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Quantitative evaluation of potentially toxic elements and associated risks in Acrisols and Ferralsols of western Ghana

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This study investigates the natural distribution of potentially toxic elements in western Ghana as affected by soil types (i.e., Acrisols and Ferralsols). Geo-accumulation indices (Igeo), Enrichment Factor (EF), and risk index (RI) were computed to evaluate soil pollution classes, while the Soil Quality Index (SQI) was calculated to assess soil quality's effect on pollution hazard. The study revealed subtle differences in contamination patterns: Acrisols exhibited slightly elevated Igeo values for elements such as Se, Mo, Fe, and Ti, suggesting localized enrichment possibly linked to natural processes or minor external inputs. In contrast, Ferralsols showed moderate Igeo values for Cr and Ni, indicating some enrichment consistent with parent material characteristics. EF values for all elements in both soil types were below 2, classifying them as "depletion to minimal enrichment" and confirming that elemental concentrations are predominantly of geogenic origin rather than anthropogenic inputs. Principal Component Analysis (PCA) effectively distinguished the two soil types, with Acrisols associated with higher trace metal concentrations and greater organic matter content, while Ferralsols were influenced more by Al and Fe oxides. Heatmap analysis further highlighted distinct element clustering, with Cr, Ni, and Se more prominent in Ferralsols, and Mo, Ti, and other trace elements showing spatial variation in Acrisols. These findings underscore the influence of pedogenic processes and mineral weathering in shaping elemental distributions across soil types in tropical environments and support a soil-type-specific management approach to ensure environmental protection and sustainable land use. The Soil Quality Index indicated that Ferralsols (SQI range: -2.65 to 1.78) had slightly lower surface horizon quality, likely due to leaching, while Acrisols (SQI range: -2.84 to 3.89) showed higher quality in deeper horizons, reflecting better nutrient retention.

KEYWORDS

metals, tropical soils, soil properties, sustainable agriculture, soil fertility

1 Introduction

Tropical ecosystems, spanning a wide range of eco-climatic conditions along the equatorial region, vary from intensely hot lowlands to snowcapped mountains and from regions with seasonal rainfall to areas with persistently humid climates (1). Among these, tropical wet evergreen forests such as those in Ghana's rainforest regions are particularly significant due to their ecological importance, drawing considerable attention from ecologists and conservationists (2). Ferralsols, which are highly weathered soils, cover approximately 9.8 million hectares, representing 7.5% of the global land area and 25% of tropical lands, with the majority found in humid tropical regions (3). These soils play a crucial role in carbon storage, ecosystem support, and climate regulation, serving as vital resources for food production, timber, and medicinal plants (4). In Ghana, Ferralsols development is closely linked to the local climate and vegetation, particularly in the forest zone, where high organic matter accumulation enhances soil properties (5). Conversely, Acrisols, commonly found in Ghana's coastal savanna zone, are prone to nutrient depletion especially nitrogen and phosphorus under continuous cultivation, making them more vulnerable to soil degradation (6). As a result, many land use systems in Sub-Saharan Africa are considered unsustainable due to persistent nutrient loss and negative nutrient balances (7).

In tropical soil, metal and metalloid behavior is strongly influenced by intense weathering, high rainfall, and the presence of iron (Fe) and aluminum (Al) oxides, which regulate their mobility and retention. These oxides play a key role in adsorbing trace elements such as chromium (Cr) and nickel (Ni), limiting their bioavailability. Manganese (Mn) and titanium (Ti) occur naturally in tropical soils, often reflecting the geochemical composition of the parent material. Essential micronutrients like copper (Cu) and zinc (Zn) can accumulate due to agricultural practices. In contrast, heavy metals such as lead (Pb) and cadmium (Cd), mainly introduced through anthropogenic activities, tend to be more mobile in acidic tropical soils, increasing environmental risks. The interactions between soil pH, organic matter, and clay content further influence metal retention and leaching, ultimately impacting soil fertility and contamination levels.

The mobility and bioavailability of metals and metalloids in terrestrial environments are largely dictated by their partitioning between solid and dissolved soil fractions. While significant advances have been made in soil health assessments, much of the research on critical metalloids has focused on temperate soils, primarily in Europe and North America (8). However, data on metal behavior in tropical soils remains limited, highlighting a crucial knowledge gap that must be addressed. Numerous studies have emphasized this scarcity of research on trace metal dynamics in tropical soils (9–16).

Given the risks associated with heavy metal contamination, ecological risk assessment in agricultural soils has gained increasing attention in recent years. Various approaches, such as the ecological risk index (IR) and the geoaccumulation index, are widely used to evaluate the impact of environmental factors on soil quality and measure the degree of contamination (17). These tools help identify

areas at risk and assess the potential ecological hazards posed by metal pollution (18).

