


Determination of Organic Matter and Trace Metals Elements (As, Sb, Cd, Hg, Ni, Pb, Cr, Zn) in the Soils of the Banks of Watercourses in Brazzaville City (Republic of Congo)

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Abstract

This work focused on determining the physico-chemical characteristics (pH, carbon and nitrogen) and trace metal elements (TMEs) content (As, Sb, Cd, Hg, Ni, Pb, Cr, Zn) of soils in the Brazzaville city. Soil samples were taken from a depth of 0 to 20 cm using a hand auger on both banks of five tributaries of the Congo River (*Djoué, Mfilou, Mfoa, Tsiémé, Djiri*) that flow through the city of Brazzaville. 90 sampling points were defined, with 3 points 250 m apart on the banks and located, for each river, at three sites: upstream, midstream and downstream. Finally, 15 composite samples representative of the study area were taken. The average pH values of the water varied between 6.5 and 7.5. These pH values show that the soils studied are neutral. Total carbon content varied between 0.7% (*Djiri*) and 1.6% (*Djoué*). Total nitrogen content ranged from 0.08% (*Djiri*) to 0.12% (*Djoué*). TMEs contents varied from 0.5 to 1.8 mg/kg for Sb, from 0.5 to 2.5 mg/kg for As, from 0.1 to 0.18 mg/kg for Cd, from 4.2 to 11.3 mg/kg for Cr, from 0.07 to 0.27 mg/kg for Hg, from 0.7



to 2.4 mg/kg for Ni, from 0 to 158 mg/kg for Pb and from 16 to 105 mg/kg for Zn. The lowest TMEs levels were observed in the soils of the *Djiri* river, while the highest levels were observed in the soils of the *Djoué* and *Tsiémé* rivers. The ANOVA and Bonferroni test did not show significant differences in the means of the parameters measured ($p > 0.05$). The TMEs levels were below the accepted standards (NF U44-041), with the exception of Pb, which had high levels downstream of the *Djoué*. According to the pollution index values calculated using soil TME content, the soils on the banks of the *Djoué* river are considered polluted, while those on the banks of the *Tsiémé* river are moderately polluted, those on the banks of the *Mfoa* and *Mfilou* rivers are slightly polluted, and the soils on the banks of *Djiri* river are unpolluted.

Keywords

Carbon, Nitrogen, Trace Metal Elements, Soil, Brazzaville, Congo

1. Introduction

Human activity generates pollution in several forms. One of these is the pollution of urban areas through the discharge of untreated wastewater, hydrocarbons, solvents, heavy metals, solid particles or mixtures of these products [1]. Soil is considered to be part of the upper layer of the earth's crust, composed of mineral particles, organic matter water, air and organisms [2]. It is the site of an intense exchange of matter and energy between air, water and rocks. As part of the ecosystem, soil plays a key role in global matter cycles [3]. As an interface, it plays key roles in the environment: as a sink or source of greenhouse gases, as a filter for many contaminants, as a flood buffer for rainwater, etc. [4]. Soil is also a major reservoir of carbon and nitrogen, playing a major role in offsetting losses due to greenhouse gas emissions. Soil carbon and nitrogen are closely linked to soil organic matter (SOM), which gives the soil physico-chemical properties that promote the sustainable functioning of ecosystems [5]. With the demographic growth that the Brazzaville city has experienced in recent years, there has been a change in land use that can have various consequences for modifications in soil carbon stocks. The consequences of this strong demographic expansion are soil stripping through the destruction of vegetation, disruption of the water cycle by modifying flows and channels, and land degradation through gully and surface stripping associated with water erosion [6]. As an attribute of urban environments, soil is the main sink for metals and other pollutants. The anthropogenic origins of these potentially toxic metals, such as lead (Pb), zinc (Zn), copper (Cu) and arsenic (As), are mainly attributed to road traffic, vehicle emissions, brake and tire wear and industrial street activities [7]. For this reason, it is necessary to characterize the soil in order to predict or understand the behaviour of pollutants and the possible consequences of pollution. This needs to acquire more information on soil for its sustainable use and good conservation requires its continuous characterization

[8]. The aim of this work is to determine the level of heavy metal pollution in Brazzaville soils using a systematic sampling strategy in the surface horizons of these soils.

