animals, bacteria and many other micro-organisms [1]. Since the beginning of the last century, the exploitation of oil deposits has steadily increased. The extraction, transport and exploitation of this source entail the risks of pollution (accidental and chronic) for the environment, which can influence the ecological balance and sometimes lead to the destruction of the ecosystem [2].

In Chad's Bongor basin, oil production began in 2007 in the Koudalwa field. In 2014, after seven years of oil exploitation at the Baobab site, a first spill was observed. This spill caused enormous environmental damage. In 2018, the Daniela Central Process Field (CPF) was inaugurated and several activities have been carried out at time. These various activities contribute significantly to soil pollution.

Pollutants from the oil industry include hydrocarbons and heavy metals. Heavy metals in environmental compartments can be provided from natural or anthropogenic origin. Heavy metals such as lead could be highly toxic to terrestrial and aquatic ecosystems. It can also act synergistically with other metals and pollutants, such as copper, cadmium and selenium.

However, some heavy metals are necessary for the biological cycles of plants, but they become toxic as soon as their concentrations exceed more than the standards. Pollution by toxic metals has accelerated dramatically since the start of the industrial revolution [3].

At this point of view, to identify the risks for giving treatment to the environment, we have focused our study on assessing heavy metal pollution in the soils of the Daniela locality.

The aim of this work is to evaluate the degree of heavy metal pollution and identify the risks to the environment in Daniela. More specifically, the aim is to characterize some of the heavy metals in the concerned sites and evaluate the level of contamination by these heavy metals.

2. Material and Methods

2.1. Presentation of the Study Area

The sampling work was carried out in the Bongor basin in south-western Chad, around 300 km at south-east of Ndjamena, the capital of Chad. In other words, 200 km from the ESSO TCHAD terminal station. Its northern latitude is 10°00' - 10°30', its eastern longitude 16°00' - 17°00'.

Our study area is Daniela (**Figure 1**). It is located in a canton called Miltou which is a small town in Chad located on the Chari, at the coffins of the provinces of Chari-Baguirmi and Moyen-Chari.

2.2. Material

Our material of study consists of suspecting the polluted soils in the Daniela oil field in Bongor Basin.

Sampling

The soil sample was chosen on the Daniela oil site where there is the basis of

their installations or equipment, fields and former mud treatment sites. Using the Arrow GPS application on our Android phone, we were able to obtain the geographical coordinates (**Table 1**) for a map of the study of the area (**Figure 1**).

The samples were taken in mid-June 2023, at the height of the rainy season, when farmers treat their fields with chemicals such as nitrogen fertilizers. This is an ideal time to take samples for soil analysis. The samples were isolated in sterilized polymer bottles and sent to the laboratory of the Unit Research of Soils Analysis and Environment Chemistry (Unité de Recherche d'Analyse des Sols et de Chimie de l'Environnement (URASCE)) at the University of Dschang, in compliance with ISO, AFNOR NF and EN standards. Samples were taken according to depth: AA1, BB1 and CC1 from 0 - 15 cm; AA2, BB2 and CC2 from 15 - 30 cm; control point B was taken from 0 to 30 cm.

