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Assessment of Soil Contamination in Koukougnanou, Central Côte d'Ivoire by Trace Metal Elements (Pb, Ni, Cr, Cd, and Mn): Distribution, Sources, and Ecological Risk

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Abstract

Mining activities are among the major sources of soil contamination by potentially toxic elements (PTEs). This study aimed to assess the soil quality of the Kouakougnanou mining site (Angovia, Côte d'Ivoire) in order to evaluate the level of contamination for environmental protection and sustainable soil management. Soil samples were collected from mining-affected areas and from non-mining areas. The concentrations of PTEs (Pb, Ni, Cr, Cd, and Mn) were determined using a Portable X-ray Fluorescence (pXRF) Geochemical Analyzer. Soil contamination was assessed using five environmental indices, namely the Contamination Factor (CF), Geo-accumulation Index (Igeo), Enrichment Factor (EF), Pollution Load Index (PLI), and Potential Ecological Risk Index (RI). The results revealed varying degrees of soil contamination depending on the element and the sampling area. The highest concentrations were recorded for nickel in non-mining soils (79.73 mg/kg) and manganese in mining-affected soils (172.45 mg/kg). The Contamination Factor indicated very high cadmium contamination, with mean CF values of 210 in non-mining soils and 420.9 in mining-affected soils. The Pollution Load Index showed mean values of 1.18 in non-mining soils and 3.33 in mining-affected soils, indicating greater environmental degradation in areas impacted by mining activities. The Potential Ecological Risk Index reached 188.03 and 328.71 for non-mining and mining-affected soils, respectively, indicating a higher ecological risk in disturbed soils. Cadmium exhibited the highest Geo-accumulation Index values, with mean Igeo values of 7.13 in non-mining soils and 8.13 in mining-affected soils. Similarly, the Enrichment Factor of cadmium reached 259,259.26 in non-mining soils and 1,315.31 in mining-affected soils, highlighting a strong anthropogenic contribution. Overall, the findings indicate that cadmium is the most critical potentially toxic element affecting the environmental quality of soils at the Kouakougnanou mining site and poses a significant ecological risk, emphasizing the need for continuous monitoring and appropriate soil management strategies.

Keywords: Potentially Toxic Elements (PTEs); Soil Contamination; Ecotoxicological Risk; Mining Activities; Portable X-ray Fluorescence (pXRF).

1. Introduction

Soil is an essential natural resource for the maintenance of ecosystems, agricultural production, and the socio-economic development of populations. It plays a fundamental role in biogeochemical cycles, water regulation, and the support of biodiversity. However, this resource is currently subjected to numerous anthropogenic pressures, particularly industrial, agricultural, and mining activities, which promote the accumulation of contaminants in the environment [1]. Among these contaminants, potentially toxic trace metals (PTTMs) occupy an important place because of their toxicity, persistence, and ability to bioaccumulate in living organisms [2].

Potentially toxic trace metals, such as lead (Pb), nickel (Ni), chromium (Cr), cadmium (Cd), and manganese (Mn), are naturally present in the Earth's crust at low concentrations [3]. Nevertheless, anthropogenic activities contribute

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significantly to the increase in their concentrations in soils. Among these sources, mining is one of the main causes of metal contamination in soils. This pollution can alter the physical, chemical, and biological properties of soils, reduce their fertility, and durably disrupt ecosystem functioning [4].

Soil contamination by PTTMs also represents a major public health issue. These elements can be transferred from soil to plants and then enter the animal and human food chain [2]. Prolonged exposure to certain metals can cause various toxic effects, including neurological, renal, respiratory, and even carcinogenic effects. Cadmium and lead are among the most concerning metals because of their high toxicity even at low concentrations [5].

In Côte d'Ivoire, the expansion of mining activities raises major environmental concerns, particularly in gold-bearing areas. The locality of Kouakougnanou, located in the Marahoué region in central-western Côte d'Ivoire, hosts a gold deposit that is actively mined and explored. While these activities contribute to local economic dynamism, they may also lead to the progressive degradation of soils and surrounding ecosystems through the accumulation of PTTMs. In this context, it is necessary to assess the contamination status of soils in order to better evaluate the environmental and health impacts associated with mining activities in this area.

The objective of this study is to assess the quality of the soils at the Kouakougnanou mining site for environmental protection and sustainable soil management. It would therefore be important to determine the concentrations of trace metals present in the soils and to assess the level of contamination through the calculation of metal pollution indices and the analysis of the associated ecological and health risks.