2. Methodology

2.1. Presentation of the Study Area

Located between latitudes 4°6' and 4°24' South and longitudes 15°6' and 15°18' East, with an average altitude of 301 m (**Figure 1**), the city of Brazzaville, capital of the Republic of Congo, is located on the banks of a lake, Pool Malebo (formerly Stanley Pool), upstream of the Kintambo rapids, the first in a series of falls and rapids that prohibit navigation on the lower Congo, the second most powerful river after the Amazon [9] [10]. Covering an area of 32,640 ha, the urban area of Brazzaville city is divided administratively into nine (09) arrondissements: 1 (Makélékélé), 2 (Bacongo), 3 (Poto-Poto), 4 (Moungali), 5 (Ouenzé), 6 (Talangai), 7 (M'filou), 8 (Madibou) and 9 (*Djiri*). This city is built on a relief of plateaux and plains, in a transitional situation between the Cataractes plateau to the south and the Mbé plateau to the north [10]. This relief has a stepped appearance, decreasing towards the Congo River, and is incised by a natural drainage network serving as primary collectors, consisting of geological ravines (Glacière, Chad, Mission), streams (*Mfilou*, Makélékélé, *Mfoa*, the Ouenzé known as Madoukoutsékélé, Kélékélé, Ngamakosso) and rivers (Loua, *Djoué*, *Tsiémé*, *Djiri*) belonging to the Stanley-Pool watershed [10]. Brazzaville has a humid tropical or “Bas-Congolais” climate with two seasons. A dry season lasting 4 months, from June to September, and a rainy season lasting 8 months, from October to May [11]. According to the latest General Census of Population and Housing [12], the population of the city of Brazzaville has risen in just over 50 years, from 124,030 in 1960 to 2,145,783 in 2023, or 34.94% of the country's population, resulting in a high demand for building space [12]. Brazzaville's soils are mainly of three types: PODZOLS, FERALSOLS and GLEYSOLS [13] [14]. Depending on the nature of the parent rock, these soils are sandy-clayey, in the case of those derived from Inkisi arkosic sandstones, or sandy in the case of those derived from Batéké sands [15].

2.2. Methods

2.2.1. Sampling and Sample Conditioning

Soil samples were taken on both banks of five tributaries of the Congo River flowing through the Brazzaville city (*Djoué*, *Mfilou*, *Mfoa*, *Djiri* and *Tsiémé* rivers). To take account of the heterogeneity of the environment, 15 sites soil sampling were determined on whole study area, comprised three sampling locations on each river: upstream, midstream and downstream. At each site and on each riverbank, three soil samples were taken at an equidistance of 250 m, giving a total of 6 soil samples taken at each site. Globally, 90 soil samples were taken over the entire study area. Taking into account the costs of chemical analysis, and ensuring that the study area was representative, a composite soil sample was made up of six

elemental samples from each sampling site. Finally, 15 composite samples representative of the study area were analysed.

