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Spatial Variability and Correlation between Trace Metal Elements and Physico-Chemical Parameters of Soils under Gold Panning in Seguela (Northwest of Côte d'Ivoire)

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Abstract

The boom in the mining sector in Côte d'Ivoire, has revealed the expansion of gold panning in several localities, with practices suspecting pollution in Trace Metal Elements (TME) which could have links with environmental parameters, such as soil and water. To elucidate this problem, the study entitled "Spatial variability and correlation between TME and physicochemical parameters of soils under gold panning" was initiated. In this context, it was useful to characterize these soils in situ and to carry out laboratory analyses on soil samples, relating to its physicochemical characteristics, particularly pH value, particle size, carbon, nitrogen and organic matter contents, C/N ratios and TME contents. The observations were made at three sites and on the three main topographic segments of this area, precisely the top of the slope, the mid-slope and the lower slope. Statistical analyses were used to look for correlations. The results reveal slightly acidic soils, with the lowest pH in the lower slope positions. It is also in these positions that the TME contents are the highest, with a decreasing concentration gradient from the surface to the depth. All these elements demonstrate, not only, the correlations between TME, topographical positions and the physicochemical characteristics of soils, but also the risks of contamination of soils, or even water resources, in TME. Hence, there is an urgency for corrective measures aimed at protecting these resources.

Keywords

Trace Metal Elements, Physicochemical Characteristics, Soil Contamination, Côte d'Ivoire

1. Introduction

In Côte d'Ivoire, the agricultural sector has always played a central role in contributing to wealth creation and feeding populations. It still represents a quarter of the Gross Domestic Product and employs almost half of the working-age population [1]. However, this sector remains subject to international market fluctuations. This instability, marked in particular by global variations in coffee and cocoa prices, led to deep socio-economic crises in the early 1980s. Conversely, gold has been a safe haven, remaining almost unaffected by current inflation [2]. It is in this context that the promulgation of new mining legislation at the end of the 1980s in most African countries, particularly in Côte d'Ivoire, will encourage private investment in this sector [3]. Mining has thus become a major economic activity. It now constitutes a source of income for a significant portion of the population and raises many hopes for development [4] [5].

However, it has been found that around mining operations, several artisanal mining activities also gravitate, so much so that gold panning becomes as widespread as agriculture and livestock breeding [6], in some areas. However, this artisanal mining activity generates numerous disadvantages, particularly at the level of natural resources, human health and social [7]. Indeed, it causes significant environmental impacts, including deforestation, physical soil degradation, soil pollution by metallic trace elements (MTEs), the loss of arable land, and landscape alteration [8]-[12]. This activity is generally carried out through trenches, pits, scraping, and turning over of the soil, as well as the use of chemical substances containing heavy metals and metalloids such as lead, cadmium, mercury and nickel. The latter, thus released into the environment, not undergoing microbial or chemical degradation, can persist for a long time in the soil and contribute to the decline of its qualities [13]; which would also present a risk of contamination of natural resources [14].

The uncontrolled and regular dumping of waste containing TMEs leads to a progressive accumulation of these pollutants in the soil [15], high concentrations of which constitute a threat to human health through accidental ingestion, direct contact or inhalation of dust suspended in the air [7], contamination of the food production chain via plant products and drinking water [16].

Faced with this problem, sustainable soil management is essential to preserve natural resources and prevent environmental pollution, as shown by several studies conducted worldwide on the concentrations and mobility of TMEs in soils and plant products [17]-[20]. The objective of this study is, therefore, to evaluate the concentration and pollution levels of TMEs in the gold panning soils of the Seguela department, in the Northwest of Côte d'Ivoire.

2. Materials and Methods

2.1. Location of the Study Area

The Seguela Department, located in the Worodougou region, in the northwest of Côte d'Ivoire, constitutes the geographical framework of this study. It is located 502 km from Abidjan, the economic capital of the country, between 7˚45'N and 8˚15'N latitude and 6˚15'W and 7˚15'W longitude, with an average altitude of 350 m (**Figure 1**). This study area includes the localities of Kouego, Tiema and Bangana, where the observations were made.

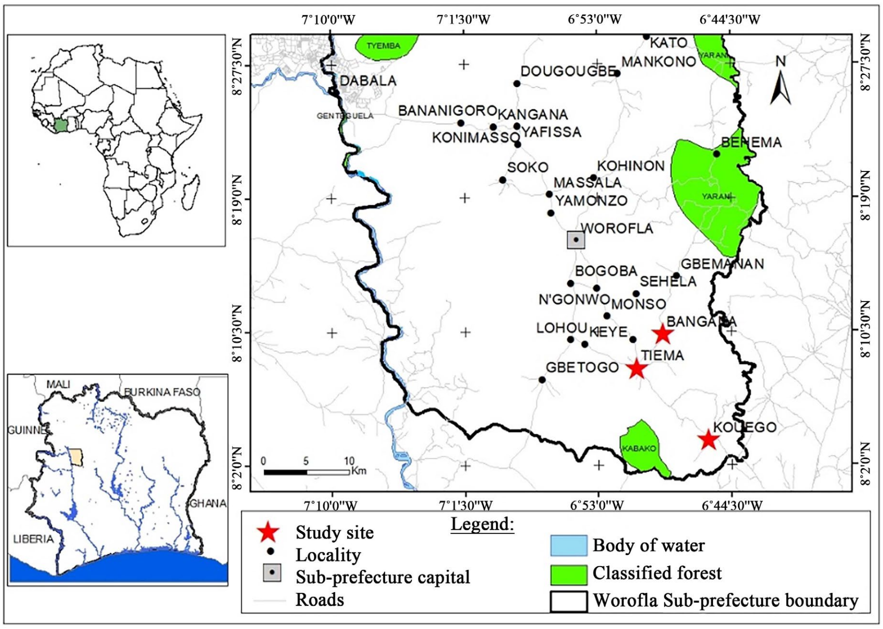


Figure 1. Location of the study area.

2.2. Climate

The climate of the department of Seguela is dominated by a savannah regime, in accordance with the Köppen-Geiger classification, and is strongly influenced by the South Sudanese climate. The region experiences a rainy season from July to October, characterized by abundant rainfall. The dry season, relatively long, extends from November to June. The average annual rainfall is 1182.8 mm, and the average annual temperature is about 28˚C, with seasonal and daily variations [21].

2.3. Vegetation

The department of Seguela is located in a transition zone between forest and savannah, characterized by vegetation that becomes progressively sparse from south to north. The vegetation cover is composed of savannahs interspersed with forest galleries.

2.4. Relief and Hydrography

The relief of the Seguela Department is dominated by granite plateaus and hills, with an average altitude of 260 m [22]. In terms of hydrography, the department is crossed by two main rivers, the Sassandra and the Yani, the latter being a tributary of the Marahoué. Many rivers, such as the Gbouan in the west, the Ouaon in the east, and the Lefegbo, representing a tributary of the Marahoué, also irrigate the region [23].

2.5. Geology and Pedology

The geological formations underlying this region are mainly Eburnean complexes, made up of granites, and Birimian complexes, composed of volcano-sedimentary rocks dating from the Middle and Lower Proterozoic (150 - 230 million years) [22]. Also note the presence of kimberlitic dykes, rich in diamonds, in the Bobi and Diarabana sectors [24]. In terms of pedogenesis, the dominant processes are ferrallitization, followed by browning, ferruginization and hydromorphy. These processes lead to the formation of ferralitic and browned soils, characterizing the pedological environment of the study area.

2.6. Material

A GPS, picks, shovels, a tape measure, a Munsell code, an electronic scale, plastic bags, a pedologist's knife and a 2 mm square mesh sieve allowed the morphological characterization and the collection of soil samples for laboratory analyses. Then, the usual laboratory equipment was used for the various analyses.

2.7. Methods

2.7.1. Description of Soil Pits

On each of the three sites in the study area, for the morpho-pedological description, three (3) soil pits were opened along a toposequence. They were each 1 m long, 0.80 cm wide and 1.20 m deep if no natural obstacle hinders the opening of the pit. Each horizon constituting the solum was described following the ORSTOM approach [25]. It made it possible to provide information on the main morphological characteristics such as the depth or thickness of the horizons, the texture of the soil, the content and nature of the coarse elements, the general porosity and the size of the pores, the drainage class, the general structure and the flow structure and the limit between the soil horizons. From these morphological features, the soil type was determined according to the standards of the World Soil Reference Base (WRB), defined by FAO [26].

2.7.2. Soil Sampling

The soil profiles were subdivided into four layers, namely 0 - 20 cm, 40 - 40 cm, 40 - 80 cm and 80 - 120 cm. Four composite soil samples were taken from each layer, starting from the bottom of the pit to the top to avoid possible contamination. The soil samples were stored in plastic bags and then sent to the laboratory for various analyses.