2. Material and methods

2.1. Study area

Kouakougnanou is a locality situated in west-central Côte d'Ivoire, within the Bouaflé Department in the Marahoué Region. The village is located approximately 5 km from Angovia and the Yaouré gold mine operated by Perseus Mining. The study area lies between longitudes 5°19′ and 5°31′ W and latitudes 6°53′ and 7°05′ N, covering an area of approximately 50 km^2 (Fig.1).

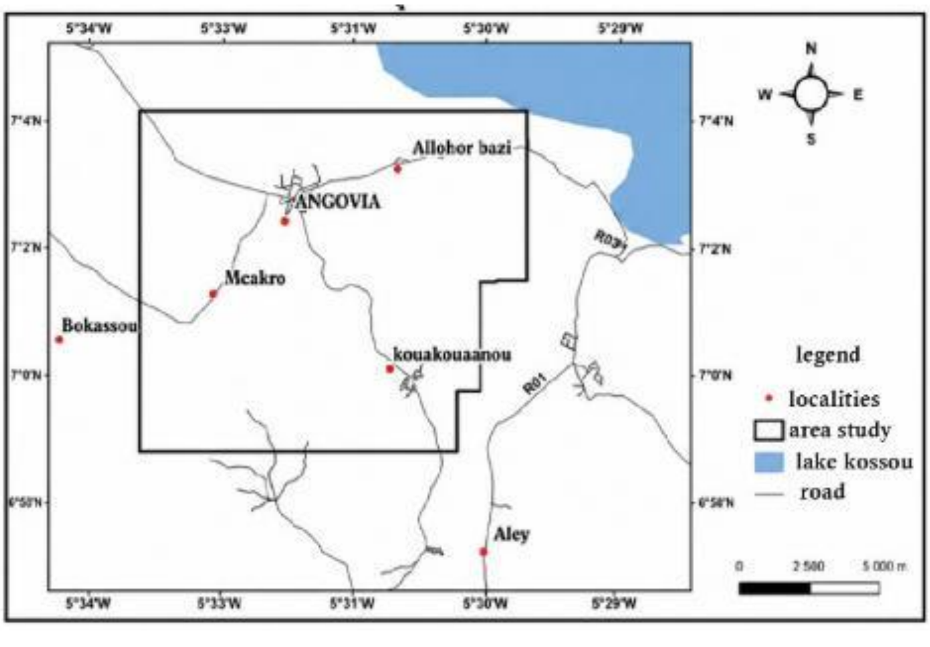

Figure 1 Location of the Study Area

he study area belongs to a complex geological setting dominated by volcanic and volcano-sedimentary formations (Fig. 2). The Yaouré area is characterized by a synclinal structure composed of tholeiitic metavolcanic rocks overlain by more felsic formations [6]. These rocks have undergone extensive hydrothermal alteration and are associated with various magmatic intrusions, including ultrapotassic and calc-alkaline bodies. The area has also been affected by east–west-oriented tectonic deformation events, accompanied by fracturing and quartz veining. Widespread lateritic weathering is observed throughout the area, promoting the concentration of gold mineralization within structurally altered zones.