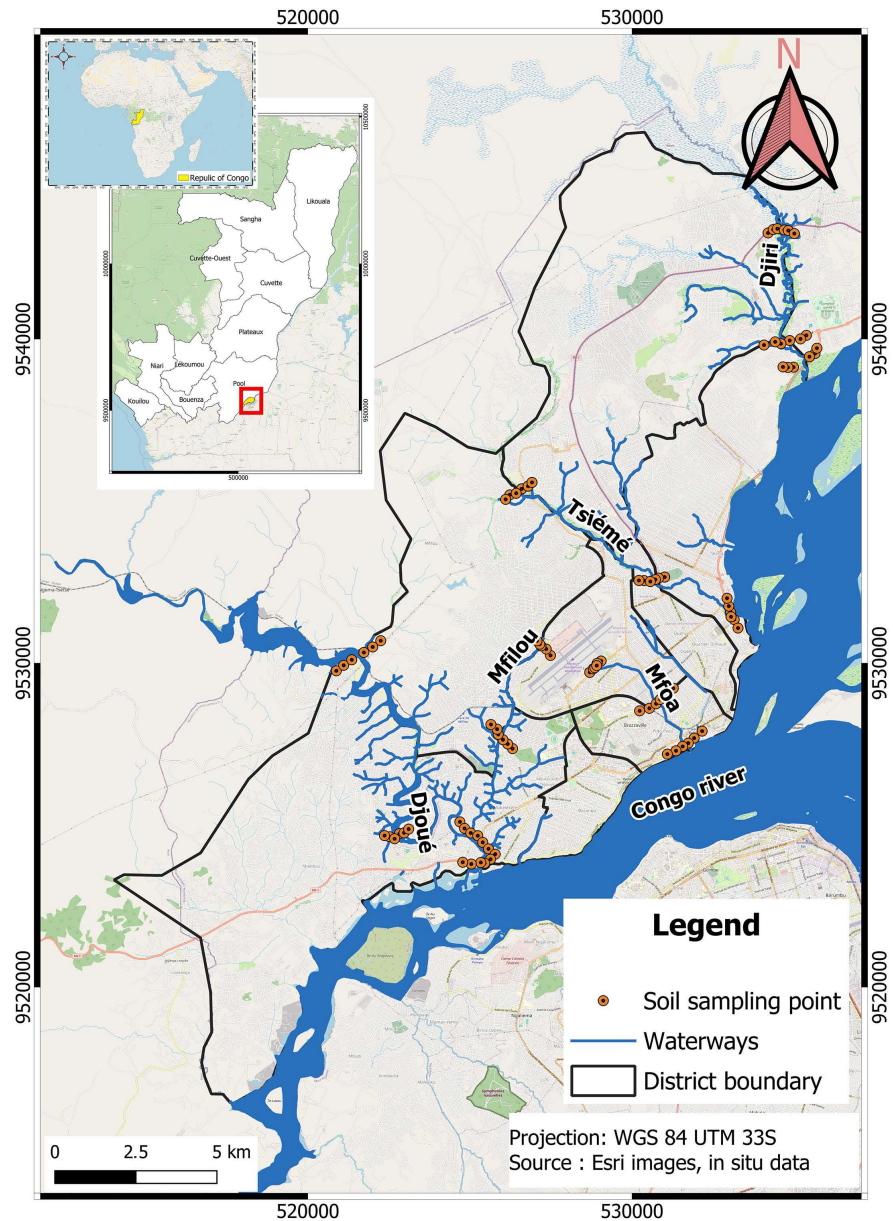


Figure 1. Study area and soil sampling sites.

The sampling points were georeferenced so that they could be represented spatially on a map (**Figure 1**). The samples were then transported to the geosciences and environment research laboratory (LARGEN) for drying and sieving (using a 2 mm square-mesh sieve) before being analysed in the analysis laboratory. After these preparation operations, the samples were stored in jars for dispatch to the analysis laboratory at the National Institute for Research in Exact and Natural Sciences (IRSEN) in Pointe Noire (Republic of Congo).

2.2.2. Laboratory Analysis

The parameters measured were: pH H₂O, pH KCl, total carbon and total nitrogen. The pH H₂O was determined by direct measurement using a bench pH meter, in a suspension of soil in distilled water or in a 1N KCl solution made with 20 g of soil in 50 mL of solution. Total carbon was determined using the Walkley and Black (1934) method, which involves wet oxidation of organic matter using a potassium dichromate/sulphuric acid mixture [16]-[18]. Total nitrogen was determined by the Kjeldahl method (1883): mineralization with H₂SO₄, distillation, then volumetric titration [18]-[20]. The C/N ratio was calculated to assess changes in soil organic matter in general [21] [22].

Eight (8) metallic trace elements were determined at the Environmental Analytics laboratory, Steenhouwerstraat 15, Rotterdam, Netherlands: mercury (Hg), arsenic (As), copper (Cu), zinc (Zn), chromium (Cr), cadmium (Cd) and antimony (Sb). These elements were measured by inductively coupled plasma optical emission spectroscopy (ICP OES). Most of the TMEs selected are elements usually found in household waste and waste from human activities observed in the city of Brazzaville. [23].

To assess the risks of soil pollution, a soil pollution index (PI) was developed, incorporating the various levels of TMEs in the surveyed soils and their accepted thresholds [24]-[27]. The determination of the PI is based on the following formula:

$$PI = \sqrt{\frac{\left(\frac{Ci}{Csi}\right)_{\max}^2 + \left(\frac{1}{n} \sum_{i=1}^n \frac{Ci}{Csi}\right)^2}{2}}$$

where $\left(\frac{Ci}{Csi}\right)_{\max}$ is the highest pollution index of a soil sample; Ci is the concentration of the TME; Csi is the normative threshold concentration of the TMEs considered and n is the number of TMEs studied.