2.7.3. Laboratory Analysis

The soil samples were analyzed to determine the physicochemical characteristics of the soil (granulometry, pH, organic matter, calcium, organic carbon, phosphorus, nitrogen, potassium) and the concentration of trace metal elements (Pb, Cu, Zn, Cd, Fe etc.) in the soils. These analyses were carried out at the National Laboratory for Testing Quality, Metrology and Analysis (LANEMA) in Abidjan.

1) Determination of soil particle size

It was determined by the densimetric method, using the Robinson pipette [27].

According to this method, 20 g of the fine fraction of soil resulting from the passage of the soil sample through a 2 mm mesh sieve was used to determine the proportions of the 5 classes (clay, fine silt, coarse silt, fine sand and coarse sand).

2) Soil acidity

The pH water was measured after contacting the soil sample with demineralized water, in a soil/water ratio of 1/2.5, using a glass electrode [28]. 20 g of soil was required for the pH measurements.

3) Carbon and organic matter

Carbon was determined by the Walkley and Black method [29]. This involves cold extraction with potassium dichromate in a sulfuric medium. The organic matter rate was calculated by multiplying the carbon content by a stable coefficient, conventionally set at 1.72 by Baize [30].

4) Total nitrogen

Nitrogen was measured by the Kjeldhal method [31]. This involves mineralization in the presence of a catalyst (Kjeldahl tablet).

5) Soil phosphorus and potassium

Assimilable phosphorus was determined using the Olsen method modified by Dabin [32]. The extraction of soluble forms of phosphorus was carried out by the formation of carbonic acid, by dissolving sodium bicarbonate; orthophosphate anions react with ammonium molybdate, in an acidic medium, to give phosphomolybdic acid, which is reduced by ascorbic acid to molybdenum blue. Total phosphorus was measured by automatic colometry of phosphomolybdate, reduced by ascorbic acid, after attacking the sample with concentrated nitric acid.

6) Determination of the concentration of heavy metals (As, Cd, Cu, Ni, Pb, Fe and Zn) in soils

This part assesses the metal contamination of the soils of the gold panning sites in the study area, and focuses in particular on estimating the spatial variability (vertical and lateral) of this contamination and the extent of the contaminated area. It will then also determine the degree of pollution of these soils.

The ICP-AES method [33] was used to determine the various metals, such as As, Cd, Cu, Ni, Pb, and Zn, that were contained in the soil samples collected.

The soil samples are dried at room temperature and then ground to have a particle size of less than 180 µm. The finely ground soil is mineralized according to the following procedure: 2 ml of concentrated HNO_3 is added to 100 mg of soil. The solution is brought to dryness at 110˚C then 3 ml of concentrated hydrofluoric acid are added and the extracts are kept for 15 hours at 140˚C. After cooling to 110˚C, 2 ml of concentrated HNO_3 is added. This operation is repeated three times and the dry extracts are taken up in 25 ml of 2M HCl before being analyzed. As, Cd, Cu, Ni, Pb and Zn concentrations were then determined by ICP-AES (inductively coupled plasma-atomic emission spectrometry; Ultima2 JY).

2.7.4. Statistical Analysis

1) Analysis of variance

Statistical analysis of the data was performed using several methods adapted to the nature of the variables studied. A one-way analysis of variance (ANOVA) test was used to compare the mean levels of trace metal elements (TMEs) between the different study sites. This parametric test is appropriate for assessing differences in means when the data distribution follows a normal distribution. In the case where the data distribution does not respect the assumption of normality, a non-parametric Kruskal-Wallis test was applied. This test is a robust alternative to ANOVA for non-normally distributed data and allows for comparison of medians between groups while controlling for variance within groups.

2) Normalized Principal Component Analysis (NPCA)

In order to examine the structure of relationships between different TME concentrations and to explore underlying patterns in the data, a normalized principal component analysis (NPCA) was conducted. This method reduces the dimensionality of the data while preserving essential information on variance and correlations between variables. NPCA was used to identify the principal components that significantly contribute to the variance of TME concentrations across study sites. The objective of this analysis was to identify variables with dominant contributions and to explore spatial and geochemical variability.

3) Heatmap with Clustering

For a deeper visualization of the relationships between TME concentrations and their distribution across study sites, a heatmap combined with hierarchical clustering was performed. This approach allows us to graphically represent the relationships between different variables (TME concentrations) and study sites, while identifying clustering patterns in the data. Soil samples were grouped into clusters based on their similarity in metal contamination profiles. A clustering algorithm was applied to identify groups of samples with similar metal pollution profiles. The heatmap was generated by associating each study site with a row and each metal with a column, with the colors representing the concentration intensity in each sample. This allowed us to quickly visualize areas with high or low pollution and facilitate the interpretation of geochemical trends in soils.

4) Software Used

All statistical analyses were performed using R Studio software, which allowed the application of ANOVA, the Kruskal-Wallis test, and NPCA analysis. Heatmap and clustering were performed using specific packages in R, including ggplot2 and pheatmap. Cspro 7.1 software was used for data management and data entry into databases.

3. Results

3.1. Gold Panning Practices in the Localities of Seguela

Gold panning practices in the three localities of Kouego, Tiema, and Bangana are relatively homogeneous. This uniformity is primarily due to the fact that the miners, mostly from Burkina Faso and Mali, migrate from one locality to another while adopting the same extraction techniques. In contrast, the indigenous populations have a lesser mastery of these practices.

3.1.1. Pits and Galleries

On gold panning sites, pits are generally circular (**Figure 2**) or rectangular shapes (**Figure 3**). Their depth varies between 3 and 20 meters. These pits lead to underground galleries, which are typically reinforced with wooden structures to prevent collapses. A production chain is established within each gallery, involving several key actors: diggers, who extract the ore underground; hoisters, responsible for bringing the ore to the surface; and transporters, who carry it to the village for processing. When the galleries become flooded, miners organize themselves to drain the water using makeshift motor pumps, ensuring the continuity of the extraction process.

Figure 2. Circular-Shaped pit.

Figure 3. Rectangular-Shaped pit.

3.1.2. Crushing and Grinding

Once extracted in the form of rock, the ore is loaded into sacks (**Figure 4**) and transported to the village for fragmentation through crushing (**Figure 5**), followed by grinding when water sources are distant. In contrast, for operations on lateritic soils or in lowlands, the ore is washed directly, bypassing the crushing and grinding steps. The work is conducted under precarious safety conditions: crushers typically do not have dust masks or protection against rock debris. Once crushed, the ore in the form of granules is transported to the mill to be ground into ore powder.

Figure 4. Bag containing rock blocks.

Figure 5. Crushing of rock blocks.

3.1.3. Washing and Gold Extraction

In the three studied locations, two washing techniques are commonly used: the calabash washing technique (**Figure 6**), also known as the panning technique, and the ramp washing technique (**Figure 7**).

Figure 6. Gold washing using the panning technique.

Figure 7. Gold washing using the ramp technique.

3.1.4. Gold Recovery

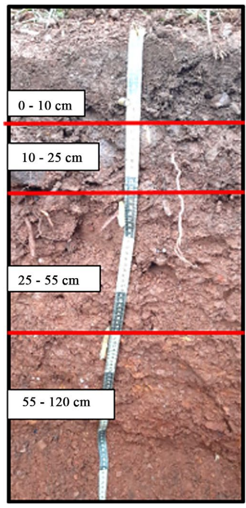
Gold recovery takes place after the final phase of washing the ore. At this stage, heavy metals, in the form of yellow or black powder, as well as gold, concentrate at the bottom of the calabash. When mercury or cyanide comes into contact with the gold particles present in the sediments or crushed ore, an "amalgam" is formed, consisting of approximately 50% mercury and 50% gold. To extract the gold, the amalgam is heated to evaporate the mercury or cyanide. During these operations, mercury is released into the air, water, and soil, leading to significant environmental and health risks.

3.1.5. Waste Disposal Methods

The methods for disposing of mining residues remain rudimentary and pose a major environmental threat. Indeed, there are characterized by a lack of containment systems. The absence of these infrastructures promotes the uncontrolled dispersion of pollutants into the environment, further increasing the risks of soil and water resource contamination.

3.2. Soil Description

Soil Description The morphological description of the soils allowed the identification of Cambisols with plinthic characteristics (expressed by the high presence of coarse elements), with some variations. **Figures 8-10** show the general characteristics of these.