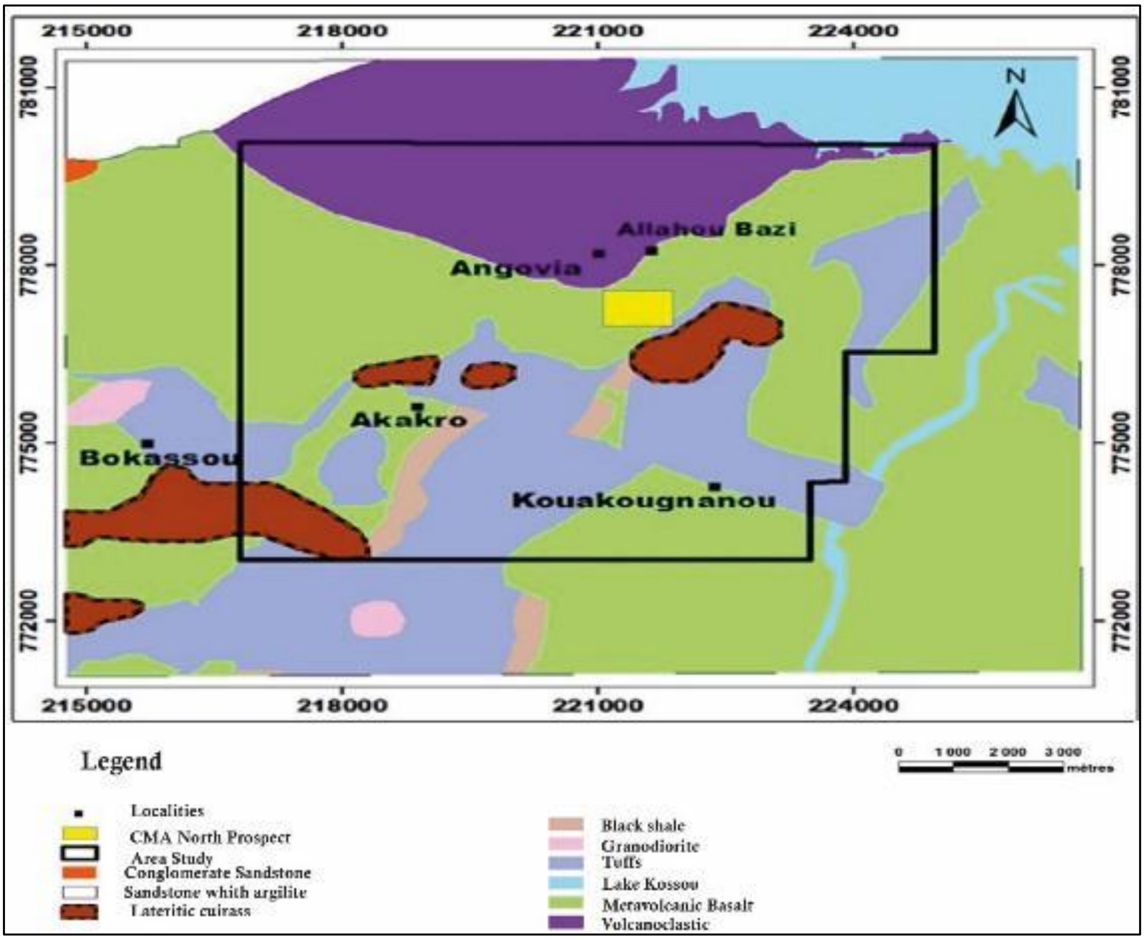

Figure 2 Geological map of the study area

2.2. Methods

Soil samples were collected from the surface layer (0–30 cm), which is the horizon most strongly influenced by anthropogenic activities and atmospheric deposition. The samples were stored under conditions designed to prevent external contamination before being transported to the laboratory for analysis.

In the laboratory, the samples underwent several pretreatment steps, including air-drying, homogenization, and sieving, to obtain representative and uniform materials suitable for analysis. Potentially toxic element (PTE) concentrations were determined directly in mg/kg (ppm) using a portable Niton X-ray fluorescence (XRF) analyzer operating in the soil calibration mode.

To assess the degree of soil contamination, the following pollution indices were calculated:

- **Contamination Factor (CF):** $FC = \frac{Cn}{C\ Background\ signal}$

  Cn : Concentrations of trace metals in the studied soils

  C Background signal : Reference concentration of the trace metal in the continental crust.

- **Pollution Load Index (PLI):** $ICP = \sqrt[n]{FC1 \times FC2 \times FC3 \times \ldots \times FCn}$

  FCi : **(CF_i)** is the contamination factor of metal *i*. Accordingly, when **PLI = 0**, no deterioration is observed; when **PLI = 1**, soil quality corresponds to the reference (background) level of pollutants; and when **PLI > 1**, the soils exhibit progressive deterioration due to increasing pollution.

- **Enrichment Factor (EF):** $FE = \frac{\left(\frac{[X]}{[R]}\right) \text{sample}}{\left(\frac{[X]}{[R]}\right) \text{Reference material}}$

[X]: concentration of the trace metal element under investigation;

[R]: concentration of the normalizing element.

EF values ranging from **0.5 to 1.5** indicate that trace metal elements (TMEs) are predominantly

derived from natural sources, whereas **EF > 1.5** suggests significant anthropogenic

- **Geo-accumulation Index (Igeo):** $\text{Igéo} = \log_2\left(\frac{Cn}{1{,}5 \times Bn}\right)$

Igeo: Geoaccumulation Index;
$\mathbf{log_2}$: base-2 logarithm;
n: element under consideration;
C: measured concentration of the element in the sample;
B: geochemical background concentration.