Based on the PI values, 4 classes of soil pollution levels have been defined: if $PI < 1$, the soil is unpolluted; if $1 \leq PI < 2$, the soil is slightly polluted; if $2 \leq PI < 3$, the soil is moderately polluted; if $PI \geq 3$, the soil is polluted.

The results of the analyses obtained were processed using Excel software for descriptive statistics, and OriginPro 9.0 for analysis of variance (ANOVA) and the Bonferroni test for comparisons of means at the 5% threshold.

3. Results and Discussion

3.1. pH H₂O and pH KCl

The pH is an important factor in the availability of nutrients, as well as toxicity problems in the soil. The values of pH H₂O and pH KCl obtained from the analyses are shown in **Figure 2** and **Figure 3**. The water pH values range from 5.1 (upstream of the *Djoué*) to 8.1 (downstream of the *Mfoa*), with an average of 7.4 ± 0.7 . pH H₂O values of between 6.5 and 7.5 were observed in the soils at all the sites sampled, with the exception of upstream of the *Djoué* river. These values,

which reflect the neutral pH of the soils, are optimal for the absorption of mineral elements in the soil, and create conditions for the availability of nutrients for most plants [28]. The pH KCl values follow the same trend, ranging from 4.3 to 8.0 for the same watercourses, with an average of 7.1 ± 0.9 . Potential soil acidity (pH H₂O-pHKCl) varies from 0.02 to 0.79, with an average of 0.40; the greatest variations are observed on the soils of the banks of the *Djoué* river and its tributary, and the *Mfilou* river. These recorded pH values are thought to be due to the low carbonate content of these soils and the constant rainfall in the area. These results are similar to those of several authors [29]-[31].

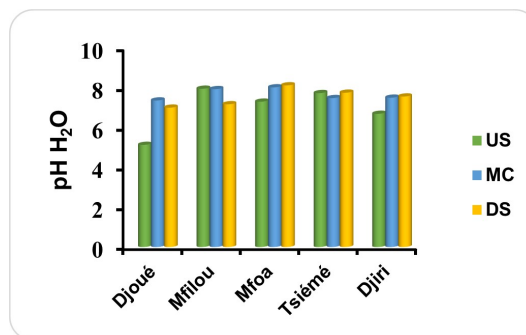


Figure 2. pH H₂O of the soil on the banks of Brazzaville's watercourses. US: upstream; MC: mid-course; DS: downstream.

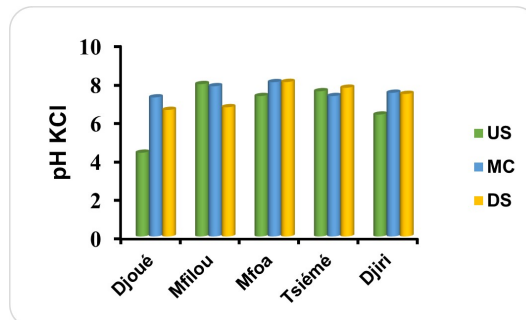


Figure 3. pH KCl of the soil on the banks of Brazzaville's watercourses. US: upstream; MC: mid-course; DS: downstream.

Comparison of the mean pH values of the soils on the banks of each river, using the Bonferroni test, shows that there is no significant difference between the riverbanks, either for pH H₂O or for KCl pH (Figure 4 and Figure 5). However, the soils on the banks of the *Djoué* river have the lowest pH values.

3.2. Total Carbon

Soil organic matter is an important indicator of soil quality degradation due to its contribution to soil stability, increasing soil water retention capacity, fixing mineral elements, and acting as a substrate for soil microorganisms [32].

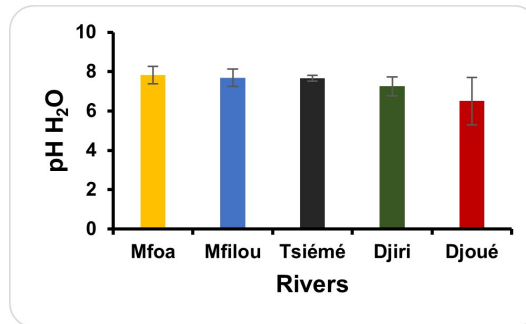


Figure 4. Average pH H₂O values for soils on the banks of Brazzaville rivers.