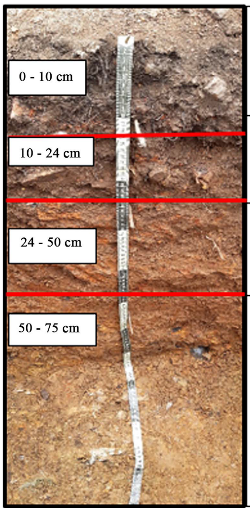
Horizon Al:
-Average depth of 0 to 10 cm with presence of organic matter
-Lumpy structure with polyhedral flow, sandy-silty texture, presence of fine subhorizontal roots
-Dark brown color (2.5YR 5/2), presence of coarse elements 50%
-Fresh soil with biological activity (earthworm), coberent and porous
-Gradual transition with a more or less regular limit

Horizon A2:
-Average depth of 10 to 25 cm with presence of organic matter;
-Lumpy structure with a sandy-silty texture, presence of millimetric to centimetric subhorizontal roots, fresh soil with moderate biologieal activity (gallery);
-dark brown color (2.5YR 3/2), presence of coarse elements (80% quatz).

Horizon B1:
-Average depth of 25 to 55 cm, organic matter apparently absent;
-Polyhedral stucture with clayey texture; -Red-brown color (2.5YR 3/1);
-Presence of coarse elements (60% quartz);
-Presence of roots (millimetric to centimetric subhorizontal;
-Fresh soil with moderate biological activity (gallery);

Horizon B2:
-Average depth of 55 to 120 cm
-Sub-angular polyhedral stucture with a silty-clayey texture;
-Red-brown color with orange-ochre spots (7.5YR 5/2)
-Presence of coarse elements;
-Presenee of roots (millimeter to centimeter sub-horizontal direction);
-Fresh soil with moderate biological activity (gallery).

Figure 8. Summit soil (Manganiferric Plinthic Cambisol).



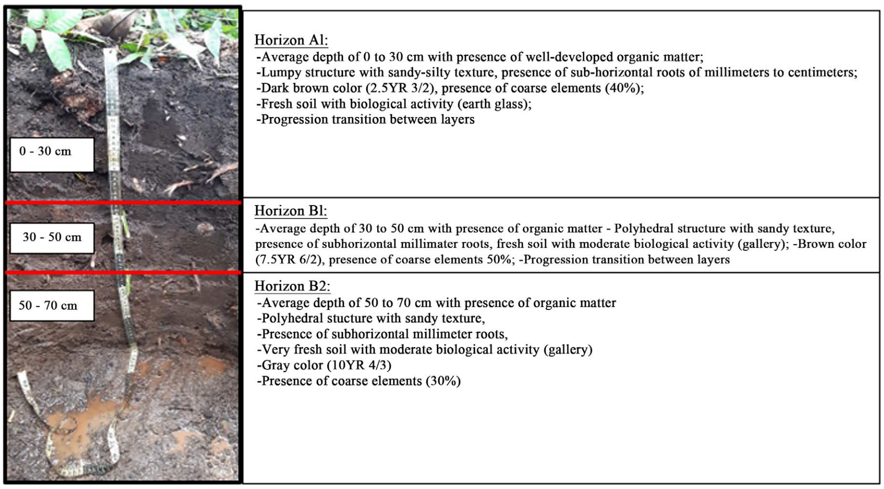
Horizon Al:
-Average depth of 0 to 10 cm with presence of organic matter
-Lumpy structure with a sandy-silty texture, presence of subhorizontal millimetric roots;
-Dark brown color (2.5YR 3/2),
-Presence of coarse elements (40%);
-Fresh soil with biological activity (earthworm).

Horizon Al2:
-Average depth of 10 to 24 cm with presence of organic matter;
-Polyhedral structure with sandy texture, presence of subhorizontal millimeter roots,
-Fresh soil with moderate biological activity (gallery);
-Dark brown color (2.5YR 5/2), presence of coarse elements (80%).

Horizon Bl:
-Average depth of 24 to 50 cm, organic matter apparently absent;
-Polyhedral stucture with clayey texture; presence of orange-ochre stain,
-Presence of subhorizontal millimetric roots,-Fresh soil with biological activity (earthworm);
-Red-brown color (7.5YR 6/1), presence of coarse elements (60% of quartez).

Horizon B22:
-Average depth of 50 to 75 cm with presence of metamorphosed parent rock;
-Sub-angular polyhedral stucture with clayed texture;
-Red-brown color with orange-ochre spots (7.5YR 4/2)
-Presence of coarse elements (40%);
-Very fresh soil with moderate biological activity (gallery).

Figure 9. Mid-slope soil (Endopetroplinthic Pseudogleyic Cambisol).



Horizon Al:
-Average depth of 0 to 30 cm with presence of well-developed organic matter;
-Lumpy structure with sandy-silty texture, presence of sub-horizontal roots of millimeters to centimeters;
-Dark brown color (2.5YR 3/2), presence of coarse elements (40%);
-Fresh soil with biological activity (earth glass);
-Progression transition between layers

Horizon Bl:
-Average depth of 30 to 50 cm with presence of organic matter - Polyhedral structure with sandy texture, presence of subhorizontal millimater roots, fresh soil with moderate biological activity (gallery); -Brown color (7.5YR 6/2), presence of coarse elements 50%; -Progression transition between layers

Horizon B2:
-Average depth of 50 to 70 cm with presence of organic matter
-Polyhedral stucture with sandy texture,
-Presence of subhorizontal millimeter roots,
-Very fresh soil with moderate biological activity (gallery)
-Gray color (10YR 4/3)
-Presence of coarse elements (30%)

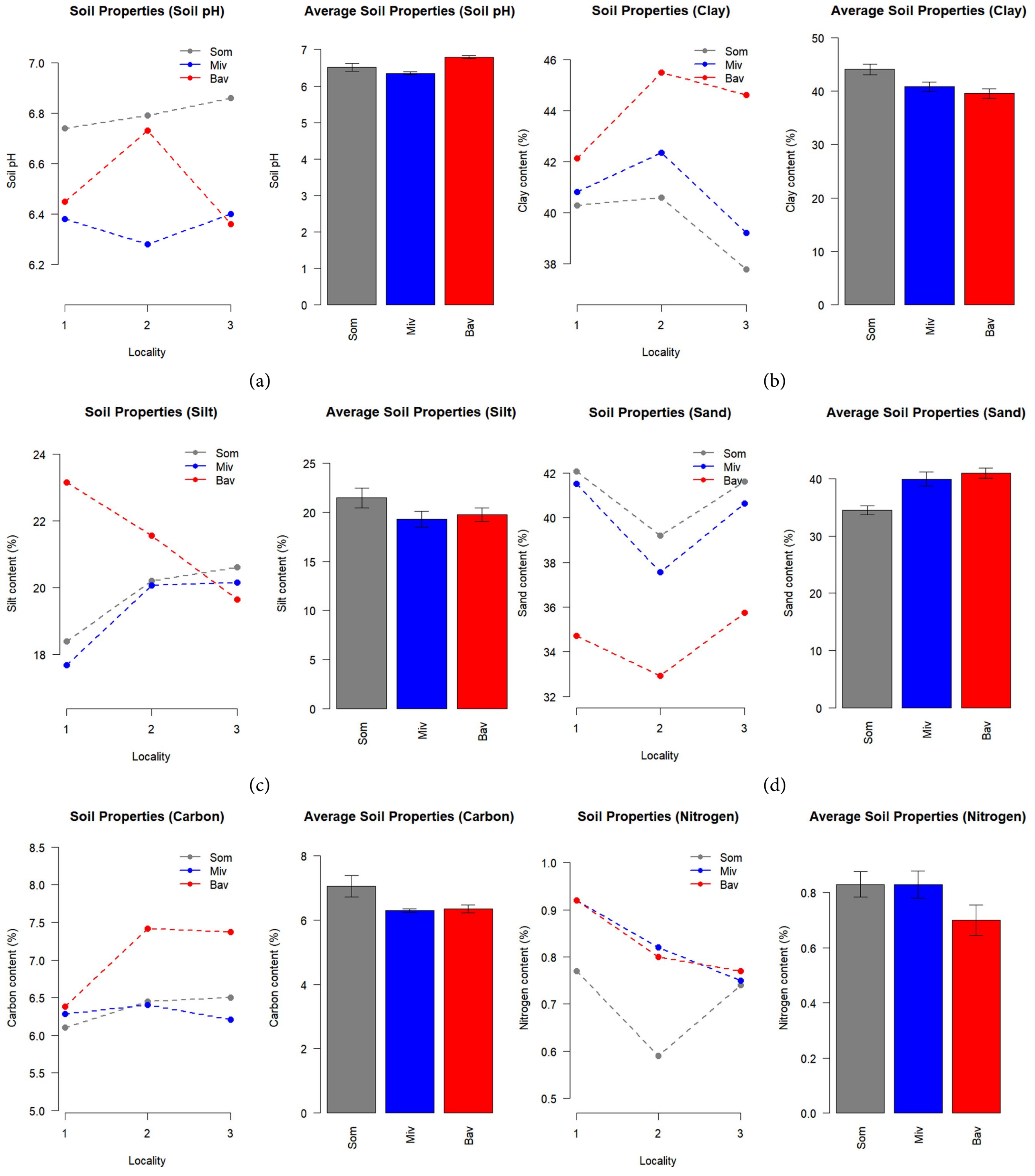
Figure 10. Lowland soil (Endostagnic Arenic Cambisol).

