Agricultural Sciences, 2024, 15, 939-961
https://www.scirp.org/journal/as
ISSN Online: 2156-8561
ISSN Print: 2156-8553

# Evaluation of the Level of Pollution by Heavy Metals of Market Garden Soils along the Chari River in Ndjamena: Case of the 9th and 7th Districts

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**How to cite this paper:** Wana, K., Taisso, M.H., Andossa, L. and Djétenbé, B. (2024) Evaluation of the Level of Pollution by Heavy Metals of Market Garden Soils along the Chari River in Ndjamena: Case of the 9th and 7th Districts. *Agricultural Sciences*, **15**, 939-961.
https://doi.org/10.4236/as.2024.158051

**Received:** January 30, 2024
**Accepted:** August 25, 2024
**Published:** August 28, 2024

## Abstract

The main aim of this study was to characterize the metal content of soils used for market gardening along the Chari river: the 7th and 9th districts of NDjaména. To achieve this, two sites were selected: Gassi and Walia, and two control sites (Gassi and Walia). A total of fifty (50) soil samples were taken (24 from the Gassi site, 24 from the Walia site and 2 as control soils) and then analyzed to determine a number of physico-chemical parameters (pH, OM and electrical conductivity) and heavy metal concentrations in the various soils. The TME content (As, Cd, Cu, Cr, Ni, Pb, Hg and Zn) of the soils was determined by plasma-coupled Atomic Emission Spectrometry. In order to assess the level of contamination in Gassi and Walia soils, the geoaccumulation index (GeoIndex), contamination factor and degree of contamination were calculated. Results for physico-chemical parameters revealed that pH ranged from acidic (4.6) to moderately neutral (6.5), electrical conductivity was higher in cultivated soils (mean 292.14 µs/cm) than in control soils (mean 149.33 µs/cm), and soils were rich in organic matter. Overall, heavy metal concentrations in cultivated soils were higher than in control soils. The pollution estimate shows that soils in the area have no moderate contamination. The increase in TME concentrations in cultivated soils is thought to be due to the input of agricultural inputs to the soil. However, these levels are below the Average shale reference and Canadian guidelines for agricultural soil quality. Principal component analysis shows that metals are positively and significantly correlated with each other, and negatively and moderately significantly correlated with each other.

**Keywords**

Contamination, Agricultural Soils, City of N'Djaména, ETM, Gassi, Walia

## 1. Introduction

Worldwide, soil contamination by heavy metals is mainly due to the repeated use of pesticides, fungicides, manures, chemical fertilizers, sewage sludge, wastewater and urban waste [1]. Once released into the environment, heavy metals accumulate mainly in soils [2]. Generally speaking, in recent decades, past and present human activities, particularly agricultural and domestic, have been releasing a wide variety of potentially hazardous substances into the environment, known globally as contaminants or pollutants [3].

Historically, the focus has been on human health rather than the environment, and then on water pollution rather than soil, because for a long time it was believed that soils were capable of self-purification. This is clearly not the case, particularly when it comes to heavy metals [4].

Naturally, trace metals come from the weathering of parent rock and atmospheric fallout from volcanism. Human activity, on the other hand, favors the diffuse contamination of agricultural soils by TMEs, notably through the use of effluents, fertilizers and pesticides, but also through the production of industrial and automotive fumes [5]. While the presence of TMEs in soils does not induce phytotoxicity, it does represent a risk of contamination of the food chain, due to the absorption of these elements by plants. The impact of human activity and the disruption it causes to ecosystems is a highly topical issue [6].

In recent years, our planet has continued to be marked by environmental changes with major repercussions that are proving increasingly incompatible with the concept of sustainable development [7].

The use of Cd-containing P fertilizers and effluents contributes to the diffuse pollution of soils by these elements [8]. Their accumulation and transfer therefore represent a risk not only to human health via contamination of the food chain, but also to the natural environment as a whole [9]. They may exist in the soil as free ions or bound to soil particles. However, a metal is only toxic to living organisms if it is in free form, in which case it is bioavailable. Heavy metals such as lead, cadmium, copper, zinc and mercury cannot be biodegraded and therefore persist in the environment for long periods [10].

In France, work by [11] on total heavy metal levels in French soils revealed high concentrations of Ni, Cd, Pb, Cu, Zn, Co and Cr in several French regions. In Tunisia, [12] showed that fertilizers contain bioavailable trace elements that can contaminate agricultural soils. In Niger, cabbage and lettuce grown on irrigated soils in the Gounti Yena valley show significant accumulation of Cd, Cr, Fe, Zn and Pb [13]. In Chad, the work of [14] shows low concentrations of Ni, Cr, Fe and Zn in market garden soils used to grow onions in the town of Abéché (eastern Chad).

The irrigated perimeters of the city of N'Djamena are located along the banks of the Chari river, and occupy an area of 6.56 hectares devoted to the cultivation of market garden produce [15]. Market gardening supplies a wide range of produce: carrots, spinach, tomatoes, okra, sorrel, chillies, parsley, eggplant, cabbage, lettuce, cassava leaves, celery, amaranth, okra spinach, peppers, zucchinis, cucumbers. Market gardeners use sewage water, water from the Chari, which is also polluted, and groundwater to water their crops. They use fertilizers (NPK and urea) combined with household waste and phytosanitary products (pesticides, herbicides and fungicides) to treat the crops. The inappropriate use of these phytosanitary products is the source of pollution of the soil used for market gardening on the banks of the Chari River. Faced with all these realities, it is important to assess the level of pollution of soils cultivated along the Chari River: the case of the 9th and 7th districts of the city of Ndjamena.

## 2. Materials and Methods

In the course of our study, we selected two arrondissements (7th and 9th) in the Walia and Gassi sites. We then sampled the market garden soils on both banks of the Chari (Walia and Gassi sides), and also sampled the control soils (**Figure 1**). The choice of these 2 sites is based on the fact that soils on the banks of the Chari River are fertilized with chemical fertilizers.

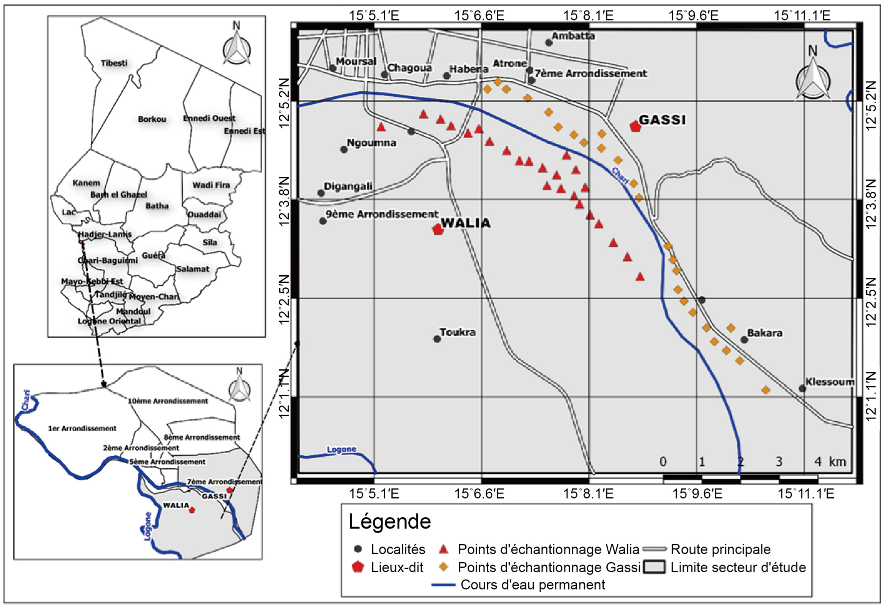

**Figure 1.** Location of study area.

### 2.1. Location of the Study Area

Chad is located between 8˚ and 23˚ degrees North latitude and 14˚ and 24˚ degrees East longitude. It covers an area of 1,284,000 km², making it the fifth largest country in Africa after Libya (1,759,540 km$^2$), the Democratic Republic of Congo (2,345,410 km$^2$), Algeria (2,381,740 km$^2$) and Sudan (2,505,810 km$^2$). It stretches 1,700 km from north to south and 1,000 km from east to west. It shares borders with Libya to the north, Sudan to the east, the Central African Republic to the south and Cameroon, Nigeria and Niger to the west.