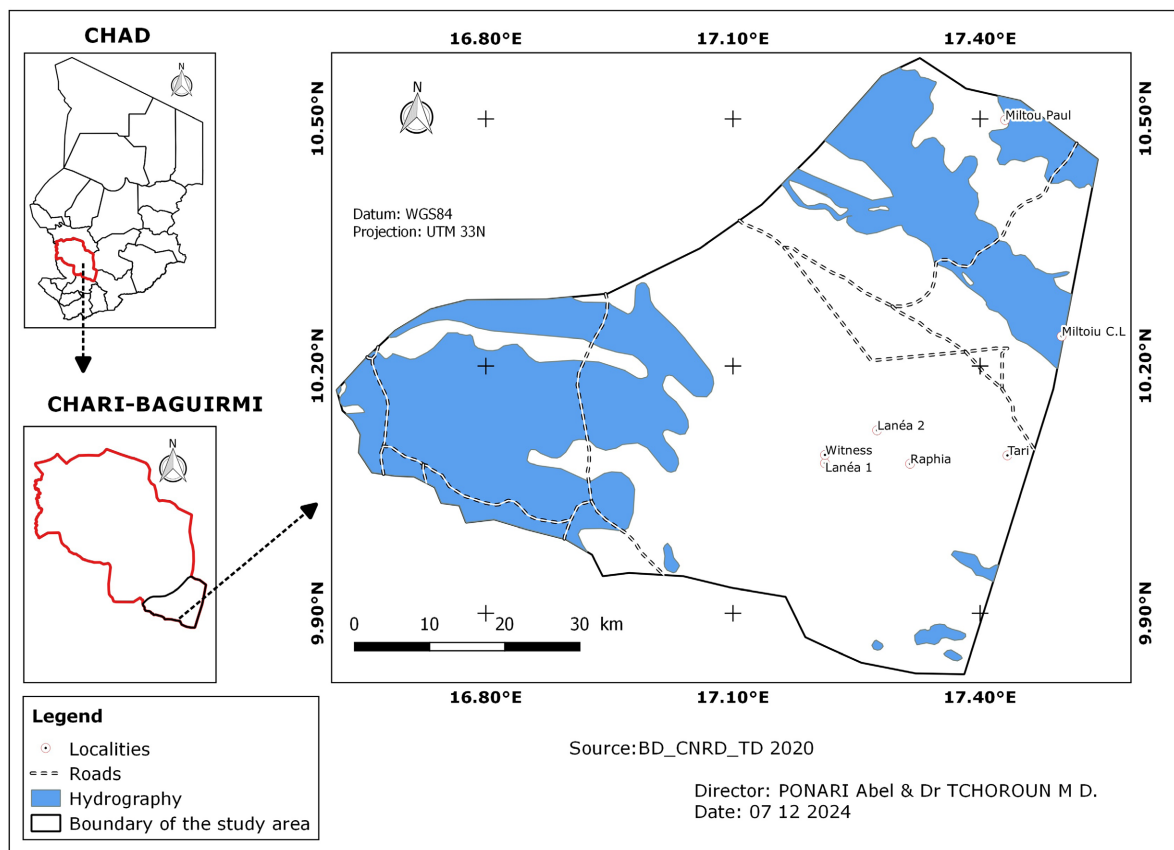


Figure 1. Map of the study area.

Table 1. Coordinates of sampling points.

Points	Longitude	Latitude
Raphia	10° 11' 15.858"N	17° 6' 15.18"E
Lanéa 1	9° 59' 2.226"N	17° 31' 18.612"E
Lanéa 2	10° 1' 22.122"N	17° 27' 51.54"E
Témoin	9° 59' 2.22"N	17° 31' 18.594"E

2.3. Methods: Sample Analysis

2.3.1. Determination of pH

The samples were suspended in distilled water at a liquid-to-solid (L/S) ratio of 10 mL/g, following the protocol of Khaoula and Aziz [4].

pH measurements were carried out using a portable multimeter. The electrode is immersed in the soil suspensions. The pH is expressed as a function of the hydronium ion concentrations present.

2.3.2. Sample Processing

The soil samples were undergone by the following operations:

- Quartering: homogenization of samples and selection of a representative sample.
- Drying: carried out in the laboratory, at room temperature and out of direct sunlight.
- Grinding: to reduce samples to a fine powder in order to bring the elements to be analyzed into solution (increasing the specific surface area of the material). It is performed by using a porcelain mortar and pestle.
- Sieving: to remove solid fragments equal to or greater than 2 mm. We will use a 125 µm mesh sieve (NF X 31-101).

Digestion of soil samples for heavy metal analysis

Heavy metals were extracted by wet digestion with ethylenediaminetetraacetic acid (EDTA) disodium salt dihydrate. This solution was prepared according to the method proposed by the European Community Bureau of Reference (BCR) [5].

Analysis by EDTA solution according to BCR procedure [6].

Protocol: 4 g of soil sample was introduced into a 50 mL centrifuge tube into which 40 mL of buffered EDTA solution at pH = 7 was added. The whole was shaken for 2 hours and then filtered through n°40 wattman paper. The filtrate passed over a cellulose membrane was read on a HachDR600 spectrometer (HACH lange GmbH) [5].

Finally, heavy metals such as iron, lead, manganese, cadmium and copper were measured directly using a standardized program on the Hach DR 6000 spectrophotometer [7] [8].