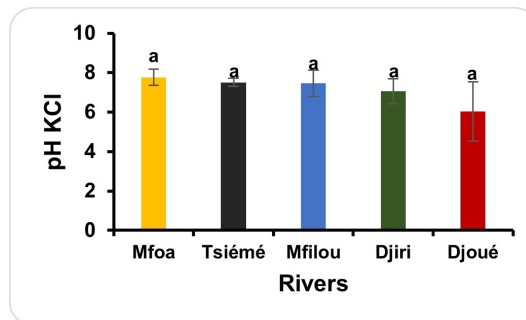


Figure 5. Average pH KCl values for soils on the banks of Brazzaville rivers.

The organic carbon content of the soils studied is shown in **Figure 6**. They range from 0.46% (upstream of the *Tsiémé*) to 1.65% (downstream of the *Djoué*), with an average of $0.83\% \pm 0.3\%$. With organic carbon contents of less than 2%, these soils have a low to medium level of organic matter fertility [33]-[36]. On the banks of all the rivers studied, organic carbon levels increase from upstream to downstream. These results can be explained by the sandy texture of the soils and the deforestation caused by accelerated urbanization, which exposes the soils and causes organic matter to leach out at depth or along the slope, thus enriching the areas located downstream of the watercourses [28] [37]-[39].

Comparison of the mean organic carbon content, using the Bonferroni test, shows that there are no significant differences ($p = 0.27$) between the soils on the banks of the rivers studied (**Figure 7**). Nevertheless, the soils bordering the *Djoué* river had the highest organic matter content (1.15%) compared with the other rivers, where organic carbon content varied between 0.61% (*Djiri* river soils) and 0.84% (*Mfilou* river soils).

3.3. Total Nitrogen

The total nitrogen content of the analyzed soils varied between 0.07% (upstream of the *Tsiémé*) and 0.16% (downstream of the *Djoué*) with an average of $0.01\% \pm 0.02\%$. Total nitrogen levels in the soils studied increased from upstream to downstream sites for the *Djoué*, *Mfilou* and *Tsiémé* rivers, whereas they moved

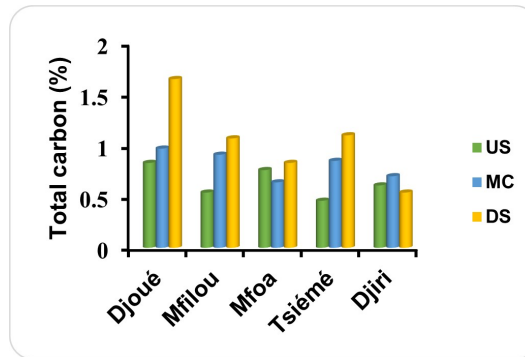


Figure 6. Organic carbon content of riverbank soils in Brazzaville.

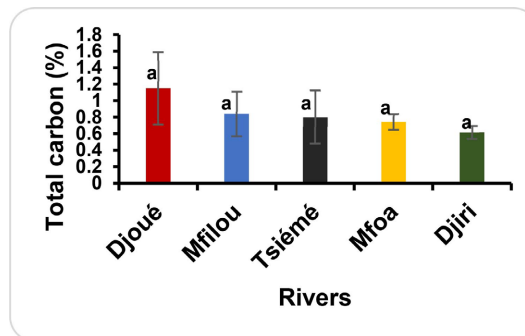


Figure 7. Average organic carbon content of Brazzaville riverbank soils.

in the opposite direction for the *Mfoa* and *Djiri* rivers (**Figure 8**). The average total nitrogen (**Figure 9**) content of the soils on the banks of the rivers studied varied between 0.08% (*Djiri* soils) and 0.13% (*Djoué* soils). According to the Bonferroni test, there was no significant difference between the soils bordering the different rivers. As with organic carbon content, total nitrogen content places these soils in the low to medium fertility categories. These low levels of total nitrogen in the soils could be attributed to the low organic matter content of these soils [8] [35] [39] [40].