The city of N'Djamena is located in western Chad between longitudes 15˚02' and 15˚07' East and latitudes 12˚03' and 12˚10' North. It lies at the confluence of the Chari and Logone rivers and covers an area of 12,000 hectares. The administrative capital and largest city of the Republic of Chad, N'Djamena is divided into ten arrondissements. The site selected for this study is located between longitudes 15˚5.1' and 15˚11.1' East and latitudes 12˚1.1' and 12˚5.2' North.

The climate in the study area is Sahelian, characterized by a short rainy period and a long dry period. It is marked by the alternation of two air masses: the Libyan anticyclone and the Saint Helena anticyclone. These are of continental and maritime origin respectively. Annual rainfall (1984 to 2014) varies from 226.1 to 775.9 mm (Ngaram Nambatingar 2011).

### 2.2. Field Method

In the field, soils were sampled and wrapped in plastic, while in the laboratory, these samples were analyzed for physico-chemical parameters and trace metals (TMEs). A total of two sites were chosen for soil sampling. These were the 7th arrondissement (Gassi site) and the 9th arrondissement (Walia site). Two control soils and 48 cultivated soils were sampled. The first control soil is 40 m from the first soil after cultivation, and the second control soil is 50 m from the second soil after cultivation. The first cultivated soil is located a few meters from the second soil after cultivation. Sampling was carried out at depths of between 10 and 30 cm (Figure 2(c) and Figure 2(f)). These samples were taken systematically in order to select representative samples. In the field, several crops were grown by market gardeners. These included: vegetables, peppers, celery, green beans, leeks, eggplants, sorrel, amaranth, tomatoes, carrots, leeks, tomatoes, eggplants, beans, etc. (Figure 2(e) and Figure 2(f)). Inputs and other chemical products (Figure 2(b)) were used to fertilize and boost production.

### 2.3. Laboratory Methods

Laboratory work focused on determining physico-chemical parameters and trace metals (TMEs) in Gassi and Walia market garden soils.

❖ **Determination of physico-chemical parameters**

Three (03) physico-chemical parameters were determined at ITRAD's Laboratoire d'Analyse de Sol, Eau et Plante in Ndjaména. These included pH (hydrogen potential), electrical conductivity (EC) and organic matter (OM). Sample preparation consists of the following steps: quartering, drying, grinding, sieving and preservation of samples in accordance with NF X 31-147 [16]. Analyses focused on determining pH, OM and electrical conductivity values for cultivated and control soils at each site (Gassi and Walia).

(a) (b) (c)

(d) (e) (f)

**Figure 2.** Photos illustrating field sampling. (a) Packaged sample; (b) Chemical box; (c) and (f) Sampling depth; (d) and (e) Crops grown.

❖ **Determination of Trace Metal Elements (TMEs)**

Heavy metals were dissolved and analyzed at the Spectrum Facility at the University of Johannesburg in South Africa. Heavy metals were determined using PERKIN ELMER OPTIMA 3,000XL Inductively Coupled Plasma Ionization (ICP - AES) Atomic Emission Spectrometry with RF power of 1,300W, plasma flow rate of 15 1/min, coolant flow rate of 0.5 l/min and nebulizer flow rate of 0.8 l/min. Standard reference materials were SRM 2 710 and SRM 2 711, used to assess the precision and accuracy of the procedure. The analyses carried out concerned eight (08) metallic trace elements, namely: Cr, Ni, Cu, Zn, As, Cd, Hg, Pb. These elements were determined in market garden soils at depths ranging from 10 to 30 cm in the control soils at each site (Gassi and Walia).

❖ **TME estimation methods**

Three methods were used to estimate trace metals in market garden soils in the study area. These were the Geoaccumulation Index (GEO), the Contamination Factor (CF) and the Degree of Contamination (DC).

## 3. Geo-Accumulation Index (GAI)

The Geo-accumulation Index was first determined by the researcher [17] to quantify the degree of metal pollution in soils. In addition, Müller defined a scale of values with six Igeo classes according to pollution intensity (**Table 1**).

The formula is:

$$\text{Igéo} = \log_2\left(\frac{C_n}{1.5\times B_n}\right)$$

Table 1. Geo-accumulation index (GAI) (Müller G. 1969).

| Igeo values | Classes | Pollution intensity |
|---|---|---|
| >5 | 6 | Extreme contamination |
| [4; 5] | 5 | High to extreme contamination |
| [3; 4] | 4 | Heavy contamination |
| [2; 3] | 3 | Moderate to heavy contamination |
| [1; 2] | 2 | Moderate contamination |
| [0; 1] | 1 | No to light contamination |
| <1 | 0 | No contamination |

Cn: Concentration measured in the sample; Bn: Soil-geochemical background; 1.5: Geochemical background exaggeration factor whose function is to take into account natural fluctuations in the soil-geochemical background; 1.5: Geochemical background exaggeration factor whose function is to take into account natural fluctuations in the soil-geochemical background.

### 3.1. Contamination Factor

The contamination factor (Cf) is used to determine the contamination status of soil samples in the study areas, in the version suggested by [18]. The table below (**Table 2**) is used to determine contamination status.

The formula is:

$$C_f = \frac{C_{metal}}{C_{background}}$$

Table 2. Contaminant factor (Thomilson *et al.*, 1980).

| Cf value | Level of contamination factor |
|---|---|
| $C_f < 1$ | Low contamination |
| $1 \le C_f < 3$ | Moderate contamination |
| $3 \le C_f < 6$ | Considerable contamination |
| $C_f > 6$ | Very high contamination |

where $C_{metal}$ is the measured concentration of a specific metal and Cbackground is the pedogeochemical background of the metal.

### 3.2. Degree of Contamination

Soil contamination was also assessed using the degree of contamination (Cd). The sum of the contamination factors for all the elements examined represents the Cd of the environment, and the four classes are recognized (**Table 3**) [19]. The $C_d$ is intended to provide a measure of the overall degree of contamination of each soil sample and has been evaluated using the equation below.

$$C_d = \sum_{i=1}^{n} C_f$$

**Table 3.** Level of contamination (Hakanson, 1980).

| Class of $Cd$ | Degree of contamination |
|---|---|
| $Cd \le 8$ | The degree of contamination is low |
| $8 \le Cd < 16$ | Degree of contamination is moderate |
| $16 \le Cd < 32$ | The degree of contamination is considerable |
| $32 \le Cd \le 80$ | The degree of contamination is very high |

### 3.3. Statistical Analysis

The results were analyzed using XLSTAT software version 2007.8.04, in which Principal Component Analysis (PCA) and Pearson's correlation matrix (n) were performed. The PCA and correlation matrix were used to highlight the various relationships that may exist between TMEs and physico-chemical parameters. The curves and graphs were produced using Excel 2016 software.

### 3.4. Statistical Analysis

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## 4. Results and Discussion

Tables 4-6 show the trace metal elements (TMEs) and physico-chemical parameters for the Gassi and Walia sites.