2.3.3. Pollution Assessment Tools (Evaluation of Soil Pollution Levels)

- Geo-accumulation index I_{geo}

This index is used to assess the degree of the contamination of soil as described in the work of Juliette *et al.* [9]. The geo-accumulation index was calculated as follows (1):

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5B_n} \right) \quad (1)$$

With C_n the heavy metal concentration in the soil sample, B_n the geochemical background value of element n , and 1.5 is the geochemical background matrix correction factor [10] [11].

According to Digué, T.M., *et al.*, [5], Igeo values are categorized into 7 classes defining the level of pollution:

- Class 0: Unpolluted ($I_{geo} \leq 0$);
- Class 1: Unpolluted to low pollution ($0 < I_{geo} \leq 1$);
- Class 2: moderate pollution ($1 < I_{geo} \leq 2$);
- Class 3: moderate to heavy pollution ($2 < I_{geo} \leq 3$);
- Class 4: heavy pollution ($3 < I_{geo} \leq 4$);
- Class 5: heavy to extreme pollution ($4 < I_{geo} \leq 5$);
- Class 6: extreme pollution ($I_{geo} \geq 6$).

- Contamination factor CF and Average Contamination Index (ACI)

The factor of contamination is commonly used to determine the level of soil contamination. It is defined by (2):

$$CF = \frac{C_m (\text{sample})}{C_m (\text{background value})} \quad (2)$$

whence C_m sample is the concentration of the metal in the sample, and C_m geochemical background represents the geochemical background of the element.

According to Adje *et al.* [12], CF is subdivided into 4 classes which are:

- Class 1: Low contamination ($CF < 1$);
- Class 2: Moderate contamination ($1 \leq CF < 3$);
- Class 3: Considerable contamination ($3 \leq CF < 6$);
- Class 4: Very heavy contamination ($CF \geq 6$).

The Average Contamination Index (ACI) was calculated by the following formula (3):

$$ACI = \frac{\sum CF}{n} \quad (3)$$

whence n is the number of elements analyzed, CF the contamination factor. Contamination occurs when $ACI > 2$ [12] [13].

- Pollution Load Index PLI

The Pollution Load Index is an important index for comparing contamination levels between sampling points [3].

The pollution load index of the three sites (Raphia, Daniela and Lanea) sampled, was determined by the formula of Rabee *et al.* [14] then Mekuria *et al.* [3] by (4):

$$PLI = \frac{\prod_1^n C_n F}{n} \quad (4)$$

With $C_n F$ representing the contamination factors for each element, n the number of heavy metals in the study.

According to Rabee *et al.* [15], soil is considered polluted if its $PLI > 1$, consequently soil is unpolluted if $PLI < 1$ [16].

- Metal contamination assessment

The contamination factor (CF) and the average contamination index (ACI), also known as the degree of contamination, were used to determine the level of soil contamination in the present study. These values are calculated according to

the formulas given above.

2.3.4. Statistical Analysis

Descriptive statistical analyses were used for metal concentrations, Igeo, CF, CI and PLI. Pearson correlation and multivariate analysis were performed to assess heavy metal sources and sampling site groups.

3. Results and Discussion

3.1. Results

3.1.1. Analysis Results

In order to obtain a good result, the samples were analyzed in two phases by the laboratory of the Unit Research of Soils Analysis and Environment Chemistry (URSAEC) of the University of Dschang.

- Determining the pH of Daniela's soils

pH is a physico-chemical parameter that influences the accumulation of heavy metals in soils. **Table 2** shows the statistical variations in pH for the different soils.

Table 2. Sample pH by depth.

Sampling points	Samples	Depth (cm)	pH			
			Minimum	Maximum	Average	Ecart-type
Raphia	AA1	0 - 15	6.89	7.09	6.99	±0.20
	AA2	15 - 30	5.98	6.78	6.38	±0.77
Lanéa 1	BB1	0 - 15	4.98	5.36	5.17	±0.38
	BB2	15 - 30	4.53	5.06	4.79	±0.53
Lanéa 2	CC1	0 - 15	3.96	4.09	4.03	±0.13
	CC2	15 - 30	3.12	3.89	5.51	±0.77
Intersection point	Control	0 - 30	3.62	4.18	3.90	±0.56

- Determination of heavy metals

The results of the quantitative analysis of heavy metals are shown in **Table 3** below, based on the sampling depth of Daniela's soils.