- **Potential Ecological Risk Index (PERI):** (RE) : $RE = \sum_{i=1}^{n} \times \left(FT_r^i \times \frac{Ci}{C0}\right)$

$\mathbf{C_i}$: concentration of the trace metal element in the studied soil;
$\mathbf{C_0}$: reference concentration of the trace metal element in the continental Earth's crust.

3. Results and discussion

3.1. Concentrations of trace metals in soil

Pb concentrations ranged from 5.39 to 325.23 mg/kg in the soil where no works had been carried out, with a mean value of 47.13 ± 71.89 mg/kg. In the soil where works had been carried out, Pb concentrations ranged from 9.96 to 31.32 mg/kg, with a mean value of 17.63 ± 5.77 mg/kg.

Ni showed concentrations ranging from 40.71 to 166.44 mg/kg in the soil without works, with a mean value of 79.73 ± 31.88 mg/kg, whereas in the soil that had undergone works, concentrations ranged from 43.94 to 107.19 mg/kg, with a mean value of 74.26 ± 26.87 mg/kg. Cr concentrations ranged from 8.66 to 113.79 mg/kg in the soil where no works had been carried out, with a mean value of 40.42 ± 27.41 mg/kg.

In the soil that had undergone works, Cr concentrations ranged from 9.84 to 50.84 mg/kg, with a mean value of 26.43 ± 8.98 mg/kg. In addition, Cd concentrations ranged from 12.93 to 48.22 mg/kg in the soil where no works had been carried out, with a mean value of 21.00 ± 11.47 mg/kg.

However, in the soil where works had been carried out, Cd concentrations ranged from 13.04 to 57.98 mg/kg, with a mean value of 42.09 ± 15.80 mg/kg. As for Mn, concentrations ranged from 0.02 to 2.11 mg/kg in the soil without works, with a mean value of 0.43 ± 0.05 mg/kg. In the soil that had undergone works, Mn concentrations fluctuated between 92.82 and 350.52 mg/kg, with a mean value of 172.45 ± 75.57 mg/kg.

3.2. Contamination Level and Risk Assessment

3.2.1. Contamination Factor

For lead (Pb), the contamination factor values in undisturbed soils ranged from 0.31 to 19.13, with a mean value of 2.77 ± 4.22. In disturbed soils, the values ranged from 0.58 to 1.84, with an average of 1.04 ± 0.33.

Regarding nickel (Ni), the CF values in undisturbed soils varied from 2.14 to 8.76, with a mean of 4.19 ± 1.64. In disturbed soils, the values ranged from 2.31 to 5.64, with an average of 3.90 ± 1.41.

For chromium (Cr), the contamination factor values in undisturbed soils ranged from 0.24 to 3.25, with a mean value of 1.14 ± 0.78. In disturbed soils, the values varied between 0.28 and 1.45, with an average of 0.75 ± 0.25.

Cadmium (Cd) exhibited the highest contamination factor among all the investigated elements. In undisturbed soils, CF values ranged from 129.3 to 482, with a mean of 210 ± 114.7. In disturbed soils, the values ranged from 130.4 to 579.8, with an average of 420.9 ± 258, indicating extremely high contamination.

In contrast, manganese (Mn) exhibited the lowest contamination factor values. In undisturbed soils, CF values ranged from 0.00037 to 0.0040, with a mean of 0.00081 ± 0.00094. In disturbed soils, the values varied from 0.17 to 0.66, with an average of 0.32 ± 0.14.

Overall, the results indicate that cadmium is the predominant contaminant in both undisturbed and disturbed soils. Nickel also exhibited considerable contamination levels, whereas lead and chromium showed variable contamination depending on the sampling sites. Conversely, manganese displayed very low contamination factor values, suggesting a negligible contribution to the overall soil contamination. The relatively high standard deviations observed for lead and cadmium indicate a marked spatial heterogeneity in their distribution across the study area, likely reflecting differences in contamination sources and local soil characteristics.

3.2.2. *Pollution Load Index (PLI)*

The mean Pollution Load Index (PLI) values calculated for the different sampling sites are presented in **Table 1**. Undisturbed soils exhibited a mean PLI value of 1.18, whereas disturbed soils showed a substantially higher mean value of 3.33. This difference indicates a greater deterioration in soil quality within areas affected by mining activities. Indeed, the higher PLI observed in disturbed soils reflects a greater accumulation of potentially toxic elements, highlighting the stronger impact of mining operations on soil contamination.