**Table 4.** Summary of results for MTE and physico-chemical parameters of Gassi soils.

| *Codes* | *Cr* | *Ni* | *Cu* | *Zn* | *As* | *Cd* | *Hg* | *Pb* | *pH* | *MO* | *CE* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***GP1*** | 50.47 | 25.81 | 19.62 | 77.95 | 1.79 | 0.03 | 0.02 | 19.06 | 5.70 | 1.96 | 235.00 |
| ***GP2*** | 60.18 | 17.12 | 13.63 | 59.03 | 1.29 | 0.01 | 0.03 | 12.03 | 6.30 | 1.30 | 251.00 |
| ***GP3*** | 34.00 | 20.10 | 14.94 | 67.15 | 1.78 | 0.05 | 0.02 | 11.70 | 6.40 | 5.57 | 298.00 |
| ***GP4*** | 50.93 | 28.70 | 19.96 | 78.42 | 2.83 | 0.01 | 0.02 | 16.80 | 6.50 | 1.45 | 205.00 |
| ***GP5*** | 70.82 | 20.23 | 15.37 | 63.10 | 2.38 | 0.06 | 0.02 | 16.50 | 5.60 | 4.95 | 270.00 |
| ***GP6*** | 72.58 | 11.55 | 9.36 | 40.51 | 0.51 | 0.01 | 0.02 | 10.87 | 4.90 | 1.53 | 256.00 |
| ***GP7*** | 37.19 | 22.44 | 14.97 | 60.22 | 1.51 | 0.03 | 0.02 | 13.97 | 5.20 | 3.61 | 530.00 |
| ***Min.*** | **34.00** | **11.55** | **9.36** | **40.51** | **0.51** | **0.01** | **0.02** | **10.87** | **4.90** | **1.30** | **205.00** |
| ***Max.*** | **72.58** | **28.70** | **19.96** | **78.42** | **2.83** | **0.06** | **0.03** | **19.06** | **6.50** | **5.57** | **530.00** |
| ***Moy.*** | **53.74** | **20.85** | **15.41** | **63.77** | **1.73** | **0.03** | **0.02** | **14.42** | **5.80** | **2.91** | **292.14** |

**Estimated pollution intensity**

- **Geo-accumulation index**

The results of the geo-accumulation index (Igeo) obtained in the different cultivated and control sites (Gassi and Walia) are shown in Table 7 and Table 8.

- **Contamination factor**

Table 9 and Table 10 show the contamination factor (CF) results for cultivated and control soils at Gassi and Walia.

- **Degree of contamination**

The results for the degree of contamination of market garden soils at the Gassi and Walia cultivated and control sites are shown in Table 11.

❖ Matrix and correlation circle for physico-chemical parameters and trace metal elements (TMEs)

Pearson correlation analysis was used to show the correlation between physico-chemical parameters (pH, OM, EC) and trace metals (TMEs) in cultivated and control soils (Figure 3).

Table 5. Summary of results for MTE and physico-chemical parameters of Walia soils.

| *Codes* | *Cr* | *Ni* | *Cu* | *Zn* | *As* | *Cd* | *Hg* | *Pb* | *pH* | *MO* | *CE* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***WP*1** | 27.30 | 13.78 | 11.04 | 38.74 | 1.20 | 0.02 | 0.01 | 9.97 | 4.80 | 0.28 | 485.00 |
| ***WP*2** | 32.59 | 18.25 | 15.05 | 56.44 | 0.98 | 0.05 | 0.02 | 11.64 | 5.30 | 0.17 | 100.00 |
| ***WP*3** | 73.55 | 15.64 | 13.05 | 74.44 | 1.14 | 0.03 | 0.01 | 10.33 | 5.30 | 0.28 | 70.00 |
| ***WP*4** | 36.78 | 19.40 | 17.92 | 78.84 | 1.00 | 0.09 | 0.03 | 11.29 | 5.40 | 0.31 | 45.00 |
| ***WP*5** | 32.01 | 16.72 | 14.17 | 158.04 | 0.92 | 0.07 | 0.01 | 11.01 | 5.60 | 0.53 | 70.00 |
| ***WP*6** | 58.39 | 19.32 | 13.86 | 51.86 | 1.72 | 0.06 | 0.02 | 12.48 | 5.60 | 0.85 | 80.00 |
| ***WP*7** | 99.55 | 11.65 | 7.76 | 33.66 | 0.79 | 0.04 | 0.04 | 7.94 | 4.90 | 0.53 | 164.00 |
| ***WP*8** | 34.80 | 16.40 | 12.78 | 61.13 | 1.01 | 0.05 | 0.02 | 12.22 | 5.00 | 1.36 | 52.00 |
| ***WP*9** | 68.91 | 18.24 | 10.79 | 47.31 | 1.68 | 0.02 | 0.01 | 9.55 | 5.40 | 1.23 | 141.00 |
| ***WP*10** | 23.21 | 10.24 | 7.82 | 34.27 | 0.27 | 0.07 | 0.03 | 8.11 | 6.20 | 1.23 | 50.00 |
| ***Min.*** | **23.21** | **10.24** | **7.76** | **33.66** | **0.27** | **0.02** | **0.01** | **7.94** | **4.80** | **0.17** | **45.00** |
| ***Max.*** | **99.55** | **19.40** | **17.92** | **158.04** | **1.72** | **0.09** | **0.04** | **12.48** | **6.20** | **1.36** | **485.00** |
| ***Moy.*** | **48.70** | **15.96** | **12.42** | **63.47** | **1.07** | **0.05** | **0.02** | **10.45** | **5.35** | **0.67** | **125.70** |

Table 6. Concentrations of TMEs and physico-chemical parameters in the control soils of Gassi (TG) and Walia (TW).

| *Codes* | *Cr* | *Ni* | *Cu* | *Zn* | *As* | *Cd* | *Hg* | *Pb* | *pH* | *MO* | *CE* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *TG* | 55.55 | 26.70 | 19.10 | 88.11 | 2.08 | 0.06 | 0.02 | 16.29 | 5.5 | 3.25 | 246 |
| *TW* | 65.99 | 30.10 | 24.45 | 91.57 | 2.21 | 0.06 | 0.04 | 18.07 | 5.5 | 2.19 | 149 |