3.1.2. Evaluation of Contamination Levels

- Determination of CF, ACI and PLI

To assess soil contamination levels in the present study, it is necessary to determine the Contamination Factor, the Degree of Contamination and the Pollution Load Index (PLI). These values were calculated using the formulas cited above (2)-(4). The geochemical backgrounds of metals such as Fe, Pb, Mn, Cd and Cu are 46000.00; 20.00; 850.00; 0.30 and 45.00 respectively [10]. These values were used in the CF calculations. **Table 4** below shows the results of this evaluation.

These values have enabled us to plot the ACI and PLI histograms in **Figure 2** and **Figure 3** below.

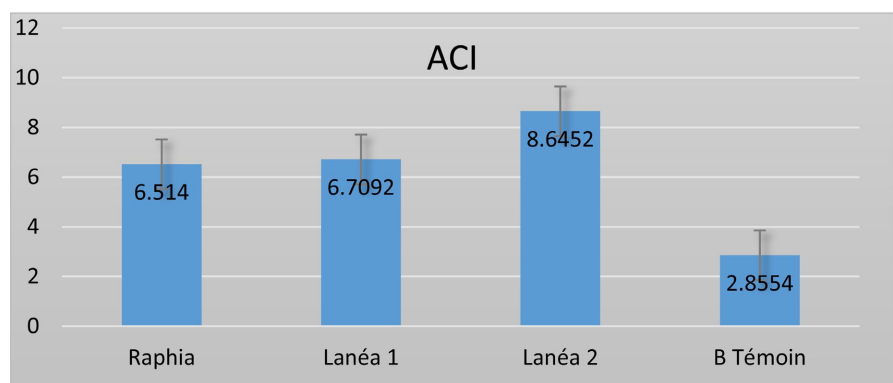
Table 3. Heavy metal content as a function of sampling depth.

Sample code	Depth (cm)	Concentration (mg/Kg)				
		Fe (mg/kg)	Pb ($\mu\text{g/kg}$)	Mn (mg/kg)	Cd (mg/kg)	Cu (mg/kg)
B control	0 - 30	16.06 \pm 0.61 ^c	0.012 \pm 0.001 ^c	79.51 \pm 0.18 ^b	3.52 \pm 0.052 ^b	110.22 \pm 5.01 ^c
AA1	0 - 15	59.73 \pm 0.33 ^a	0.023 \pm 0.002 ^b	166.14 \pm 0.38 ^a	4.28 \pm 0.01 ^b	815.25 \pm 0.02 ^a
AA2	15 - 30	53.92 \pm 0.37 ^a	0.017 \pm 0.001 ^b	161.95 \pm 0.52 ^a	6.50 \pm 0.012 ^a	526.39 \pm 0.15 ^a
BB1	0 - 15	16.01 \pm 0.36 ^b	0.035 \pm 0.002 ^a	5.24 \pm 0.01 ^c	5.01 \pm 0.001 ^a	220.77 \pm 0.006 ^b
BB2	15 - 30	15.45 \pm 0.37 ^b	0.023 \pm 0.002 ^b	49,78 \pm 0,12 ^b	1.79 \pm 0.012 ^c	292.33 \pm 1.15 ^b
CC1	0 - 15	7.2 \pm 0.27 ^c	0.012 \pm 0.001 ^c	6.70 \pm 0.02 ^c	1.76 \pm 0.012 ^c	183.61 \pm 5.17 ^c
CC2	15 - 30	10.51 \pm 0.40 ^c	0.01 \pm 0.0012 ^c	11.39 \pm 0.025 ^c	4.72 \pm 0.012 ^b	344.51 \pm 0.01 ^b
Geochemical background	-	46000	20.00	850.00	0.3	45.00
WHO (2009) $\mu\text{g/kg}$	-	-	15 - 50	20 - 50	5	2000

Values with the same superscript letters in the columns are not significantly different ($p < 0.05$) according to Duncan's multiple comparison test.

Table 4. Results of heavy metal contamination assessment.