Table 1 Variation in the Pollution Load Index (PLI) Across the Studied Sites

Area	ICP
Non-mining areas	1,18
Mining-affected areas	3,33

3.2.3. Potential Ecological Risk Index (PERI)

The mean Potential Ecological Risk Index (PERI) values were 188.03 for undisturbed soils and 328.71 for disturbed soils. These results indicate that areas affected by mining activities are exposed to a higher ecological risk than undisturbed areas. The increase in PERI observed in disturbed soils suggests a significant contribution of potentially toxic elements (PTEs) to the degradation of the local environment. These findings highlight the adverse environmental impact of mining activities on soil ecological quality (**Table 2**).

Table 2 Variation in the Ecological Risk of Potentially Toxic Elements (PTEs)

Area	RE
Non-mining areas	188,03
Mining-affected areas	328,71

3.2.4. Geo-accumulation Index (Igeo)

For lead (Pb), the Igeo values in undisturbed soils ranged from −2.27 to 3.67, with a mean of 0.88 ± 2.82. In disturbed soils, the values ranged from −1.37 to 0.29, with an average of −0.53 ± 0.32. Nickel (Ni) also exhibited positive Igeo values in both soil categories. In undisturbed soils, the index ranged from 0.51 to 2.55, with a mean of 1.48 ± 0.56. In disturbed soils, the values varied between 0.62 and 1.91, with an average of 1.38 ± 0.51.

For chromium (Cr), the Igeo values in undisturbed soils ranged from −2.64 to 1.12, with a mean of −0.40 ± 0.68. In disturbed soils, the values varied from −2.42 to −0.05, with an average of −1.00 ± 0.31.

Cadmium (Cd) exhibited the highest geo-accumulation levels among all the investigated elements. In undisturbed soils, Igeo values ranged from 6.43 to 8.33, with a mean of 7.13 ± 0.79. In disturbed soils, the values varied between 6.44 and 8.59, with an average of 8.13 ± 0.87.

In contrast, manganese (Mn) was characterized by strongly negative Igeo values. In undisturbed soils, the index ranged from −11.99 to −8.55, with a mean of −10.85 ± 1.22. In disturbed soils, the values ranged from −3.14 to −1.18, with an average of −2.23 ± 0.40

3.2.5. Enrichment Factor (EF)

The results indicate that lead (Pb) exhibited highly variable enrichment levels across the investigated sites. In undisturbed soils, EF values ranged from 837.84 to 47,825.00, with a mean of 3,419.75 ± 5,210.34. In contrast, disturbed soils showed considerably lower values, ranging from 2.79 to 3.41, with an average of 3.24 ± 2.36.

Nickel (Ni) also exhibited high enrichment factors. In undisturbed soils, EF values varied from 5,783.78 to 23,675.68, with a mean of 5,172.84 ± 4,973.42. In disturbed soils, the values ranged from 8.55 to 13.59, with an average of 12.19 ± 10.07.

For chromium (Cr), relatively high enrichment factors were observed in undisturbed soils, where EF values ranged from 648.65 to 8,783.78, with a mean of 1,407.41 ± 2,364.15. In disturbed soils, the values were substantially lower, varying from 1.65 to 2.20, with an average of 2.34 ± 1.79.

Among all the investigated elements, cadmium (Cd) exhibited the highest enrichment levels. In undisturbed soils, EF values ranged from 116,216.22 to 1,205,000.00, with a mean of 259,259.26 ± 408,354.62. Disturbed soils also displayed high EF values, ranging from 767.06 to 1,315.31, with a mean of 1,315.31 ± 1,842.86.

Manganese (Mn) maintained a constant enrichment factor of 1 in all analyzed samples. This is because Mn was used as the reference element for the calculation of the Enrichment Factor

4. Discussion

The assessment of potentially toxic element (PTE) concentrations, contamination factors (CF), geo-accumulation index (Igeo), enrichment factor (EF), pollution load index (PLI), and potential ecological risk index (PERI) revealed varying degrees of soil contamination depending on the element and soil type[7].

4.1. Concentrations of Potentially Toxic Elements in Soils

The concentration data showed that nickel (Ni) exhibited the highest mean concentration in undisturbed soils, whereas manganese (Mn) predominated in disturbed soils. The elevated Ni concentrations may be attributed to the natural weathering of metal-rich parent materials or to anthropogenic activities such as mining, agriculture, and industrial operations [3]. Similar findings were reported by [3], who demonstrated that high Ni concentrations in soils are commonly associated with both anthropogenic inputs and metal-rich geological substrates. [8] reported elevated Ni concentrations in industrial soils in Poland. The marked increase in Mn concentration in disturbed soils may be explained by soil disturbance resulting from mining activities, which enhances the mobilization or accumulation of this element [1]. This observation is consistent with the findings of [9], who reported that anthropogenic activities modify the distribution and mobility of metals in soils. Cadmium (Cd) exhibited relatively high concentrations in both soil types. This finding is of particular concern because Cd is highly toxic even at low concentrations [5]. According to [2], the major anthropogenic sources of Cd in soils include mining activities, industrial discharges, phosphate fertilizers, and atmospheric deposition. The elevated Cd concentrations observed in the present study are comparable to those reported by [1], who identified Cd as one of the most critical contaminants in polluted soils.