3.3. Lateral Dynamics of Some Physical and Chemical Characteristics of Gold Mining Soils

Figures 11(a)-(h) present data on pH, particle size (sand, clay and silt), carbon, nitrogen, carbon/nitrogen ratio and the proportion of organic matter in the different soil horizons of the gold mining sites studied. According to Figure 11(a), the average pH of gold mining soils varies from 6.4 to 6.8 depending on the sites. The lowest pH is observed at mid-slope in Tiema and the highest at the summit in Bangana. It was also observed that the pH of soils in the topographic positions of the summit is closer to neutral (6.7 to 6.9) and decrease almost to reach relatively lower values at the lower slope. Figures 11(b)-(d) show variations in the proportion of sand, silt and clay between sites. High clay contents are recorded at the lower slope in Tiema and low contents at the summit in Bangana. However, the graphs in Figure 5(b) show that the clay content increases from the topographic positions of the summit to the lower slope positions. This trend is the opposite of that of sand, observed in Figure 5(d) which also shows that high sand contents are observed at the summit in Kouego and low contents at the lower slope in Tiema. As for silts, high contents are observed at the lower slope in Kouego and low contents at mid-slope in Kouego (Figure 11(c)). The carbon rate varies between sites and decreases with depth. Carbon rates vary from 6.19% to 6.87%, the lowest being recorded at the summit in Kouego and the highest at the lower slope in Tiema. The high nitrogen content is recorded at the lower slope in Kouego, while the low contents are obtained at the top in Tiema. The high organic matter content is observed at the lower slope in Tiema, while the low content is at the top in Kouego. The high C/N ratio is recorded at the top in Tiema, while the lowest ratio is observed at the mid-slope in Kouego.

3.4. Vertical Dynamics of Some Physical and Chemical Characteristics of Gold Panning Soils

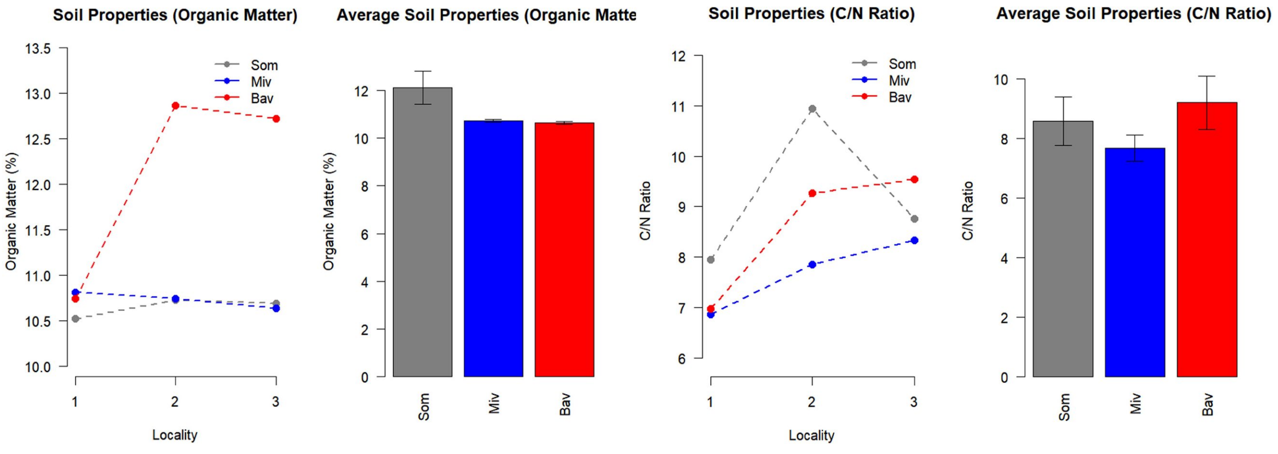
The analysis of the correlations between the different soil properties reveals a complex structuring of the edaphic parameters, varying significantly according to the sampling depth and the location. This vertical variability is translated relatively to each locality by the clustering observable in **Figure 12**. It shows that the consideration of the physicochemical characteristics according to the different soil horizons reveals overall four groups:



(a) (b)

(c) (d)

(e) (f)



(g) (h)

Figure 11. (a) Evolution of pHwater according to the toposequence and localities (1. Kouego, 2. Tiema, 3. Bangana Som. Summit MV. Mid-slope BV. Lower slope). (b) Evolution of Clay content according to the toposequence and localities (1. Kouego, 2. Tiema, 3. Bangana Som. Summit MV. Mid-slope BV. Lower slope). (c) Evolution of Silt content according to the toposequence and localities (1. Kouego, 2. Tiema, 3. Bangana Som. Summit MV. Mid-slope BV. Lower slope). (d) Evolution of Sand content according to the toposequence and localities (1. Kouego, 2. Tiema, 3. Bangana Som. Summit MV. Mid-slope BV. Lower slope). (e) Evolution of Carbon content according to the toposequence and localities (1. Kouego, 2. Tiema, 3. Bangana Som. Summit MV. Mid-slope BV. Lower slope). (f) d. Evolution of Nitrogen content according to the toposequence and localities (1. Kouego, 2. Tiema, 3. Bangana Som. Summit MV. Mid-slope BV. Lower slope). (g) Evolution of Organic matter content according to the toposequence and localities (1. Kouego, 2. Tiema, 3. Bangana Som. Summit MV. Mid-slope BV. Lower slope). (h) Evolution of C/N Ratio according to the toposequence and localities (1. Kouego, 2. Tiema, 3. Bangana Som. Summit MV. Mid-slope BV. Lower slope).

- The group of Kouego soil horizons, marked by C/N ratios and carbon and organic matter contents significantly lower than the average values observed in the area, this intensifies from the surface horizons to the deep horizons for the carbon and organic matter contents but for the C/N ratio, the opposite is observed;
- The group of the first surface horizons (0 - 20 cm) of Tiema and Bangana, characterized by relatively high carbon, organic matter, silt and sand contents against relatively low clay contents and C/N ratio;
- The group of the second surface horizons (20 - 40 cm) of Tiema and Bangana first two surface horizons of Bangana and Tiema, with the same trends as the previous group, but with relatively lower values than the latter;
- The group of the third and fourth horizons (40 - 80 cm and 80 - 120 cm) of Tiema and Bangana, where relatively low sand, silt and nitrogen contents are observed, with in return, high clay contents and C/N ratio.

3.5. Implications for the Understanding of Pedogenic Processes

The vertical organization of soil properties reveals a complex structuring of pedological horizons. The variations observed in the values of the parameters according to depth testify to the existence of distinct pedogenetic processes according to the horizons. This vertical differentiation appears more or less marked according to the sites, suggesting an influence of local environmental conditions on the evolution of soils.

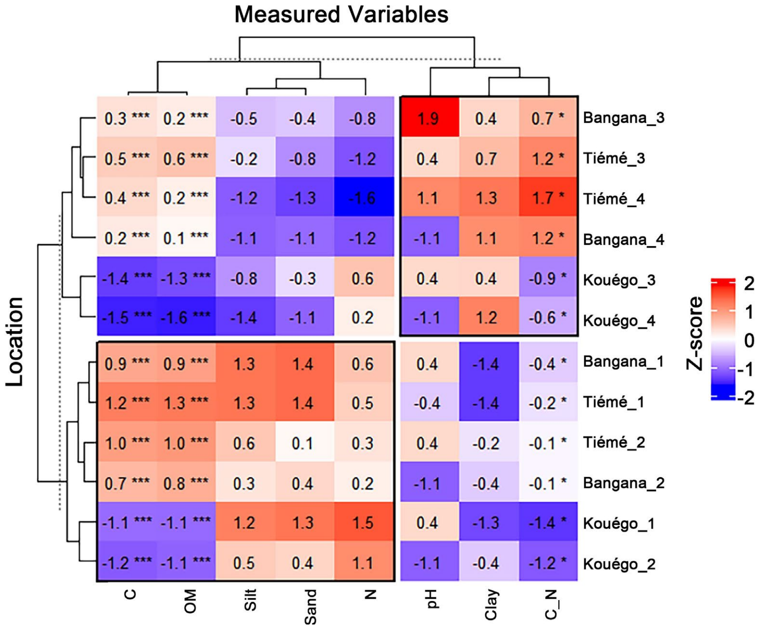


Figure 12. Clustering of localities and identification of groups according to physicochemical components.