Sampling points	Contamination Factor (FC)					ACI	PLI
	FC_Fe	FC_Pb	FC_Mn	FC_Cd	FC_Cu		
Raphia	0.0013	0.0012	0.1955	14.2556	18.1166	6.5140	1.58 $\times 10^{-5}$
Lanéa 1	0.0012	0.0009	0.1905	21.6556	11.6976	6.7092	1.04 $\times 10^{-5}$
Lanéa 2	0.0003	0.0018	0.0062	16.6989	4.9059	8.6452	5.49 $\times 10^{-8}$
Control	0.0003	0.0006	0.0935	11.7333	2.4493	2.8554	9.67 $\times 10^{-8}$

**Figure 2.** Average soil contamination index in Daniela.

- Determination of the Geoaccumulation Index (Igeo)

The geo-accumulation index values for Daniela soils are shown in **Table 5**.

3.1.3. Statistical Analysis Results

Descriptive statistical analysis using Principal Component Analysis (PCA) enabled us to plot the correlations of compounds in space after rotation (**Figure 4**).

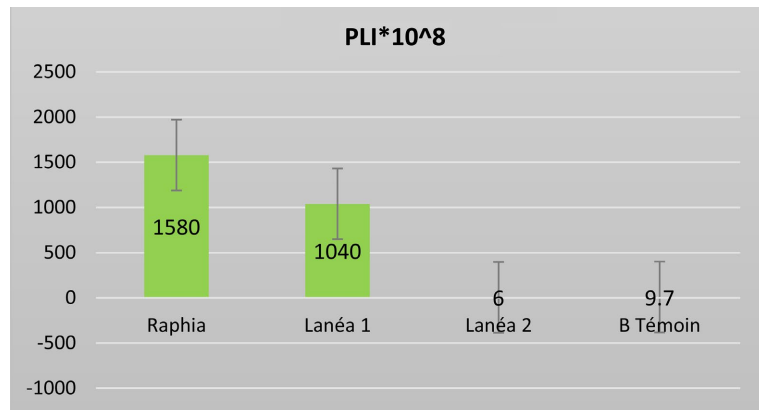


Figure 3. Daniela soil pollution load index.

Table 5. Geo-accumulation index for Daniela soils.

Sites	Contamination Factor (FC)	Igeo Fe	Igeo Pb	Igeo Mn	Igeo Cd	Igeo Cu
Raphia	AA1	2.59×10^{-4}	2.3×10^{-4}	0.039	2.85	3.62
	AA2	2.34×10^{-4}	1.7×10^{-4}	0.038	4.33	2.34
Lanéa 1	BB1	6.96×10^{-5}	3.5×10^{-4}	1.23×10^{-3}	3.34	0.98
	BB2	6.72×10^{-5}	2.3×10^{-4}	0.012	1.19	1.30
Lanéa 2	CC1	3.13×10^{-5}	1.2×10^{-4}	1.58×10^{-3}	1.17	0.82
	CC2	4.57×10^{-5}	1.0×10^{-4}	2.68×10^{-3}	3.15	1.53
B Control	B Control	6.98×10^{-5}	1.2×10^{-4}	0.0187	2.347	0.49
	Geochemical background	46000	20	850	0.3	45

Value of the geochemical background of the earth's crust [5].