**Table 7.** Geoaccumulation indices for Gassi soils.

| *Codes* | *IgéoCr* | *IgéoNi* | *IgéoCu* | *IgéoZn* | *IgéoAs* | *IgéoCd* | *IgéoHg* | *IgéoPb* |
|---|---|---|---|---|---|---|---|---|
| *GP*-1 | −0.0171 | −0.04 | −0.03 | 0.00 | −0.22 | −0.70 | −0.65 | −0.13 |
| *GP*-2 | 0.0593 | −0.22 | −0.19 | −0.12 | −0.37 | −1.18 | −0.48 | −0.33 |
| *GP*-3 | −0.1887 | −0.15 | −0.15 | −0.07 | −0.23 | −0.48 | −0.65 | −0.34 |
| *GP*-4 | −0.0132 | 0.00 | −0.02 | 0.00 | −0.03 | −1.18 | −0.65 | −0.18 |
| *GP*-5 | 0.1300 | −0.15 | −0.14 | −0.09 | −0.10 | −0.40 | −0.65 | −0.19 |
| *GP*-6 | 0.1406 | −0.39 | −0.35 | −0.28 | −0.77 | −1.18 | −0.65 | −0.37 |
| *GP*-7 | −0.1498 | −0.10 | −0.15 | −0.11 | −0.30 | −0.70 | −0.65 | −0.26 |
| *GP*-8 | 0.1433 | −0.35 | −0.35 | −0.32 | −0.62 | −0.57 | −0.65 | −0.51 |
| *GP*-9 | 0.2580 | −0.36 | 1.34 | 0.25 | −0.58 | −0.06 | −0.48 | 1.98 |
| *GP*-10 | 0.2877 | −0.41 | −0.43 | −0.35 | −0.87 | −0.88 | −0.65 | −0.48 |
| *GP*-11 | −0.3293 | −0.36 | −0.14 | 0.18 | −0.83 | −0.57 | −0.95 | −0.30 |
| *GP*-12 | 0.1023 | −0.25 | −0.24 | −0.22 | −0.40 | −0.88 | −0.65 | −0.32 |
| *GP*-13 | −0.2020 | −0.26 | −0.24 | −0.15 | −0.49 | −0.33 | −0.65 | −0.26 |
| *GP*-14 | 0.0313 | −0.01 | 0.01 | 0.07 | −0.15 | −0.27 | −0.35 | −0.11 |
| *GP*-15 | 0.1547 | −0.12 | −0.10 | −0.07 | −0.32 | −0.70 | −0.65 | −0.22 |
| *GP*-16 | 0.1353 | −0.17 | −0.14 | −0.10 | −0.35 | −0.48 | −0.35 | −0.23 |
| *GP*-17 | −0.0198 | −0.08 | −0.07 | −0.03 | −0.27 | −1.18 | −0.65 | −0.19 |
| *GP*-18 | −0.0348 | −0.20 | −0.25 | −0.19 | −0.25 | −0.88 | −0.65 | −0.36 |
| *GP*-19 | 0.2565 | −0.40 | −0.42 | −0.36 | −0.67 | −0.70 | −0.65 | −0.32 |
| *GP*-20 | −0.1477 | −0.19 | −0.19 | −0.14 | −0.36 | −0.88 | −0.48 | −0.33 |
| *GP*-21 | 0.1044 | −0.11 | −0.09 | −0.04 | −0.29 | −0.57 | −0.65 | −0.20 |
| *GP*-22 | −0.4765 | −0.46 | −0.55 | −0.57 | −0.62 | −1.18 | −0.65 | −0.65 |
| *GP*-23 | −0.4066 | −0.39 | −0.33 | −0.06 | −0.57 | −0.48 | −0.35 | −0.35 |
| *GP*-24 | 0.0523 | −0.01 | 0.00 | −0.04 | −0.05 | −0.57 | −0.48 | −0.14 |
| *TG* | 0.0245 | −0.03 | −0.04 | 0.05 | −0.16 | −0.40 | −0.65 | −0.19 |

**Table 8.** Geoaccumulation indices for Walia soils.

| *Codes* | *IgéCr* | *IgéoNi* | *IgéoCu* | *IgéoZn* | *IgéoAs* | *IgéoCd* | *IgéoHg* | *IgéoPb* |
|---|---|---|---|---|---|---|---|---|
| *WP*-1 | −0.28 | −0.32 | −0.28 | −0.30 | −0.40 | −0.88 | −0.95 | −0.41 |
| *WP*-2 | −0.21 | −0.19 | −0.14 | −0.14 | −0.49 | −0.48 | −0.65 | −0.34 |
| *WP*-3 | 0.15 | −0.26 | −0.21 | −0.02 | −0.42 | −0.70 | −0.95 | −0.39 |
| *WP*-4 | −0.15 | −0.17 | −0.07 | 0.00 | −0.48 | −0.22 | −0.48 | −0.35 |
| *WP*-5 | −0.21 | −0.23 | −0.17 | 0.31 | −0.51 | −0.33 | −0.95 | −0.36 |
| *WP*-6 | 0.05 | −0.17 | −0.18 | −0.18 | −0.24 | −0.40 | −0.65 | −0.31 |
| *WP*-7 | 0.28 | −0.39 | −0.43 | −0.36 | −0.58 | −0.57 | −0.35 | −0.51 |
| *WP*-8 | −0.18 | −0.24 | −0.22 | −0.11 | −0.47 | −0.48 | −0.65 | −0.32 |

Continued

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ***WP*-9** | 0.12 | −0.19 | −0.29 | −0.22 | −0.25 | −0.88 | −0.95 | −0.43 |
| ***WP*-10** | −0.35 | −0.44 | −0.43 | −0.36 | −1.04 | −0.33 | −0.48 | −0.50 |
| ***WP*-11** | 0.08 | 0.02 | 0.05 | 0.01 | −0.13 | −0.40 | −0.65 | −0.09 |
| ***WP*-12** | −0.20 | −0.31 | −0.33 | −0.32 | −0.52 | −0.70 | −0.35 | −0.38 |
| ***WP*-13** | −0.26 | −0.40 | −0.44 | −0.44 | −0.82 | −0.48 | −0.95 | −0.47 |
| ***WP*-14** | 0.09 | −0.12 | −0.12 | −0.02 | −0.32 | −0.40 | −0.65 | −0.07 |
| ***WP*-15** | −0.12 | −0.22 | −0.23 | −0.20 | −0.44 | −0.88 | −0.35 | −0.28 |
| ***WP*-16** | 0.27 | −0.17 | −0.13 | −0.02 | −0.34 | −0.22 | −0.48 | −0.27 |
| ***WP*-17** | 0.22 | −0.21 | −0.20 | −0.19 | −0.32 | −0.48 | −0.35 | −0.32 |
| ***WP*-18** | 0.13 | −0.30 | −0.30 | −0.22 | −0.55 | −0.70 | −0.65 | −0.42 |
| ***WP*-19** | −0.16 | −0.25 | −0.27 | −0.26 | −0.31 | −0.88 | −0.95 | −0.34 |
| ***WP*-20** | 0.20 | −0.42 | −0.45 | −0.44 | −0.59 | −0.57 | −0.48 | 0.01 |
| ***WP*-21** | 0.12 | −0.08 | −0.03 | −0.05 | −0.29 | −0.40 | −0.35 | −0.16 |
| ***WP*-22** | −0.05 | −0.15 | −0.11 | −0.06 | −0.30 | −0.48 | −0.48 | −0.22 |
| ***WP*-23** | 0.17 | −0.26 | −0.27 | −0.28 | −0.55 | −0.70 | −0.65 | −0.38 |
| ***WP*-24** | −0.09 | −0.15 | −0.26 | −0.18 | −0.34 | −0.18 | −0.95 | −0.22 |
| ***TW*** | 0.10 | 0.02 | 0.07 | 0.07 | −0.13 | −0.40 | −0.35 | −0.15 |

Table 9. Gassi contamination factor.

| ***Codes*** | ***CfCr*** | ***CfNi*** | ***CfCu*** | ***CfZn*** | ***CfAs*** | ***CfCd*** | ***CfHg*** | ***CfPb*** |
|---|---|---|---|---|---|---|---|---|
| ***GP*-1** | 1.44 | 1.36 | 1.40 | 1.50 | 0.90 | 0.30 | 0.33 | 1.12 |
| ***GP*-2** | 1.72 | 0.90 | 0.97 | 1.14 | 0.65 | 0.10 | 0.50 | 0.71 |
| ***GP*-3** | 0.97 | 1.06 | 1.07 | 1.29 | 0.89 | 0.50 | 0.33 | 0.69 |
| ***GP*-4** | 1.46 | 1.51 | 1.43 | 1.51 | 1.41 | 0.10 | 0.33 | 0.99 |
| ***GP*-5** | 2.02 | 1.06 | 1.10 | 1.21 | 1.19 | 0.60 | 0.33 | 0.97 |
| ***GP*-6** | 2.07 | 0.61 | 0.67 | 0.78 | 0.26 | 0.10 | 0.33 | 0.64 |
| ***GP*-7** | 1.06 | 1.18 | 1.07 | 1.16 | 0.76 | 0.30 | 0.33 | 0.82 |
| ***GP*-8** | 2.09 | 0.67 | 0.67 | 0.72 | 0.36 | 0.40 | 0.33 | 0.46 |
| ***GP*-9** | 2.72 | 0.66 | 32.88 | 2.66 | 0.40 | 1.31 | 0.50 | 142.24 |
| ***GP*-10** | 2.91 | 0.58 | 0.56 | 0.67 | 0.20 | 0.20 | 0.33 | 0.50 |
| ***GP*-11** | 0.70 | 0.65 | 1.08 | 2.29 | 0.22 | 0.40 | 0.17 | 0.75 |
| ***GP*-12** | 1.90 | 0.84 | 0.87 | 0.90 | 0.60 | 0.20 | 0.33 | 0.72 |
| ***GP*-13** | 0.94 | 0.83 | 0.87 | 1.06 | 0.49 | 0.70 | 0.33 | 0.82 |
| ***GP*-14** | 1.61 | 1.45 | 1.55 | 1.78 | 1.06 | 0.80 | 0.67 | 1.15 |
| ***GP*-15** | 2.14 | 1.13 | 1.19 | 1.28 | 0.72 | 0.30 | 0.33 | 0.91 |
| ***GP*-16** | 2.05 | 1.02 | 1.09 | 1.20 | 0.67 | 0.50 | 0.67 | 0.89 |
| ***GP*-17** | 1.43 | 1.25 | 1.28 | 1.41 | 0.81 | 0.10 | 0.33 | 0.96 |