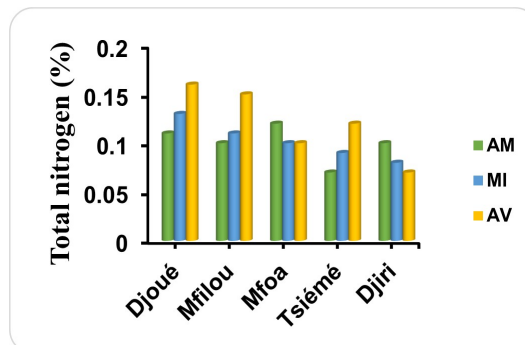


Figure 8. Total nitrogen content of Brazzaville riverbank soils.

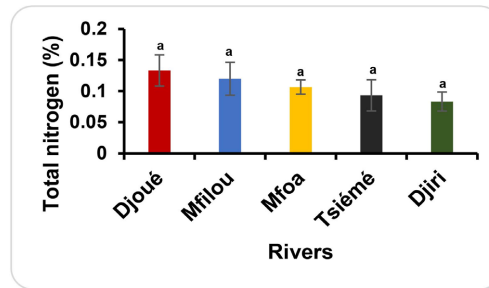


Figure 9. Average total nitrogen content of Brazzaville riverbank soils.

3.4. C/N Ratio

As shown in **Figure 10**, the C/N ratios of the soils studied vary between 5 (upstream of the *Mfilou*) and 10 (downstream of the *Djoué*). It can be seen that the C/N ratios of the soils at the sites located upstream of the watercourses are lower than those of the soils at the sites located in the middle reaches and downstream of the watercourses.

Figure 11 shows the variations in mean C/N ratio values, which range from 7 (*Mfoa* and *Mfilou* soils) to 9 (*Djoué* soils). According to the Bonferroni test, the C/N ratio values are not significantly different between the rivers ($P > 0.05$). These values reflect well-decomposed organic matter in the *Djoué* soils and rapid mineralization of organic matter in the soils on the banks of the other rivers [5] [21] [22] [33] [40].

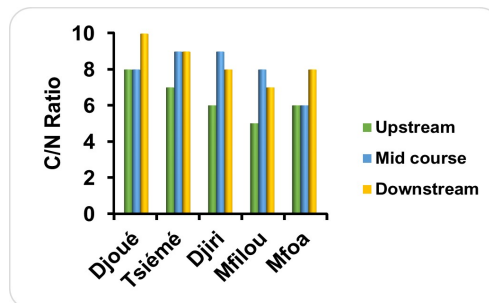


Figure 10. Total nitrogen content of Brazzaville riverbank soils.

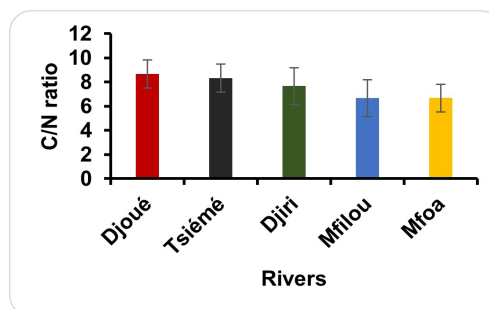


Figure 11. Average total nitrogen content of Brazzaville riverbank soils.

3.5. Distribution of Trace Metal Content in Soil

The results of the analysis of trace metal elements in soil samples from the Brazzaville city are shown in **Figures 12-19**. These results show that the mean values of trace metal concentrations in soils vary according to the metal element. Furthermore, they do not show any significant difference ($p > 0.05$) between the analyzed elements and the banks of the rivers where the samples were taken. Nevertheless, these values are all below accepted standards, i.e. 300 ppm for Zn, 150 ppm for Chromium, 100 ppm for Pb, 50 ppm for Nickel, 25 ppm for As, 30 ppm for Sb, 1 ppm for Hg, and 2 ppm for Cd [41]-[45]. Only lead has a value above the standard, at the site downstream of *the Djoué River* (**Figure 18**), where there is heavy vehicle traffic and the dumping of solid metal waste. Lead is present in lubricants, tyres and brake pads [46]. These results are similar to those obtained in urban soils by several authors in Brazzaville [39], Niamey [44], Dakar [45], Sidi Bel Abbas [46], Cotonou [47], Kinshasa [48] and Lagos [49] where Pb values are higher than accepted standards.