4.2. Contamination Levels and Ecological Risk

The contamination factor analysis identified Cd as the most significant contaminant in the investigated soils. The extremely high CF values recorded for Cd indicate severe soil contamination [7]. Similar results were reported by [10], who found that Cd exhibited the highest contamination factors in soils affected by anthropogenic activities. Nickel also showed relatively high CF values, indicating moderate to considerable contamination. The Geo-accumulation Index (Igeo) results revealed that Cd exhibited the highest values in both undisturbed and disturbed soils, indicating extremely strong contamination by this element [11]. Similar observations were reported by [8], who demonstrated that high Cd Igeo values generally reflect substantial anthropogenic inputs. Nickel exhibited moderate pollution levels, whereas chromium (Cr) and manganese (Mn) generally displayed negative or low Igeo values, indicating unpolluted to slightly polluted conditions. The Enrichment Factor (EF) analysis showed extremely high values for Cd and substantial enrichment for Ni, indicating a strong anthropogenic contribution to the accumulation of these elements in the studied soils [12]. These findings are consistent with those of [9], who reported that elevated EF values generally reflect contamination resulting from human activities. According to [12], EF values greater than 40 indicate extremely severe enrichment, which is consistent with the Cd values obtained in the present study. The Pollution Load Index (PLI) values exceeded 1 in both soil types, indicating deterioration of soil quality due to PTE contamination [13]. Similar findings were reported by [14], who showed that elevated PLI values are indicative of severe soil pollution associated with anthropogenic activities. The Potential Ecological Risk Index (PERI) results indicate that the investigated soils are exposed to a considerable ecological risk [7]. The elevated risk values associated with certain PTEs suggest that these elements may pose significant threats to terrestrial organisms, vegetation, and surrounding water resources [1]. These findings are in agreement with those of [15], who identified Cd as the principal contributor to ecological risk in contaminated soils. The relatively high standard deviations observed for several PTEs indicate pronounced spatial heterogeneity in both element concentrations and contamination levels. This variability may be attributed to the uneven distribution of pollution sources, differences in parent material composition, and the intensity of anthropogenic activities within the study area [3]. Similar observations were reported by [16] in studies of contaminated urban soils. Overall, the different contamination indices consistently demonstrate that the investigated soils are significantly influenced by anthropogenic activities, particularly with respect to Cd and Ni contamination. Mining-related disturbances appear to have altered both the distribution and behavior of PTEs within the soils. These findings emphasize the need for continuous environmental monitoring and appropriate management strategies to mitigate the ecological and potential human health risks associated with PTE accumulation in the study area [1-2].

5. Conclusion

This study aimed to assess soil contamination by trace metal elements (TMEs) — lead (Pb), nickel (Ni), chromium (Cr), cadmium (Cd), and manganese (Mn) — in the study area, using several pollution and ecological risk indices. The results reveal a variable presence of TMEs depending on soil type: Ni dominates in undisturbed soils, likely reflecting a natural geochemical background, while Mn is more concentrated in soils that have undergone earthworks, which could indicate an input of exogenous materials or reworking of the pedological horizons. Cd, for its part, shows notable concentrations in both soil types. All of the calculated indices converge on the same finding: Cd is the most concerning element in the study area. It emerges as the primary contaminant according to the contamination factor (CF), the geoaccumulation index (Igeo), and the ecological risk index (ERI), and its high enrichment factor (EF) confirms a largely anthropogenic origin. Ni also shows marked enrichment and moderate pollution in certain zones, although its origin may be partly natural. Furthermore, the pollution load index (PLI), which exceeds 1 in both soil types, confirms an overall degradation of soil quality. The high spatial variability observed (elevated standard deviations) suggests heterogeneous pollution sources, potentially linked to local anthropogenic activities (to be specified according to context: road traffic, industrial or agricultural activities.

Compliance with ethical standards

Disclosure of conflict of interest

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

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