Continued

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ***GP*-18** | 1.38 | 0.94 | 0.84 | 0.96 | 0.83 | 0.20 | 0.33 | 0.65 |
| ***GP*-19** | 2.71 | 0.59 | 0.56 | 0.65 | 0.32 | 0.30 | 0.33 | 0.71 |
| ***GP*-20** | 1.07 | 0.97 | 0.96 | 1.08 | 0.66 | 0.20 | 0.50 | 0.70 |
| ***GP*-21** | 1.91 | 1.16 | 1.23 | 1.35 | 0.77 | 0.40 | 0.33 | 0.95 |
| ***GP*-22** | 0.50 | 0.52 | 0.43 | 0.40 | 0.36 | 0.10 | 0.33 | 0.34 |
| ***GP*-23** | 0.59 | 0.61 | 0.71 | 1.32 | 0.40 | 0.50 | 0.67 | 0.68 |
| ***GP*-24** | 1.69 | 1.45 | 1.51 | 1.37 | 1.34 | 0.40 | 0.50 | 1.08 |
| ***TG*** | 1.59 | 1.41 | 1.36 | 1.69 | 1.04 | 0.60 | 0.33 | 0.96 |

Table 10. Walia contamination factor.

| ***Codes*** | ***CfCr*** | ***CfNi*** | ***CfCu*** | ***CfZn*** | ***CfAs*** | ***CrCd*** | ***CfHg*** | ***CfPb*** |
|---|---|---|---|---|---|---|---|---|
| ***WP*1** | 0.78 | 0.73 | 0.79 | 0.75 | 0.60 | 0.20 | 0.17 | 0.59 |
| ***WP*2** | 0.93 | 0.96 | 1.08 | 1.09 | 0.49 | 0.50 | 0.33 | 0.68 |
| ***WP*3** | 2.10 | 0.82 | 0.93 | 1.43 | 0.57 | 0.30 | 0.17 | 0.61 |
| ***WP*4** | 1.05 | 1.02 | 1.28 | 1.52 | 0.50 | 0.90 | 0.50 | 0.66 |
| ***WP*5** | 0.91 | 0.88 | 1.01 | 3.04 | 0.46 | 0.70 | 0.17 | 0.65 |
| ***WP*6** | 1.67 | 1.02 | 0.99 | 1.00 | 0.86 | 0.60 | 0.33 | 0.73 |
| ***WP*7** | 2.84 | 0.61 | 0.55 | 0.65 | 0.40 | 0.40 | 0.67 | 0.47 |
| ***WP*8** | 0.99 | 0.86 | 0.91 | 1.18 | 0.50 | 0.50 | 0.33 | 0.72 |
| ***WP*9** | 1.97 | 0.96 | 0.77 | 0.91 | 0.84 | 0.20 | 0.17 | 0.56 |
| ***WP*10** | 0.66 | 0.54 | 0.56 | 0.66 | 0.14 | 0.70 | 0.50 | 0.48 |
| ***WP*11** | 1.80 | 1.56 | 1.68 | 1.52 | 1.10 | 0.60 | 0.33 | 1.23 |
| ***WP*12** | 0.94 | 0.73 | 0.71 | 0.72 | 0.46 | 0.30 | 0.67 | 0.63 |
| ***WP*13** | 0.82 | 0.60 | 0.55 | 0.55 | 0.22 | 0.50 | 0.17 | 0.50 |
| ***WP*14** | 1.84 | 1.14 | 1.14 | 1.42 | 0.71 | 0.60 | 0.33 | 1.27 |
| ***WP*15** | 1.15 | 0.90 | 0.89 | 0.95 | 0.54 | 0.20 | 0.67 | 0.78 |
| ***WP*16** | 2.82 | 1.01 | 1.10 | 1.42 | 0.69 | 0.90 | 0.50 | 0.80 |
| ***WP*17** | 2.47 | 0.93 | 0.94 | 0.97 | 0.72 | 0.50 | 0.67 | 0.72 |
| ***WP*18** | 2.02 | 0.75 | 0.76 | 0.91 | 0.43 | 0.30 | 0.33 | 0.57 |
| ***WP*19** | 1.05 | 0.84 | 0.81 | 0.82 | 0.74 | 0.20 | 0.17 | 0.68 |
| ***WP*20** | 2.37 | 0.57 | 0.54 | 0.55 | 0.39 | 0.40 | 0.50 | 1.53 |
| ***WP*21** | 1.99 | 1.25 | 1.40 | 1.35 | 0.77 | 0.60 | 0.67 | 1.05 |
| ***WP*22** | 1.33 | 1.07 | 1.17 | 1.30 | 0.75 | 0.50 | 0.50 | 0.91 |
| ***WP*23** | 2.22 | 0.82 | 0.80 | 0.78 | 0.42 | 0.30 | 0.33 | 0.62 |
| ***WP*24** | 1.21 | 1.05 | 0.83 | 0.99 | 0.69 | 1.00 | 0.17 | 0.90 |
| ***TW*** | 1.89 | 1.58 | 1.75 | 1.76 | 1.11 | 0.60 | 0.67 | 1.06 |

**Table 11.** Degree of contamination at Gassi and Walia.

(a)

| *Codes* | *Degree of contamination* |
|---|---|
| ***GP*-1** | 4.70 |
| ***GP*-2** | 3.57 |
| ***GP*-3** | 3.90 |
| ***GP*-4** | 5.37 |
| ***GP*-5** | 5.01 |
| ***GP*-6** | 2.65 |
| ***GP*-7** | 3.74 |
| ***GP*-8** | 2.75 |
| ***GP*-9** | 134.98 |
| ***GP*-10** | 2.71 |
| ***GP*-11** | 3.19 |
| ***GP*-12** | 3.40 |
| ***GP*-13** | 3.19 |
| ***GP*-14** | 5.50 |
| ***GP*-15** | 4.27 |
| ***GP*-16** | 4.16 |
| ***GP*-17** | 4.25 |
| ***GP*-18** | 3.56 |
| ***GP*-19** | 3.02 |
| ***GP*-20** | 3.36 |
| ***GP*-21** | 4.38 |
| ***GP*-22** | 1.63 |
| ***GP*-23** | 2.84 |
| ***GP*-24** | 5.50 |
| ***TG*** | 207.91 |

(b)

| *Codes* | *Degree of contamination* |
|---|---|
| ***WP*-1** | 4.59 |
| ***WP*-2** | 6.06 |
| ***WP*-3** | 6.93 |
| ***WP*-4** | 7.43 |
| ***WP*-5** | 7.82 |
| ***WP*-6** | 7.20 |
| ***WP*-7** | 6.59 |
| ***WP*-8** | 6.00 |
| ***WP*-9** | 6.38 |