The low concentrations of trace metal elements in the sampling sites are thought to be due either to the leaching of elements such as cadmium, which is fairly mobile [48], or to the absence of industry, or to the absence of intensive agriculture, using large quantities of pesticides and chemical inputs, in the Brazzaville city [50]. These results are similar to those of several authors showing that the total content of trace metals in soils varies according to the type of soil, the metal element, the type of waste buried and the presence of a source of contamination or pollution in or near the sampling site [44] [48] [49] [51] [52].

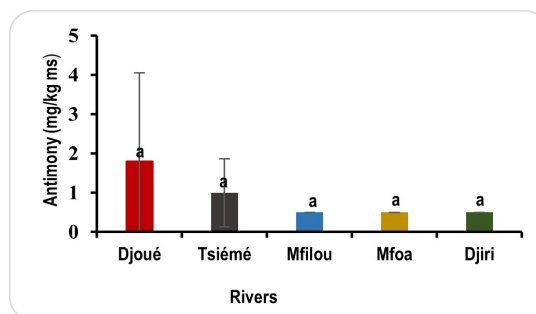


Figure 12. Average antimony levels along rivers.

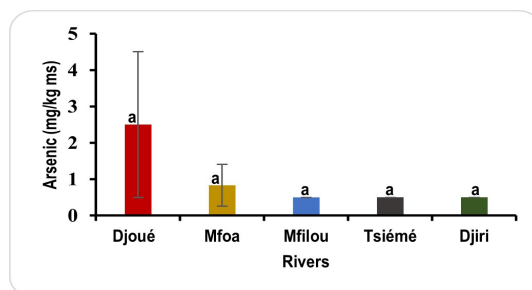


Figure 13. Average antimony levels along rivers.

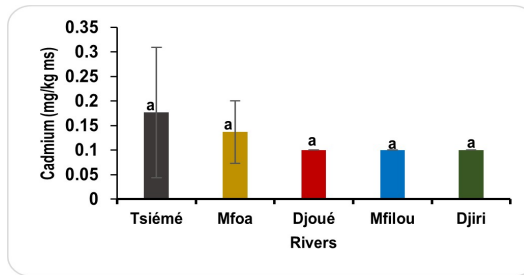


Figure 14. Average antimony levels along rivers.

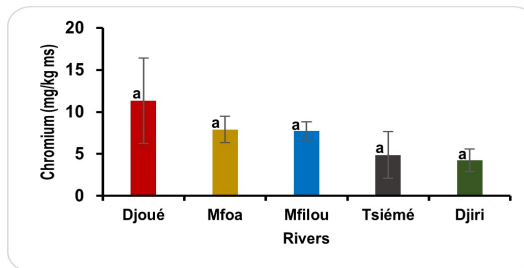


Figure 15. Average antimony levels along rivers.

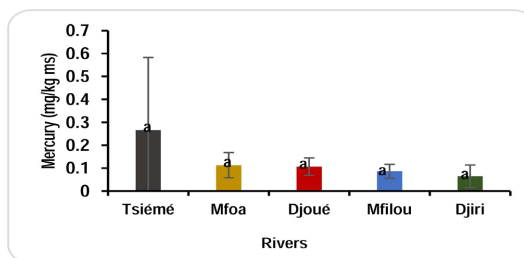


Figure 16. Average antimony levels along rivers.

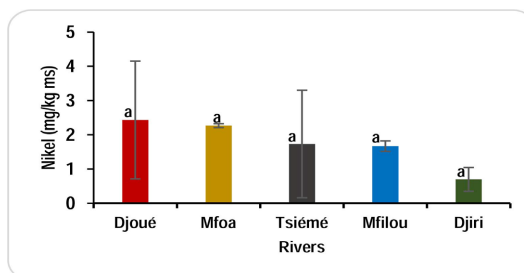


Figure 17. Average antimony levels along rivers.

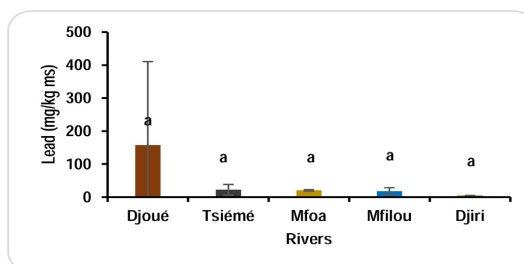


Figure 18. Average antimony levels along rivers.