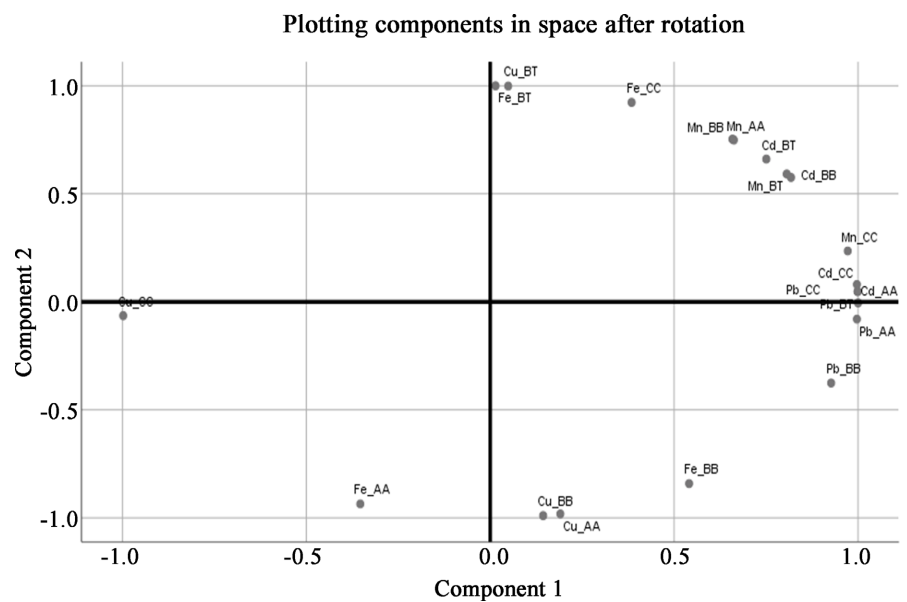


Figure 4. Trace of principal components such as heavy metals in Daniela soils.

3.2. Discussion

3.2.1. pH of Daniela Soil Samples

According to **Table 2**, the pH of soil solutions varies with depth and sampling point. As depth increases, pH decreases according to sampling point, respectively from 6.89 ± 0.20 to 5.98 ± 0.77 for Raphia, from 4.98 ± 0.38 to 4.53 ± 0.53 for Lanéa1 and from 3.96 ± 0.13 to 3.12 ± 0.77 for Lanéa 2.

There is a significant difference between depths (0.20 to 0.77), with a higher pH in the Raphia sample at pH = 7.09, followed by Lanéa 1 at pH = 5.36 and finally Lanéa 2 at pH = 4.09. There is an uneven distribution of pH values across the sampling points. Analysis of the pH values shows a trend towards very acid soil at Lanéa 2, acid soil at Lanéa 1 and neutral soil at Raphia. This trend would appear to be influenced partly by the nature of the soil, but much more by anthropogenic inputs.

3.2.2. Heavy Metal Content in Daniela Soils

The results of these analyses show that, at the Raphia and Lanéa1 sites, iron content decreases with increasing depth. The first sample level is 15 cm deep and the second level is 30 cm. At level 1, in Raphia, the analysis gives an iron content of 59.71 mg/Kg at the first level, while at level 2 it decreases to 53.89 mg/Kg. At Lanéa 1, level 1 gives an iron content of 15.985 mg/Kg, while level 2 gives 15.455 mg/Kg. On the other hand, at Lanéa 2, the iron content increases with depth, from 7.18 mg/Kg to 10.495 mg/Kg.

Regarding to lead, at all three sites—Raphia, Lanéa 1 and Lanéa 2—lead content decreased with increasing depth. At the Raphia site, it decreases from 0.023 µg/Kg to 0.017 µg/Kg, at the Lanéa 1 site it decreases from 0.035 µg/Kg to 0.023 µg/Kg and at Lanéa 2, it drops from 0.012 µg/Kg to 0.08 µg/Kg.

Manganese content decreases with increasing depth at the Raphia and Lanéa 1 sites, respectively from 166.175 mg/Kg to 161.95 mg/Kg, and from 5.235 mg/Kg to 49.795 mg/Kg. At the Lanéa 2 site, the content increases with depth, from 6.695 mg/Kg to 11.395 mg/Kg.

Cadmium content increases with depth at the Raphia and Lanéa 2 sites. At the Raphia site, it is 4.165 mg/Kg at first level, rising to 6.63 mg/Kg at 2nd level depth. At Lanéa 2, it is 1.805 mg/Kg, rising to 4.67 mg/Kg at 2nd level. On the other hand, at Lanéa 1, the content decreases with depth, from 4.925 mg/Kg to 1.775 mg/Kg at 2nd level.

Copper content is high in this part of the study. At Raphia, it is 819.745 mg/Kg on the first level and decreases to 522.77 mg/Kg on the 2nd level. At the Lanéa1 and Lanéa2 sites, copper content increases with depth. Respectively from 223.32 mg/Kg to 293.315 mg/Kg and from 180.66 mg/Kg to 345.42 mg/Kg.

The results show that soil Trace Metal Element (TME) changes the value of concentration according to the metal element. Copper is the element with the highest maximum and average concentrations in the zone. The high concentration values of copper in the said soils, comparing to other elements, have also been reported [17] [18].