**Continued**

| | |
|---|---|
| ***WP*-10** | 4.23 |
| ***WP*-11** | 9.82 |
| ***WP*-12** | 5.15 |
| ***WP*-13** | 3.91 |
| ***WP*-14** | 8.46 |
| ***WP*-15** | 6.08 |
| ***WP*-16** | 9.24 |
| ***WP*-17** | 7.92 |
| ***WP*-18** | 6.08 |
| ***WP*-19** | 5.30 |
| ***WP*-20** | 6.84 |
| ***WP*-21** | 9.07 |
| ***WP*-22** | 7.51 |
| ***WP*-23** | 6.30 |
| ***WP*-24** | 6.83 |
| ***TW*** | 10.41 |

**Table 12.** Pearson correlation matrix table (a) for the Gassi site.

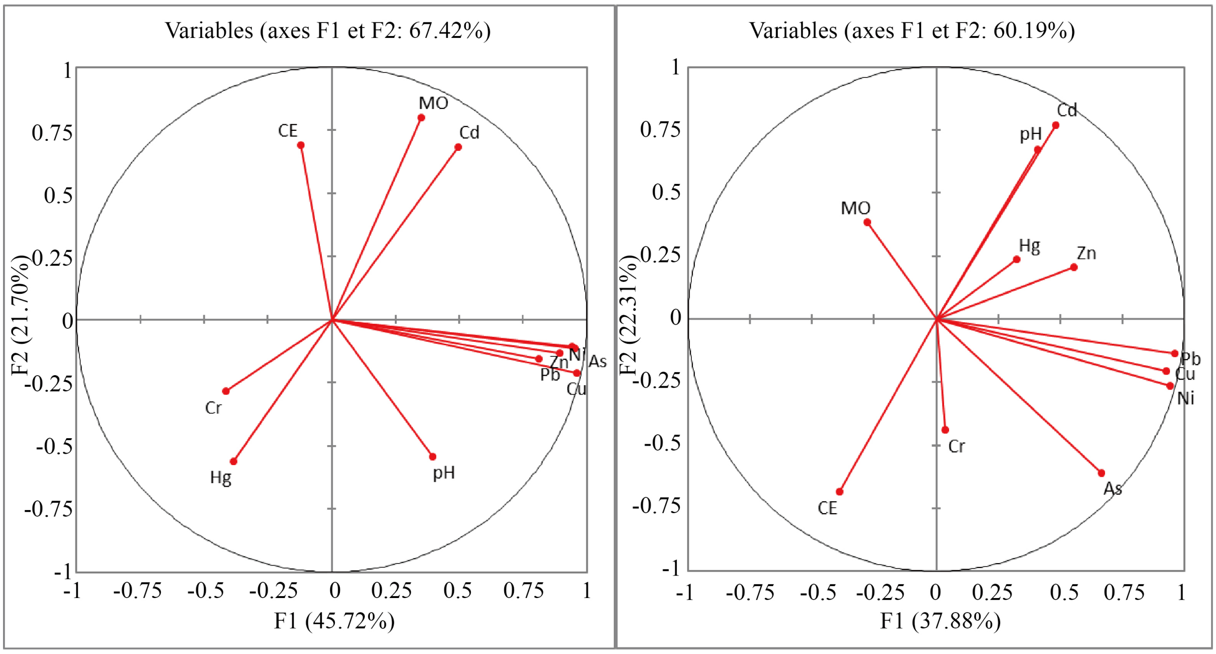
| ***Variables*** | ***Cr*** | ***Ni*** | ***Cu*** | ***Zn*** | ***As*** | ***Cd*** | ***Hg*** | ***Pb*** | ***pH*** | ***MO*** | ***CE*** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Cr*** | 1 | | | | | | | | | | |
| ***Ni*** | −0.46 | 1 | | | | | | | | | |
| ***Cu*** | −0.37 | **0.98** | 1 | | | | | | | | |
| ***Zn*** | −0.37 | **0.93** | **0.95** | 1 | | | | | | | |
| ***As*** | −0.21 | **0.83** | **0.82** | **0.76** | 1 | | | | | | |
| ***Cd*** | −0.13 | 0.27 | 0.28 | 0.44 | 0.38 | 1 | | | | | |
| ***Hg*** | 0.18 | −0.32 | −0.25 | −0.21 | −0.28 | −0.42 | 1 | | | | |
| ***Pb*** | −0.02 | **0.81** | **0.86** | **0.74** | **0.70** | 0.29 | −0.36 | 1 | | | |
| ***pH*** | −0.37 | 0.35 | 0.40 | 0.38 | **0.53** | −0.12 | 0.37 | 0.06 | 1 | | |
| ***MO*** | −0.32 | 0.13 | 0.10 | 0.25 | 0.29 | **0.93** | −0.42 | 0.01 | −0.04 | 1 | |
| ***CE*** | −0.50 | −0.04 | −0.20 | −0.21 | −0.22 | 0.15 | −0.16 | −0.21 | −0.41 | 0.33 | 1 |

**Table 13.** Pearson correlation matrix table (b) for the walia site.

| ***Variables*** | ***Cr*** | ***Ni*** | ***Cu*** | ***Zn*** | ***As*** | ***Cd*** | ***Hg*** | ***Pb*** | ***pH*** | ***MO*** | ***CE*** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Cr*** | **1** | | | | | | | | | | |
| ***Ni*** | 0.13 | **1** | | | | | | | | | |
| ***Cu*** | −0.04 | **0.94** | **1** | | | | | | | | |
| ***Zn*** | −0.18 | 0.40 | 0.51 | **1** | | | | | | | |

Continued

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***As*** | 0.37 | **0.84** | **0.66** | 0.14 | **1** | | | | | | |
| ***Cd*** | −0.38 | 0.21 | 0.39 | 0.43 | −0.22 | **1** | | | | | |
| ***Hg*** | 0.31 | 0.23 | 0.26 | −0.21 | 0.00 | 0.46 | **1** | | | | |
| ***Pb*** | 0.00 | **0.94** | **0.93** | 0.40 | **0.75** | 0.26 | 0.26 | **1** | | | |
| ***pH*** | −0.23 | 0.24 | 0.24 | 0.24 | 0.01 | 0.57 | 0.23 | 0.22 | **1** | | |
| ***MO*** | −0.08 | −0.25 | −0.42 | −0.27 | −0.12 | −0.03 | −0.05 | −0.22 | 0.26 | **1** | |
| ***CE*** | −0.08 | −0.21 | −0.23 | −0.33 | 0.10 | −0.61 | −0.27 | −0.18 | −0.56 | −0.29 | **1** |



(a) (b)

**Figure 3.** Correlation circles for: a) Gassi and b) Walia.

## 5. Discussion

Physico-chemical parameters of GASSI and Walia soils

The study of physico-chemical parameters focused mainly on the determination of pH levels, organic matter and electrical conductivity. pH, OM and EC are considered the main parameters controlling the bioavailability of heavy metals in soil [20] and [21]. **Table 4** and **Table 5** show OM values at the Gassi and Walia sites. They range from 1.30% to 5.57%, with an average of 2.91% at the Gassi site, and from 0.17% to 1.36%, with an average of 0.67% at the Walia site. According to Denis B. (2000) and [22], these soils are rich in OM. OM levels at our sites are above the norm. These OM values observed in the Gassi (G) and Walia (W) market garden sites are below the values obtained in the Gassi control site (2.19%) (**Table 6**) and in the Walia control site (TW) (**Table 6**). This could be explained by the fact that the control soils are located at a distance from the market garden sites. The behavior of heavy metals in the soil is highly dependent on the nature and proportion of the various soil components. Soil organic matter has a high specific surface area and can also play an important role in controlling soil acidity [23].