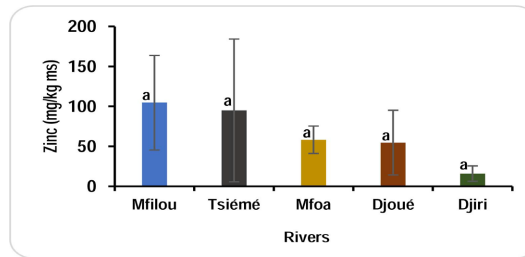


Figure 19. Average zinc levels along rivers.

The pH values, most of which are alkaline or close to neutral, could also be the cause of the low presence of trace metals elements in the soils, as the low mobility of trace metals is due to alkaline pH [35] [45] [53]-[55]. Soils on the banks of the *Djoué* with an acid pH have the highest levels of most of the trace metals elements determined, namely Sb, As, Cr, Ni and Pb. The highest levels of Hg and Cd are found in the soil on the banks of the *Tsiémé*, where people dump large quantities of household waste [44] [48] [49] [51].

Assessment of the soil pollution index for the surveyed soils

For soils on the riverbanks in the city of Brazzaville, the PI values and their significance are given in **Figure 20**. Although TMES values are below threshold levels at most of the sampling sites, the PI values show that the soils of the *Djoué* river are polluted with TMES, those of the *Tsiémé* river are moderately polluted and the soils of the banks of the *Mfoa* and *Mfilou* rivers are slightly polluted. Soil on the banks of the *Djiri* river is unpolluted. This soil quality would seem to be linked to the rate of land use and urbanisation along the banks of these rivers: rivers with polluted soils run through neighbourhoods that are more or less old and often densely populated [10] [12].

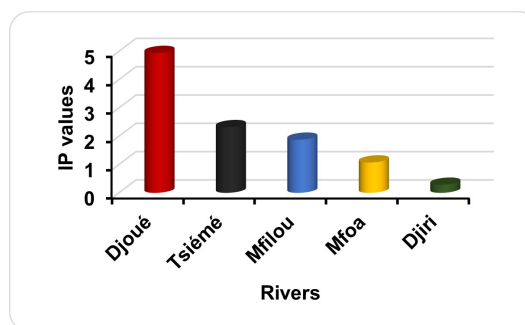


Figure 20. Pollution Index of the soils of the different rivers banks.

4. Conclusions

The aim of this study was to assess the levels of organic matter and trace metals in the soil on the banks of the tributaries of the Congo River that flow through the Brazzaville city. The study revealed that the pH values of the soils vary from 5.1 to 8.1. These soils are weakly acidic to basic; this could reduce the mobility of trace metal elements (TMEs) in the soil. Organic carbon values ranged from 0.54 to 1.1

(%), and total nitrogen from 0.07 to 0.16 (%). The C/N ratio shows that all the analyzed soils are subdivided into two (02) groups: soils with well-decomposed organic matter and soils with poorly mineralized organic matter.

The levels of trace metals elements (Pb, Ni, Hg, As, Sb, Cd, Zn and Cr) did not show any significant differences between the sampling sites on the riverbanks. The values for the various TMEs were below the AFNOR U44-41 standard for TMEs pollution in soils, with the exception of lead, whose levels were exceptionally high in the soil sample from downstream of the *Djoué* river, which is exposed to heavy vehicle traffic and the dumping of solid household waste. The low concentrations of TMEs in the soils are thought to be due either to the pH of the soil, which is close to neutral or only slightly alkaline, because the pH of the soil solution and the redox potential (Eh) directly and indirectly influence all the chemical processes and therefore also regulate the dynamics of the TMEs in the soil. In addition, the low levels of TMEs could be explained by the absence of industry, or to the fact that intensive agriculture, using large quantities of pesticides and chemical inputs, is not practiced in the Brazzaville city. Although TMEs values are below threshold levels at most of the sampling sites, the PI values show that the soils of the *Djoué* river are polluted with TMEs, those of the *Tsiémé* river are moderately polluted and the soils of the banks of the *Mfoa* and *Mfilou* rivers are slightly polluted. To mitigate the harmful effects of TMEs in Brazzaville's soils, the population needs to be made aware of the need to adopt good household waste management practices. The municipality should set up a waste treatment system and implement the most appropriate processes for cleaning up the city.

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Conflicts of Interest

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

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