Whatever the element considered, the results show that levels vary according to horizon. The results also show that average soil concentrations of these elements are higher in surface horizons than in deeper horizons, and higher in deeper horizons than in surface horizons. The high TME values (Cd and Cu) in the surface soil layers could be linked to anthropogenic contamination. In fact, certain anthropogenic activities (agricultural inputs, mining, industry, etc.) lead to contamination and accumulation of TME in surface soil layers [17] [19]. As for the high average levels in the deeper layers, this suggests their natural origin in the soil.

Furthermore, the maximum concentrations of the various elements in the soils of the study area remain low comparing with those obtaining in certain types of soil, notably in France, with the exception of Cu and Cd, which exceeded the French limit. The results show that heavy metal levels in soils vary from one sampling site to another. These results are in line with those of numerous authors [17] [19] [20], who have shown that TME or heavy metal concentrations in soils vary according to the metal element, the sampling site and, for the same soil type, from one horizon to another.

In the absence of national standards for trace metal or heavy metal content in Chadian soils, the concentration values obtained were compared with the limit values of the French standard AFNOR U44 - 41. The present results indicate that the maximum and mean values for TME concentrations (Pb, Iron, Mn) are below the limit values of this standard. On the other hand, concentrations of metals such as cadmium and copper are well above the French standard. The results obtained therefore suggest that the soils at the various sites in the area are of relatively compromised quality in terms of the concentrations of TME (Cd and Cu) at each site sampled.

3.2.3. Evaluation of Contamination Levels

- Contamination factor (CF) and Average Contamination Index (ACI)

According to **Table 4** of the above assessment of contamination levels, after calculation it shows that all the contamination factor values for Fe, Pb and Mn are below 1 at all the sites sampled. However, those for Cd and Cu are well above 6, which means, according to ADJE Koudjo's rules listed above, that there is real Cd and Cu contamination at all sites.

In fact, the average contamination index, which is the sum of all contamination factors over the number of metals to be analyzed, is calculated to be well over 2. So the high values contamination factor for Cadmium and Copper impacted on the ACI results, ($ACI > 2$) so all sites are contaminated (**Figure 2** and **Table 4**).

- Pollution Load Index PLI

The pollution load index (PLI) is the product of all the contamination factor values and the number of elements to be analyzed. According to **Table 4**, its values are too small ($\ll 0$). To represent it in the Histogram, we multiply all PLI values by a common number 108, (**Figure 3**).

- Geo-accumulation index of heavy metals in Daniela soils

The geo-accumulation indices Igeo Fer, Igeo Pb and Igeo Mn in all sampled

sites are less than one, (Table 5). This implies that the soils are not polluted by these elements. On the other hand, the Igeo Cadmium is greater than 2 and the Igeo Cu is greater than 1, which, according to the Leila Sahli rules set out above, implies that these sites are contaminated.

3.2.4. Descriptive Statistical Analysis Results

From the plot of the components in space after rotation (Figure 4), we see that the metals are always within a radius of value 1 from the origin. The elements Mn_CC, Cd_CC, Pb_CC, Cd_AA, Pb_AA, Pb_BB must have a common origin contamination. Cu_BT and Fe_BT must also have a common source of contamination, as must Cu_BB and Cu_AA.

On the other hand, Cu_BT and Fe_BT and Cu_BB and Cu_AA are negatively correlated with respect to component axis 2, *i.e.* the sources of their contamination are not identical.

4. Conclusions

The aim of this study was to assess heavy metal soil pollution at the Daniela oil site in the Bongor basin. This site is an agricultural area that is home of several crude oil storage, processing and transport centers (OGM, FPF, CPF), several oil wellhead platforms and several connections or branches of pipelines carrying crude from one point to another.

The results show that heavy metal concentrations in soils vary widely. They vary according to the metal element at the sampling site, and from one horizon to another within the same soil type. The results also showed that the maximum concentration values for the various elements (Fe, Pb and Mn) are below the AFNOR limits, but those for Cd and Cu are above the AFNOR limits. Furthermore, the average ACI pollution index for each site is greater than 2, whatever the soil horizon is considered. This suggests that the sites in the area are subject to soil contamination by some elements (Cd and Cu). Consequently, the soils in this part of Daniela can be considered relatively like compromised.

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Conflicts of Interest

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

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