The asterisk symbols displayed on the map in the heatmap indicate the significance levels ("*"p < 0.05, "**"p < 0.01, "***" pour p < 0.001). The numbers in the heatmap are not correlation coefficients, but the standardized raw values (Z-score = (value − mean)/standard deviation), for each measurement according to the localities. The colors of the heatmap represent the Z-scores, which are calculated with the formula: Blue: values below the mean, White: values close to the mean, Red: values above the mean. Each locality, followed by a number from 1 to 4, represents the different depths of data collection on the site. More precisely, the depth levels are defined as follows: 1 corresponds to 0-20 cm, 2 to 20 - 40 cm, 3 to 40 - 80 cm, and 4 to 80 - 120 cm.

3.6. Concentrations of Trace Elements in Gold Mining Soils

The results in **Table 1** show that the average concentrations of trace elements in gold mining soils vary depending on the metallic element and the sampling locations. In the Seguela department, high concentrations of As, Cd, Pb, Ni, Zn, Al, and Fe are recorded in the soils of Kouego (**Table 1**), with average concentrations of 6.92 mg/kg, 4.83 mg/kg, 57.50 mg/kg, 130.87 mg/kg, 20.97 mg/kg, 2.99 mg/kg, and 40555.92 mg/kg, respectively. Meanwhile, the Bangana locality shows the lowest concentrations of As, Cd, Pb, Ni, Zn, Al, and Fe, with average concentrations of 2.94 mg/kg, 3.36 mg/kg, 30.15 mg/kg, 128.93 mg/kg, 18.96 mg/kg, 0.66 mg/kg, and 39,800 mg/kg, respectively, and soils from Tiema with average concentrations of 2.86 mg/kg, 2.82 mg/kg, 30.12 mg/kg, 129.32 mg/kg, 18.70 mg/kg, 0.71 mg/kg, and 39856.34 mg/kg. Furthermore, high concentrations of Cu are recorded in the soils of Tiema, with a total average of 99.02 mg/kg, while the highest concentrations of Hg and HCN are recorded in Bangana soils, with average values of 0.35

mg/kg and 0.83 mg/kg, respectively. Our results also show that the average concentrations of the nine trace elements (Cd, Pb, Cu, Ni, Hg, HCN, Al, and Fe) in the localities of Kouego, Tiema, and Bangana exceed the threshold values set by Bowen's standard for trace elements in uncontaminated soils. On the other hand, the average concentrations of Zn in the localities of Kouego, Tiema, and Bangana are below the accepted limit values according to Bowen's standard. Moreover, the average concentrations of As and Hg in Tiema are also below the accepted limits according to Bowen's standard, and the average concentrations of As in Bangana are below the accepted limits. The abundance order of the elements is as follows: Fe > Ni > Cu > Pb > Zn > As > Cd > Al > HCN > Hg. The results from the one-way ANOVA tests (Table 2) show highly significant differences between the average trace element concentrations across the different study locations. However, no significant differences were observed between the average concentrations of As, Cd, Ni, Zn, and Al in the Tiema and Bangana locations, except for Kouego. Additionally, the average concentrations of Pb in the gold mining soils from the Kouego and Tiema locations form the same group and are statistically different from those of Bangana. The average values for Cu, Hg, HCN, and Fe are statistically different across the three locations.

Table 1. Descriptive statistics of the average concentrations of trace elements (mg/kg) in gold mining soils.

Métals	Kouego			Tiema			Bangana			Bowen standard
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	
As	6.45	7.64	6.92a ± 0.47	2.45	3.54	2.86b ± 0.46	2.5	3.55	2.94b ± 0.37	6
Cd	4.38	5.65	4.83 ± 0.56	1.3	6.48	2.82 ± 1.70	1.4	6.33	3.36 ± 1.69	0.35
Pb	56.42	58.52	57.50 ± 0.81	28.08	35.4	30.12 ± 2.40	27.75	35.58	30.15 ± 2.84	35
Cu	89.55	90.45	90.08 ± 0.32	98.32	99.75	99.02 ± 0.53	96.41	100.28	97.77 ± 1.82	30
Ni	130.3	131.8	130.87 ± 0.62	127.58	132.25	129.32 ± 1.52	127.7	131.9	128.93 ± 1.29	50
Zn	20.17	21.63	20.97 ± 0.57	17.65	20.68	18.70 ± 1.41	17.95	19.75	18.96 ± 0.62	90
Hg	0.18	0.33	0.27 ± 0.05	0.05	0.15	0.07 ± 0.03	0.05	0.94	0.35 ± 0.39	0.1
HCN	0.62	0.74	0.66 ± 0.05	0.6	0.82	0.71 ± 0.07	0.6	0.99	0.83 ± 0.13	0.5
Al	2.7	3.21	2.99 ± 0.18	0.65	0.88	0.71 ± 0.08	0.55	0.75	0.66 ± 0.06	-
Fe	40464	40648	40555.92 ± 71.22	39788	39955	39856.34 ± 67.99	39754	39865	39800 ± 44.62	-

Table 2. Average concentration of trace elements (mg/kg) in gold mining soils according to the study locations.

Metals	Kouego	Tiema	Bangana	F	P-Value	Significance
As	6.92 b	2.86 a	2.94b a	233.06	2.2e−16	≤0.001
Cd	4.83 b	2.82 a	3.36 a	40.116	1.868e−12	≤0.001
Pb	57.50 b	30.12 b	30.15 a	1692.6	2.2e−16	≤0.001
Cu	90.08 a	99.02 c	97.77 b	965.38	2.2e−16	≤0.001
Ni	130.87 b	129.32 a	128.93 a	24.611	7.683e−10	≤0.001

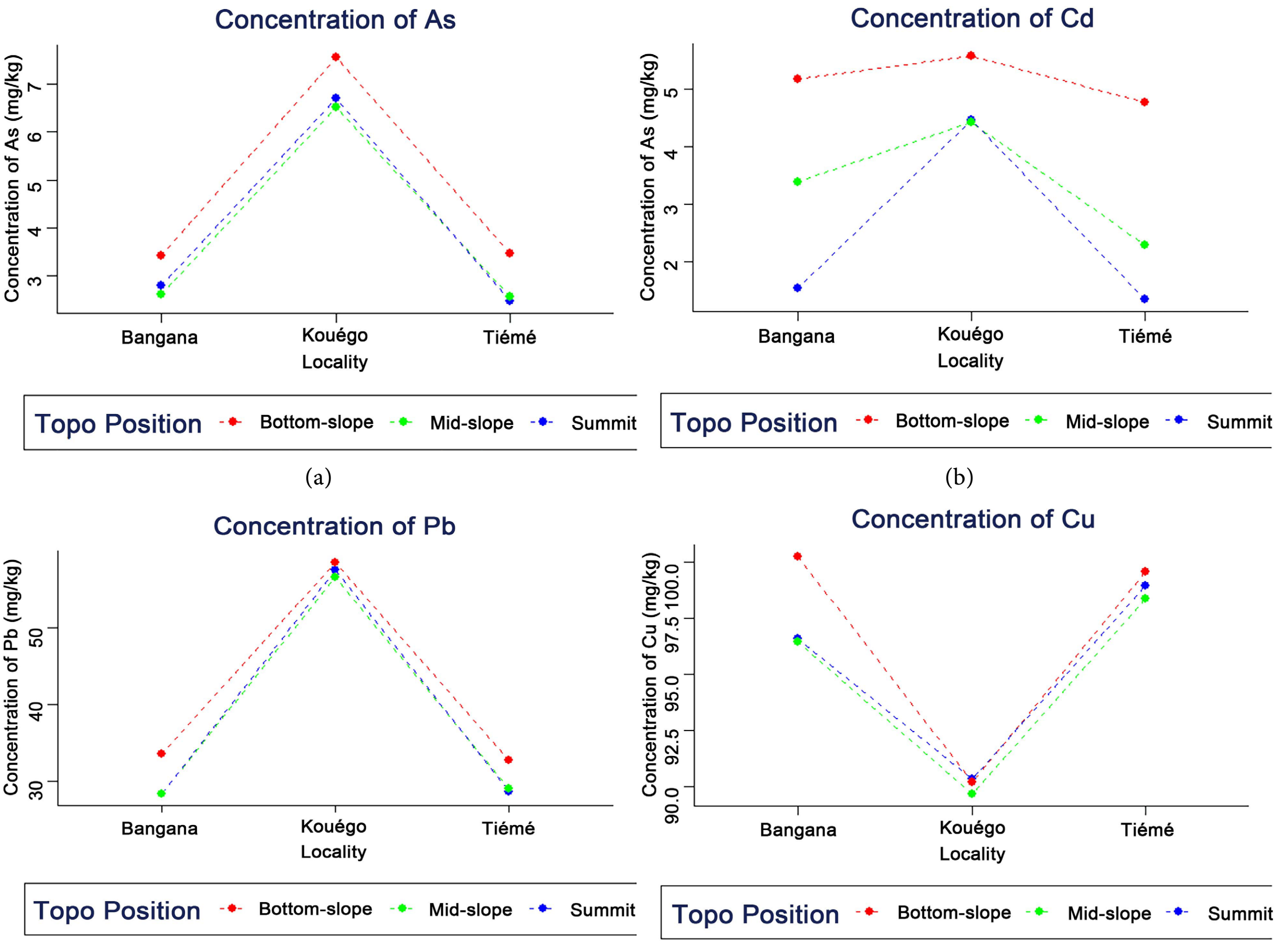
Continued

Zn	20.97 b	18.70 a	18.96 a	44.173	4.505e−13	≤0.001
Hg	0.27 bc	0.07 a	0.35 c	76.848	3.478e−16	≤0.001
HCN	0.66 bc	0.71 c	0.83 d	819.33	2.2e−16	≤0.001
Al	2.99 c	0.71 a	0.66 a	548.89	2.2e−16	≤0.001
Fe	40555.92 c	39856.34 ab	39800 a	622.75	2.2e−16	≤0.001

The different letters (a, b, c, d) indicate that the average values are significantly different.