Indeed, the mobility and bioavailability of metallic elements are largely dependent on the pH of the medium [24]. Zn, Pb, Ni, Cd and Cu are more mobile and bioavailable at acid pH than at neutral pH [25]. These elements are therefore more bioavailable in control soils than in cultivated soils.

Zn, Pb, Ni, Cd and Cu are more mobile and bioavailable at acid pH than at neutral pH [25]. Thanks to its colloidal properties, organic matter plays a very important role in the retention of heavy metals [26]. Temperature can have an indirect influence in the presence of organic matter, for example by increasing its degradation, which can produce acidic, complexing substances [27].

As for pH, values range from 4.90 to 6.50 at the Gassi site and from 4.80 to 6.20 at the Walia site (**Table 4** and **Table 5**). The results show that the soils in our study area are acidic to moderately neutral. These results are similar to those obtained on clay-textured market garden soils in Dschang (Cameroon) [28]. **Table 6** shows acid pH values (5.5) in the control sites of Gassi (TG) and Walia (TW). According to Bourrelier P.H. and Berthelin J. (1998), this acidity in these control soils is linked to the nature of the soils or to hydroxide precipitation, which generates a low acidity in the environment and adsorbs heavy metals.

With regard to electrical conductivity, it varies significantly in Walia cultivated soils (from 45 to 485 µs/cm) and less significantly (205 to 530 µs/cm) in Gassi cultivated soils (from 205 to 530 µs/cm) (**Table 4** and **Table 5**). It is 246 µs/cm in the control soils of Gassi (TG) and 149 µs/cm in the control soils of Walia (TW) (**Table 6**). These results therefore show that the cultivated soil samples from Gassi are more conductive than the control soils from both sites (Gassi and Walia) and the cultivated soils from Walia. Soil conductivity is an index of soluble salt content in the soil. It expresses the approximate concentration of ionizable solutes present in the sample, *i.e.* its degree of salinity. This electrochemical property is based on the fact that the conductance (inverse of electrical resistance) of a solution increases as the concentration of ions, the carriers of electrical charges, increases. The high conductivity values obtained in this study reflect the high mineral loading of these TMEs ($Cr^{2+}$, $Pb^{2+}$, $Ni^{2+}$, $Cu^{2+}$, $Cd^{2+}$, $Zn^{2+}$) in the various soils studied [29].

**Heavy metal contamination of Gassi and Walia market garden soils**

To assess soil contamination levels, eight (08) trace metals were analyzed: Cr, Ni, Cu, Zn, As, Cd, Hg and Pb were analyzed and the results are presented in **Table 4** and **Table 5**.

The average Cu concentration was 15.41 kg/mg in the Gassi market garden soils (**Table 4**) and 12.42 kg/mg in the Walia market garden soils (**Table 5**). These levels of contamination are lower than the concentration obtained in the control soils of Gassi (TG) (19.10 mg/kg) (**Table 6**) and Walia (TW) (24.45 mg/kg) (**Table 6**). These results could be explained by the pH values of the two study sites.

The concentrations recorded in the soils studied are higher than those obtained in market garden soils (8 mg/kg) from Dschang in Cameroon [30] and are lower than the Canadian standard (63 mg/kg) [31].

The Cu content of these soils could be explained by the significant and repeated use of chemical inputs for soil fertilization [32].

According to the Canadian Soil Quality Guidelines, the average As concentration (1.73 mg/kg) in Gassi soils is lower than the average concentration recorded in its control soil (2.80 mg/kg), while the average concentration (1.07 mg/kg) in Walia cultivated soils is lower than the average recorded in its control soil (2.10 mg/kg). These levels are below the Canadian standard (5.9 mg/kg). However, they are higher than those obtained in French soils (0.1 - 0.52 mg/kg) and the concentrations obtained by [33] in soils from the Niéki valley in south-eastern Côte d'Ivoire (0.003 - 0.012 mg/kg) and those obtained by [34] in cultivated soils from Farcha/N'Djamena/Chad (0.52 mg/kg). These high levels could be explained by the frequent use of pesticides, particularly herbicides.

According to Denis B. (2000), the average Cd concentration (0.03 mg/kg) in Gassi's market garden soils (**Table 4**) is lower than the average concentration in its control soil (0.06 mg/kg) and the average Cd concentration in Walia's cultivated soils (0.05 mg/kg) (**Table 5**) is also lower than the average concentration in its control soil (0.06 mg/kg) (**Table 6**). These levels are not in the same range as Cd levels (0.30 mg/kg) in soils cultivated in France. It is also lower than the average concentration (0.14 mg/kg) obtained by [35] in roadside agricultural soils in Yixing city (China). The presence of Cd in agricultural soils could be due to the repeated use of phosphate fertilizers such as NPK and urea, which mainly contribute cadmium to the soil.

The mean Cr concentration (53.74 mg/kg) in the cultivated soils of Gassi (**Table 4**) is lower than the mean concentration in its control soil (55.55 mg/kg) (**Table 6**). The average Cr concentration (48.76 mg/kg) (**Table 5**) in Walia cultivated soils is lower than the concentration in its control soil (65.99 mg/kg). From these results, we can say that Cr concentrations in the market garden soils are below those of their control soils. These concentrations are lower than the Average shale reference (90 mg/kg) and higher than the UCC (35 mg/kg). They are also lower than those obtained by [36] in cultivated soils (81.60 mg/kg and 86.96 mg/kg) along lakes Bini/Dang (Ngaoundéré/Cameroon). This low Cr content may be due either to metal migration to underlying horizons, or to phytoextraction by plants [37]. These results corroborate those obtained by [38] on cultivated soils close to the Dhaka export zone in Bangladesh.

La concentration moyenne en Ni (20,85 mg/kg) (**Table 4**) enregistrée dans les sols maraichers de Gassi est inférieure à celle obtenue dans son sol témoin (26.70 mg/kg) et la concentration moyenne en Ni obtenue dans les sols maraichers de Walia (15.96 mg/kg) (**Table 5**) est aussi inférieure à celle de son sol témoin (30.10 mg/kg) (**Table 6**). Ces concentrations sont inférieures à la référence d'Average shale (68 mg/kg) et supérieures à l'UCC (19 mg/Kg).

Les quantités de Ni d'origine anthropique reçues par les sols sont relativement faibles [39] et généralement inférieures aux normes concernant les quantités que l'on peut apporter. Les concentrations élevées en Ni dans les sols témoins de Gassi et de Walia pourraient s'expliquer par des phénomènes naturels (roches mères riche en Ni) ou encore à la circulation des différents moyens de transport qui laissent échapper les gaz et qui sont susceptibles d'induire une quantité du Ni dans le sol, donc une toxicité dans le sol [40].

Similarly, the average Zn concentration (63.77 mg/kg) (**Table 4**) in Gassi cultivated soils is lower than the average concentration recorded in its control soil (88.11) and the average concentration recorded in Walia cultivated soils (63.47 mg/kg) (**Table 5**) is also lower than that of its control soil (91.57 mg/kg) (**Table 6**). These concentrations are lower than the Average shale reference (95 mg/kg) and higher than the UCC (52 mg/kg). The average concentrations recorded in the soils of the study area are extreme and higher than the average concentrations (32.36 mg/kg and 30.08 mg/kg) obtained by Bichara, R. M. (2013) in the cultivated soils of Farcha/Ndjamena/Chad. This high concentration of Zn could be explained by the excessive use of herbicides, pesticides and fungicides to increase production, by the highly polluted water from the waste discharged by the industries installed along the banks of the Chari River to irrigate crops, and by atmospheric fallout, mainly from industrial activity and the traffic of various means of transport [40].