3.7. Lateral Dynamics of TMEs in Gold Panning Soils

Figures 13(a)-(j) present the lateral dynamics of TMEs in gold panning soils of the three study locations. All these figures show in their quasi-totality that the TME contents in the soils subject to gold panning are higher at the level of the topographic position of the lower slope. This trend is more marked for Cadmium, with the average contents obtained at the lower slope approximately double those observed at the mid-slope and triple the contents observed at the top. In addition, except for the contents of Cyanide and Mercury, the highest contents of all TMEs were recorded at Kouego.

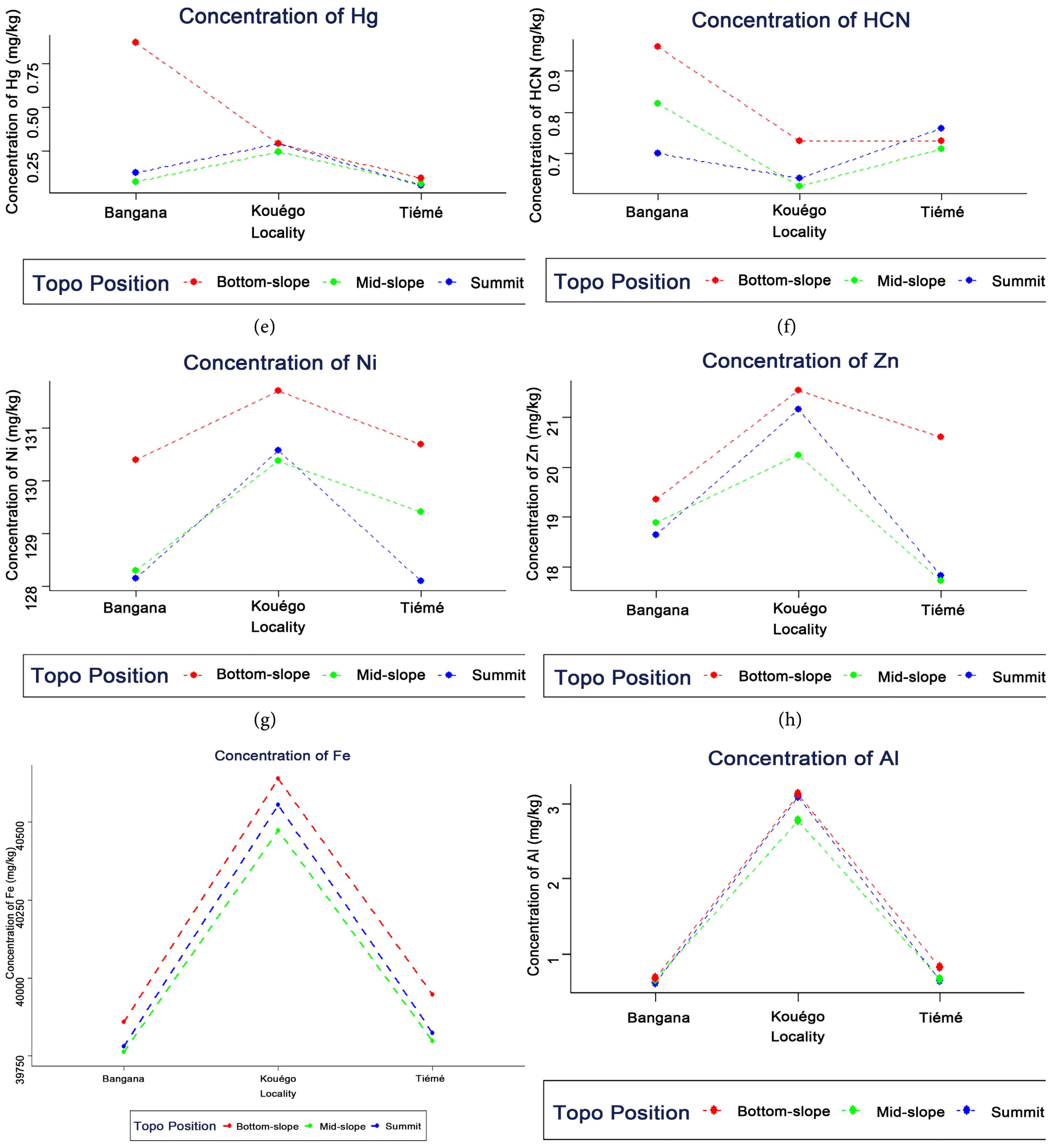


(a)

(b)

(c)

(d)



(e) (f)

(g) (h)

(i) (j)

Figure 13. (a) Changes in arsenic content as a function of toposequence and locality (1. Kouego, 2. Tiema, 3. Bangana). (b) Cadnium content as a function of toposequence and locality (1. Kouego, 2. Tiema, 3. Bangana). (c) Changes in lead content as a function of toposequence and location (1. Kouego, 2. Tiema, 3. Bangana). (d) Changes in copper content as a function of toposequence and locality (1. Kouego, 2. Tiema, 3. Bangana). (e) Changes in mercury content as a function of toposequence and locality (1. Kouego, 2. Tiema, 3. Bangana). (f) Changes in cyanide content as a function of toposequence and locality (1. Kouego, 2. Tiema, 3. Bangana). (g) Changes in nickel content as a function of toposequence and locality (1. Kouego, 2. Tiema, 3. Bangana). (h) Changes in zinc content as a function of toposequence and locality (1. Kouego, 2. Tiema, 3. Bangana). (i) Changes in iron content as a function of toposequence and locality (1. Kouego, 2. Tiema, 3. Bangana). (j) Changes in aluminium content as a function of toposequence and locality (1. Kouego, 2. Tiema, 3. Bangana).

3.8. Vertical Dynamics of TMEs in Gold Panning Soils

Figure 14 presents the vertical evolution of TMEs in the different gold mining soils of the three study locations. It shows that the TME contents of gold mining soils vary according to the TME, the location and the horizons. At Kouego, high levels of As (6.99 mg/kg and 6.96 mg/kg), Cd (4.88 mg/kg and 4.85 mg/kg), Cu (90.14 mg/kg and 90.13 mg/kg), Ni (130.96 mg/kg and 130.92 mg/kg), Hg (0.32 mg/kg and 0.29 mg/kg), HCN (0.67 mg/kg) and Al (3.07 mg/kg and 3.02 mg/kg) are recorded respectively at the surface horizons 0 - 20 cm and 20 - 40 cm. However, high Pb (57.53 mg/kg and 57.51 mg/kg), Zn (21.02 mg/kg and 20.99 mg/kg) contents are recorded at the underlying horizons (40 - 80 cm and 80 - 120 cm). At Tiema, high Cd (2.44 mg/kg and 2.41 mg/kg), Zn (18.78 mg/kg and 18.73 mg/kg), Hg (0.09 mg/kg and 0.07 mg/kg), HCN (0.77 mg/kg and 0.71 mg/kg) and Al (0.73 mg/kg and 0.72 mg/kg) contents are recorded at the horizons of depths 40 - 80 cm and 80 - 120 cm, respectively. On the other hand, high As (2.95 mg/kg and 2.90 mg/kg) and Cu (99.16 mg/kg and 90.08 mg/kg) contents are recorded at the surface horizons 0 - 20 cm and 20 - 40 cm. Furthermore, high Pb (31.15 mg/kg and 31.11 mg/kg) and Ni (130.52 mg/kg and 129.60 mg/kg) contents are obtained at the intermediate horizons (20 - 40 cm and 40 - 80 cm). At Bangana, high As (3.06 mg/kg and 2.99 mg/kg), Cd (2.87 mg/kg and 2.86 mg/kg), Cu (97.84 mg/kg and 97.81 mg/kg) and Al (0.64 mg/kg and 0.63 mg/kg) contents are recorded respectively at the surface horizons 0 - 20 cm and 20 - 40 cm. While high Zn (129.03 mg/kg and 128.92 mg/kg), Hg (0.10 mg/kg and 0.09 mg/kg) and HCN (0.05 mg/kg) contents are recorded at the depth horizons 40 - 80 cm and 80 - 120 cm. As for the highest Pb (31.11 mg/kg and 30.66 mg/kg) and Ni (0.64 mg/kg and 0.63 mg/kg) contents, (129.74 mg/kg and 129.20 mg/kg), they are obtained at the level of the intermediate horizons (20 - 40 cm and 40 - 80 cm).

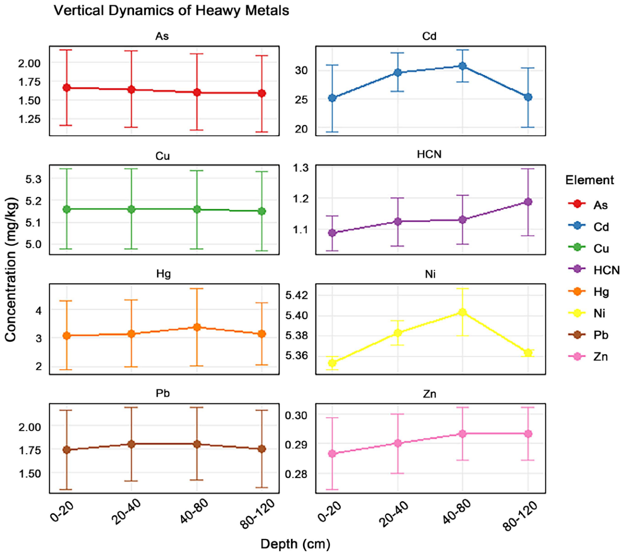
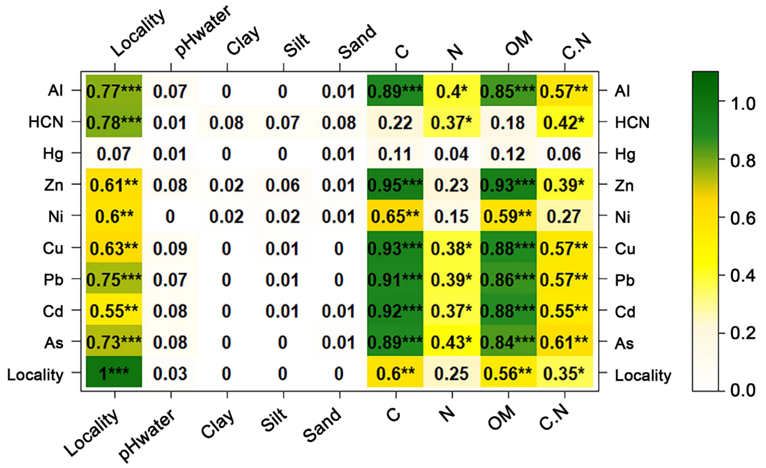


Figure 14. Vertical dynamics of concentrations of trace metal elements in soils of different gold panning sites.

3.9. Relationships between Physicochemical Properties and TMEs after Standardized Principal Component Analysis (NPCA)

Figure 15 shows overall significant correlations between localities, the majority of TMEs (As, Cd, Pb, Cu, Ni, Zn, HCN and Al), granulometric parameters and organic matter components (C, N, C/N), thus indicating particular links between the different sites studied of TMEs that could be the result of pollution.



	Locality	pHwater	Clay	Silt	Sand	C	N	OM	C.N
Al	0.77***	0.07	0	0	0.01	0.89***	0.4*	0.85***	0.57**
HCN	0.78***	0.01	0.08	0.07	0.08	0.22	0.37*	0.18	0.42*
Hg	0.07	0.01	0	0	0.01	0.11	0.04	0.12	0.06
Zn	0.61**	0.08	0.02	0.06	0.01	0.95***	0.23	0.93***	0.39*
Ni	0.6**	0	0.02	0.02	0.01	0.65**	0.15	0.59**	0.27
Cu	0.63**	0.09	0	0.01	0	0.93***	0.38*	0.88***	0.57**
Pb	0.75***	0.07	0	0.01	0	0.91***	0.39*	0.86***	0.57**
Cd	0.55**	0.08	0	0.01	0.01	0.92***	0.37*	0.88***	0.55**
As	0.73***	0.08	0	0	0.01	0.89***	0.43*	0.84***	0.61**
Locality	1***	0.03	0	0	0	0.6**	0.25	0.56**	0.35*

Figure 15. Correlations between the main components, physicochemical parameters and trace metal elements of gold panning sites.

3.10. Structuring of Unrotated Principal Components

Principal component analysis (PCA) was used to reduce the dimensionality of the data while identifying the dominant factors responsible for the observed variability. In the present study, the first four principal components (PC1 to PC4) explained a significant proportion of the total variance, reflecting major processes in the dynamics of the soils studied. Together, the principal components (PCs) explained 98% of the variability in the measured soil properties. The Kaiser-Meyer-Olkin coefficient (KMO) was used to assess the sampling adequacy for factor analysis, with a KMO of 0.62, indicating an acceptable level. Bartlett's test of sphericity showed a P value of less than 0.0001, which was highly significant (χ^2 (136) = 1115.19; P = 0.000), justifying the pursuit of a precise factor analysis.

3.11. Principal Component Analysis and Interpretation of Relationships

3.11.1. Analysis of the First Principal Component (PC1)

The first principal component (PC1) explains a large part of the total variance (58%) and shows marked correlations with the following notable observations:

- A strong positive correlation with the silt fraction (0.97) indicates a close association between this component and silt soils.
- A maximum negative correlation with clay (−1.0) suggests a clear opposition between these two textural fractions.
- A positive correlation with total nitrogen (N) (0.77) and a significant negative

correlation with the C/N ratio (−0.64) reflect the influence of organic matter on this component.

These results indicate that PC1 mainly represents soil texture, contrasting silt soils with clay soils, while integrating the modulating effect of organic matter on soil structure and fertility.

3.11.2. Second Principal Component (PC2) Analysis

The second principal component (PC2, 25%) is dominated by correlations with trace metal elements (TMEs) and organic properties. Observations include:

- Very strong positive correlations with lead (Pb, 1.0), cadmium (Cd, 0.98), arsenic (As, 0.99), nickel (Ni, 0.83), and aluminum (Al, 0.99).
- Significant negative correlations with organic matter (OM, −0.94), hydrogen cyanide (HCN, −0.64), and locality (−0.86).

These results show that PC2 essentially characterizes soil metal contamination, contrasting toxic element concentrations with organic matter content.

3.11.3. Third Principal Component (PC3) Analysis

The third principal component (PC3), with 9% of the variances, reflects more subtle variations, with moderate correlations:

- A notable negative correlation with mercury (Hg, −0.57), indicating a potential role of this component in secondary contamination processes;
- Moderate correlations with nickel (Ni, 0.4), suggesting a complex interaction between these variables.

This component seems to capture specific dynamics of redistribution or interaction of TMEs, in relation to secondary processes such as complexation or chemical precipitation.

3.11.4. Fourth Principal Component (PC4) Analysis

The fourth principal component (PC4) is associated with residual variations (6%), with generally weak correlations:

- Moderate negative correlation with HCN (−0.49);
- Notable influence on Hg (−0.7).

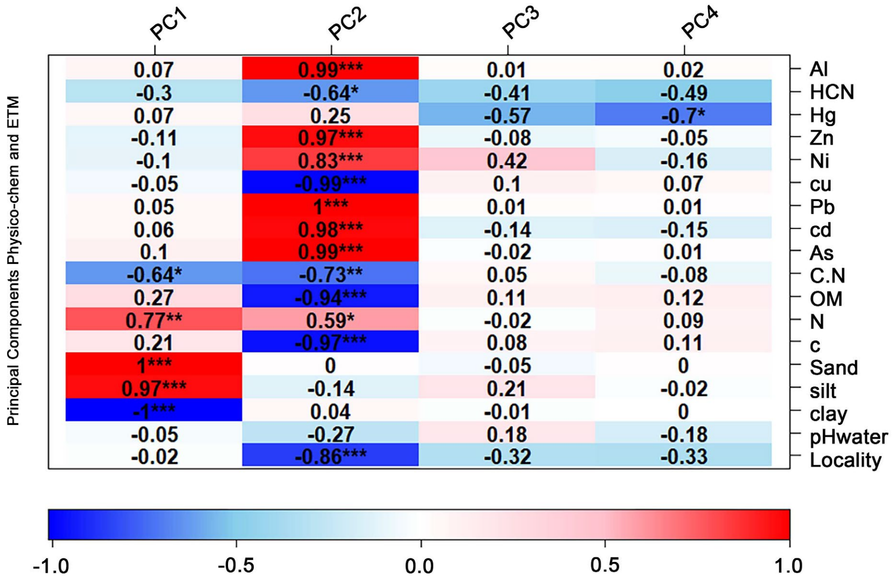
These results suggest that PC4 captures marginal variations, probably related to local or specific phenomena, such as punctual external inputs or secondary chemical interactions.