The average Pb concentration (14.42 mg/kg) (**Table 4**) recorded in Gassi's cultivated soils is lower than the average concentration obtained in its control soil (16.29 mg/kg) (**Table 6**). The same observation was made with regard to the average concentration in the cultivated soils of Walia (10.45 mg/kg) (**Table 5**), which is also lower than that of its control soil (18.07 mg/kg) (**Table 6**). These average lead levels in the cultivated and control soils are lower than the Average shale reference (20 mg/kg) estimated by [41] and the UCC reference (17 mg/Kg). They are also below the Canadian standard and below the limit (60 mg/kg) set by [42]. These values are well below the limit value (100 mg/kg) set by the WHO [43]. The increase in lead content in cultivated soils could be explained by the use of chemical inputs (fertilizers and pesticides) [44].

The mean Hg concentration (0.02 mg/kg) (**Table 4**) recorded in Gassi's market garden soils is equal to that obtained in its control soil (0.02 mg/kg) (**Table 6**) and the mean Hg concentration (0.02 mg/kg) (**Table 5**) obtained in Walia's cultivated soils is lower than that of its control soil (0.04 mg/kg) (**Table 6**). These concentrations are lower than those obtained by [45] in agricultural soils in mainland France. The concentrations observed in the cultivated soils of Gassi and Walia could be due to the use of phytosanitary products by its market gardeners. Those observed in the control soils of Gassi and Walia could be due to natural phenomena. Mercury is considered by the WHO to be one of ten chemicals or groups of chemicals of very high concern for public health.

- **Assessment of pollution intensity**

To estimate contamination levels, three methods were used, namely the geo accumulation index (Igéo), the contamination factor (Fc) and the degree of contamination (Dc).

Table 7 and Table 8, *i.e.* Gassi and Walia respectively, present the results of the geoaccumulation index (Igéo). Table 7 (Gassi) shows that all TMEs are zero-contaminated, with the exception of Cu and Pb, which are moderately contaminated.As for Table 8 (Walia), all MTEs show zero contamination.

The results of the contamination factor calculation presented in Table 9 (Gassi) show that all the TMEs are moderately contaminated, with the exception of Pb, which is very highly contaminated in sample 9 (GP-9) (142.24) and Cu (GP-9) (32.88). This could be due to the application of chemicals and pesticides, which would lead to an increase in heavy metal emissions, particularly Pb. These results confirm the very high presence of Pb in sample 9 from Gassi. Table 10 presents the contamination factors at the Walia site. From this table (Table 10), it can be seen that all the TMEs analyzed are moderately contaminated. The results of the degree of contamination presented in Table 11(a) (Gassi) and Table 11(b) (Walia) show that all the ETMs present a low degree of contamination to a very high degree of contamination (134.98 and 207.91) respectively GP-9 and control soil of Gassi (TG).

- **Statistical analysis**

Pearson correlation matrices were used to establish correlations between the heavy metals studied and physico-chemical parameters (pH, OM and EC) at a level of significance ($P < 0.05$). The various correlations observed are presented in Table 12 and Table 13 on the one hand, and in Figure 3(a) and Figure 3(b) on the other.

Table 12 and Figure 3(a) show that most of the heavy metals at the GASSI site are positively and significantly correlated with each other. This positive and significant correlation between metals could be explained by a possible common origin. The negative correlation, on the other hand, points to different origins between these elements. Indeed, positive and highly significant correlations are observed between As/Ni, As/Cu, Pb/Ni, Cu/Ni, Cu/Zn, Cd/MO, Pb/Zn, Zn/Ni, Pb/Cu, whereas they are negative and significant between many metals. Positive and moderately significant correlations are observed between Pb/As, As/pH and moderately significant negative correlations are observed between many metals. Table 13 and Figure 3(b) reveal that a small proportion of the heavy metals at the WALIA site show positive and significant correlations with each other.

These are Cu/Ni, Pb/Ni, Pb/Cu, As/Ni. In fact, there are non-significant negative and positive correlations between many metals. Positive and moderately significant correlations are observed between Cu/As, As/Pb.

**•Some techniques for removing heavy metals from soil**

The numerous cases of heavy metal pollution generate a large number of contaminated sites that need to be rehabilitated. The physico-chemical methods used in situ and ex situ to remediate these sites have the disadvantage of being costly and cumbersome to implement [46]-[48].

✓**Principle of the phytoremediation technique**

Phytoremediation is defined as the use of plants to extract or transform organic and also inorganic pollutants (most notably heavy metals) [48]. More specifically, the types of phytoremediation strategies particularly used in heavy metal remediation are described below:

✓**Phytostimulation**: Plants secrete root exudates that can be used by microbial communities to promote their development and activities. This microbial stimulation in the rhizosphere modifies the bioaccumulation, biological oxidation/reduction and biomethylation of heavy metals [49].

✓**Phytoextraction:** Use of plants that absorb heavy metals from the soil through their roots, then transfer and accumulate them in their harvestable parts (leaves, stems and roots). The heavy metals complex with organic acids or amino acids synthesized by the plant. The heavy metals are then recovered by incinerating or composting the plant biomass [49].

✓**Phytovolatilization:** Use of plants that absorb organic contaminants and other toxic products, transforming them into volatile elements of low or no toxicity and releasing them into the atmosphere via their leaves [49].

Phytostabilization: Use of plants to reduce the bioavailability of pollutants through runoff (lateral or deep) or immobilize pollutant compounds by chemically binding them through precipitation, stabilization, absorption or trapping by the plant. This technique prevents the dispersion of pollutants in surface and groundwater [50].

❖ **Phytoextraction of soils contaminated by heavy metals**

Among the various phytoremediation methods, the most widely used is phytoextraction, applied particularly for heavy metal remediation. Phytoextraction uses plants capable of taking up heavy metals, transferring them and accumulating them in their aerial parts, which are then harvested. After harvesting by traditional agricultural methods, the plant tissues that have concentrated the heavy metals are treated by drying, incineration or composting. This technique represents an alternative or a complement to physico-chemical treatments of soil contaminated by heavy metals. There are two phytoextraction strategies: assisted (induced) phytoextraction and continuous phytoextraction [51].

## 6. Conclusions

In order to assess the level of metal pollution in market garden soils bordering the Chari watercourse, a study was carried out at the Gassi and Walia sites, located in the 7th and 9th districts of the city of Ndjaména.

The results of the physico-chemical parameters obtained show that the pH of the study area is acidic to moderately neutral. The pH of the control soil is acidic. Zn, Pb, Ni, Cd and Cu are more mobile and bioavailable at acid pH than at neutral pH. This confirms the values observed in this study. The organic matter content of the soils studied is above the norm. Organic matter levels in cultivated soils are lower than in control soils. Conductivity varies more in WALIA cultivated soils (45 to 485 µs/cm) than in GASSI cultivated soils (205 to 530 µs/cm). Cultivated soils are more conductive than control soils.

Evaluation of heavy metal concentrations shows relatively high levels of trace metals, such as Ni, Cu, Cd, As, Pb and Hg, and are generally below reference values. Calculations of the geoaccumulation index (Igeo) show zero to moderate contamination, while the contamination factor (Fc) reveals moderate contamination, with the exception of Pb, which shows very high contamination in GP-9 and TG. All ETMs have a low degree of contamination, with the exception of GP-9 and TG. The correlations observed between the various ETMs in the study area are positive and significant. The very high levels of Pb may be a source of contamination for all crops grown along the Chari stream. All in all, this study confirms that agricultural practices contribute significantly to the input of TMEs into soils. It is important to remember that the high availability of these pollutants in the soil represents a potential danger to human health. To remedy this soil pollution problem, several phytoremediation methods can be used. Among these methods, phytoextraction is the most widely used for the decontamination of heavy metals in soil.

## Conflicts of Interest

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

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