3.11.5. Correlation Heatmap

The correlation heatmap (**Figure 16**) illustrates the relationships between physicochemical variables and principal components, providing essential information on the structuring of the data.

Asterisks indicate statistical significance levels of correlations, with more stars indicating greater significance.

This analysis reveals a data structure consistent with an environmental system where soil physical properties and metal contamination are the main structuring factors.



	PC1	PC2	PC3	PC4
Al	0.07	0.99***	0.01	0.02
HCN	-0.3	-0.64*	-0.41	-0.49
Hg	0.07	0.25	-0.57	-0.7*
Zn	-0.11	0.97***	-0.08	-0.05
Ni	-0.1	0.83***	0.42	-0.16
cu	-0.05	-0.99***	0.1	0.07
Pb	0.05	1***	0.01	0.01
cd	0.06	0.98***	-0.14	-0.15
As	0.1	0.99***	-0.02	0.01
C.N	-0.64*	-0.73**	0.05	-0.08
OM	0.27	-0.94***	0.11	0.12
N	0.77**	0.59*	-0.02	0.09
c	0.21	-0.97***	0.08	0.11
Sand	1***	0	-0.05	0
silt	0.97***	-0.14	0.21	-0.02
clay	-1***	0.04	-0.01	0
pHwater	-0.05	-0.27	0.18	-0.18
Locality	-0.02	-0.86***	-0.32	-0.33

Figure 16. Heatmap of the relationships between physicochemical properties and TMEs after analysis of standardized principal components.

4. Discussion

4.1. Morphological Characteristics of Soils

The morphological characterization of the gold mining soils of the Seguela localities made it possible to identify Cambisols with plinthic, pseudogleyic or arenic aspects, expressed respectively by high loads of coarse elements, going as far as induration, hydromorphic spot and a texture presenting a relative abundance of sand and silt. According to [34], induration is due to an accumulation of iron from the surface horizons, which are more draining. Also, the appearance of hydromorphic spots from the mid-slope testifies to the presence of a temporary water table, more visible on the lower slope. Indeed, the contrast between the very low clay content of the surface horizons and the very high rates in the deep horizons, leads to a slowdown in the vertical dynamics of the water. The consequences of these processes are mainly translated by low useful depth of soil for agricultural development and an accentuation of mechanical erosion following soil work. The rejuvenation which characterizes pedogenesis, with the abundance of diversely colored spots in a matrix more or less subject to induration reflects a process of neoformation characteristic of Cambisols as mentioned by [35].

4.2. Physical and Chemical Characteristics of Soils

The soils of the gold panning sites observed in this study show that they are weakly acidic overall, varying between 6.4 and 6.8. According to [36], would not present a constraint for the availability of nutrients that can be absorbed by plants and would not promote the accumulation of toxic metals, such as aluminum or manganese. However, it was found in some soil profiles that the underlying horizons were more acidic than the surface horizons. This is contrary to the normal evolution profile of pH in the soil which indicates an increase in pH with soil depth

[37], except in the case of soils that regularly benefit from remedial measures as reported by [38]. Thus, this change in pH in the soils of the present study would be the sign of an inversion of the soil profile due to the soil excavation technique practiced in places by these gold miners or to the accumulation, on the surface horizons of the soil, of waste rock from ore extraction. pH is considered one of the important factors that determines the concentration of TMEs in the soil, its mobility and its availability for plants [39]. In addition, according to [40], the variation in pH seems to be the factor whose action on the mobility of metals is the most determining. Lowering the pH promotes the mobility of TMEs, in particular by dissolving metal salts or destroying the retention phase. Conversely, increasing the pH causes immobilization by forming insoluble compounds or increasing the cation exchange capacity. These similar results have been reported by several authors such as [34] in soils located around the Gbétogo mine in Seguela, [41] in gold mining soils in the Lore Lindu National Park area of Indonesia and [42] on gold mining sites located in the Kombo-Laka region of Cameroon. For these authors, the origin of the acidity of gold mining soils generally results from the complexity of exchanges on the colloidal surface. Indeed, the soil solution dominated by acidic cations, mainly Al^{3+} cations, stimulate the concentration and activity of H^+ ions in the soil solution [43], which leads to a decrease in soil pH [44]-[47]. The results show that organic matter is more abundant in the surface horizons (0 - 20 and 20 - 40 cm) and decreases with depth. It oscillates between 10.57% and 11.64% from one site to another, this relative abundance of organic matter would reflect the vegetation of the gold panning sites in the study area. This vegetation was mainly composed of gallery forest or cashew cultivation, which provided organic matter. These results are contrary to those of [41] who showed that the organic matter content in gold mining soils is very low. For them, a mining area undergoes a degradation of physical properties and a significant loss of organic matter and nutrients, which leads to a decrease in soil productivity. However, the relatively low values of the C/N ratio oscillating between 6.76 and 10.62 of gold mining soils, especially Kouego soils, is indicative of a more or less rapid mineralization of organic matter which could soon lead to this degradation of the fertility of soils under gold mining mentioned by [41].

4.3. Concentration of Trace Elements (TEs) in Soils

The concentrations of TEs obtained from the soils of the gold mining sites in the Seguela localities vary depending on the sampling site and the metallic element considered. Our results are similar to those of several authors [15] [17] [42]-[49], who have shown that the total concentrations of TEs in soils vary depending on the soil type, the extent of the gold mining area, the metallic element, and contamination sources (fertilizers, pesticides, atmospheric fallout). Next, the average concentrations of TEs obtained were compared to Bowen's standard. The results show that the average concentrations of seven TEs (As, Cd, Pb, Cu, Ni, Hg, and HCN) at the gold mining sites in the Kouego locality exceed the limits set by

Bowen's standard for uncontaminated soils. These concentrations, higher than Bowen's standard, suggest that gold mining activities are a source of soil pollution. According to [1], the high Pb levels could be explained by the fact that gold ores are often associated with sulfide ores, including galena (PbS), the primary ore of Pb.

4.4. Vertical and Lateral Concentration of TMEs

Taking into account the vertical and lateral dynamics of TME concentrations in gold panning sites in the Seguela department, the evolution of the contents according to the horizons and the topography could be explained by several factors, in particular textural differentiation, pH, organic matter content and iron and/or manganese content [42]. Thus, TME concentrations, high in the surface horizons, except for zinc, observed in the Seguela area, are similar to those obtained by some authors [15] [44] [49]), who also showed that the TME contents of the surface horizons of soils are higher than those of the deep horizons. This could be linked to anthropogenic contamination. Indeed, certain anthropogenic activities such as the supply of agricultural inputs, mining operations, would lead to contamination and accumulation of TMEs in the surface horizons of the soil [15] [17] [44] [48] [49]. On the other hand, the high levels of Zn in the deep horizons (80 cm - 120 cm) suggest that it would come mainly from the natural pedogeochemical background [34], but also from the leaching phenomenon. Because according to [50], the TME concentrations of soil undergoing leaching and leaching must increase with depth. The rust stains observed in the profiles attest to this phenomenon of migration of certain metals in the profiles. From the point of view of the lateral evolution of TME contents, the high concentrations recorded at the bottom of the slope, compared to the topographic positions of the summit and mid-slope, indicate a lateral transfer of TME from the summit to the lower slope. These results are consistent with those of [34] and [51], because for them, this evolution would be due to water or wind erosion. Furthermore, the accumulation of TME towards the topographic positions of the lower slope, often characterized by the presence of a shallow water table as observed in the area subject to this study, would be an indicator of the pollution of groundwater and surface water in gold panning areas.

5. Conclusion

This study aimed to evaluate the gold panning soils of the Department of Seguela through a detailed physical and chemical characterization. The morphological description of the soils made it possible to identify Cambisols marked by a high load of coarse elements, induration in the topographic positions of the summit and mid-slope, then by hydromorphy, with the presence of a sheet of water at a shallow depth in the ground, at the level of the lower slope. This slope position was identified as an area of accumulation of TME, which would present a risk of pollution of the soil and especially of water resources. The analysis of certain parameters such as pH, shows in places a phenomenon of inversion of the soil profile causing underlying horizons to pass to the surface. This was associated with relatively low values of the C/N ratio, which would be the cause of an ongoing degradation of soil fertility. The consequence would be an increase in the availability of TME in the superficial horizons of the soil exploited for agricultural purposes. However, this study showed that the most abundant TME in these gold mining soils is Cadmium which is very carcinogenic to humans. The gold panning soils of the Seguela department would present risks of contamination for human food via water and cultivated soils. To further explore these conclusions, additional studies could focus on the long-term effects of TME contamination on biodiversity and human health. Furthermore, the establishment of integrated soil monitoring and management programs will help to better prevent and mitigate the negative impacts of gold panning on the environment.

Conflicts of Interest

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

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