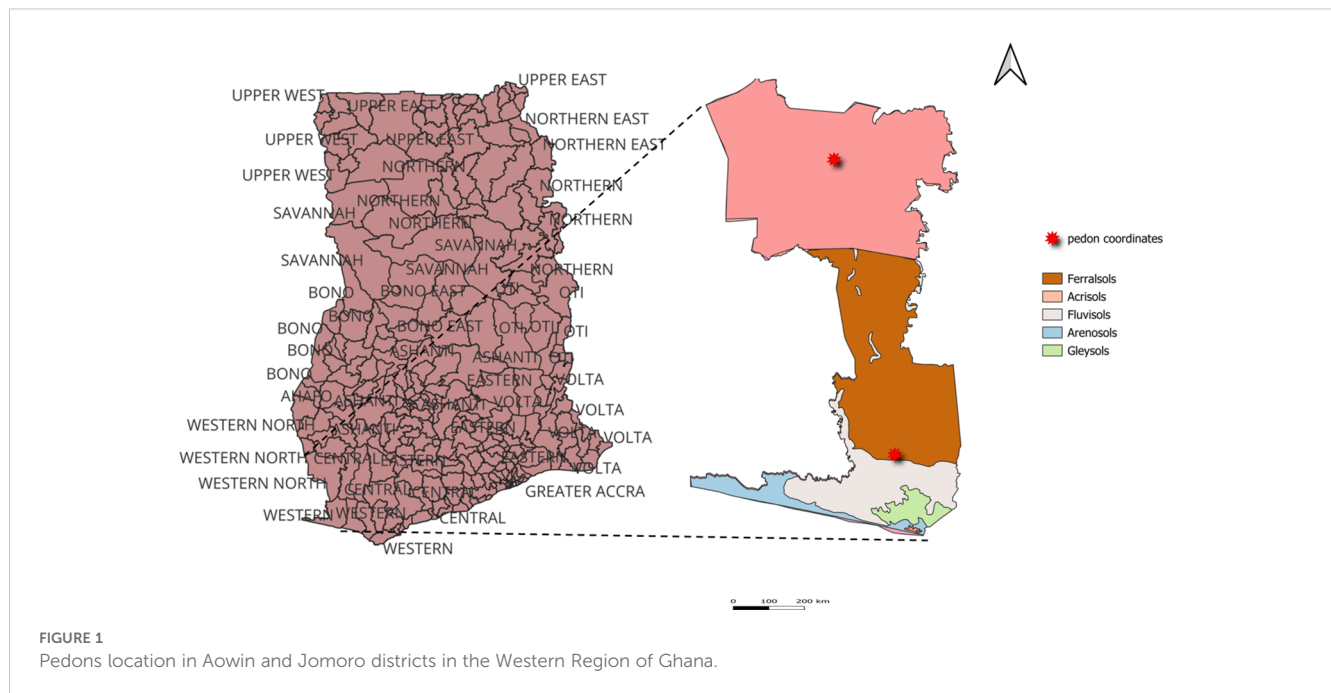
Western Ghana has been chosen as the study site due to its significance as a major agricultural hub, particularly for cocoa and oil palm cultivation where Acrisols and Ferralsols are widely distributed. According to Driessen et al. (19) and FAO (20) Acrisols correlate with several subgroups of Alfisols and Ultisols of the USDA system of classification. These are acidic, highly weathered soils (but less weathered than the Ferralsols) with accumulation of low activity clay in an argic subsurface horizon with low base saturation. They are found mainly on old land surfaces with hilly or undulating topography with wet monsoonal climate (19). Acrisols under a protective forest cover have a porous surface. Whereas Ferralsols are equivalent to the Oxisols of the USDA system, are leached and deeply weathered red soils of western Ghana. They occur typically in level to undulating land of Pleistocene age or older. They have stable microaggregates, good porosity, permeability and infiltration. The chemical fertility of these soils, whose clay fraction is dominated by low activity clays (kaolinite) and oxides of iron and aluminium, is poor for crop production (21). Soil pH is low, base saturation low and effective cation exchange capacity is only 3 to 4 cmol/kg soils. There is high retention by the soil colloids of applied phosphate leading to reduction in its immediate availability to crops. By and large, the agricultural environment in western Ghana is exigent. The land surface is generally very old, consist of sand and alluvial materials, and many of the materials of present-day soils have undergone both through anthropogenic and natural pedogenesis processes as the result, physical and chemical soil properties are inherently poor. Climate change and poor management aggravates the situation. Furthermore, there remains a considerable knowledge gap regarding the extent of metal accumulation in these soils and its potential impact on soil fertility and crop safety. Therefore, this study aims to assess and monitor soil quality in this vital agricultural zone, providing valuable insights for better soil management practices.

2 Materials and methods

2.1 Description of the study site

2.1.1 Study site location

The study site is located in the western region of Ghana, specifically within the Aowin and Jomoro districts (See Figure 1). This area is endowed with dense forests primarily dominated by wet evergreen and Moist Semi-Deciduous Forests, which are typical of the humid tropical zone. These forests are characterized by high species diversity, closed canopies, and significant timber resources. Additionally, the region features riverine zones and coastal plains. The soil in this area are predominantly Ferralsols and Acrisols, supporting agricultural and commercial plantation activities with adequate soil management. Two soil pedons were selected for analysis, each representing different cropping systems. The first pedon, located in Ferralsols under an oil palm farm, is situated at



coordinates N5°9'53.44853" and W2°37'53.41997". This pedon consists of five soil horizons. The second pedon is the Acrisols, which is dominant in a cocoa farm, is positioned at N5°51'17.43514" and W2°46'23.70695", and includes four distinct horizons.

2.1.2 Study site characterization

The study area spans two ecological zones: the Coastal Rainforest Zone (CPh4) in the Jomoro district, where the first pedon is located, and the Cocoa Forest Zone (CF1) in the Aowin district, where the second pedon is situated. The altitudes range from 97 meters above sea level in Jomoro to 134 meters in Aowin.

The region experiences a humid tropical climate, with an average annual rainfall of 1,500–2,000 mm, primarily distributed between April and October. The dry season extends from November to March, with the heaviest rainfall typically occurring during the summer months. The mean maximum temperature is 32–34°C, recorded in March, while the mean minimum temperature is 22–24°C, observed in August. Relative humidity peaks at 80–90% during the wet season and declines to 60–70% in the dry season.

Agricultural activities dominate the land use in the region, with major crops including oil palm (*Elaeis guineensis*), cocoa (*Theobroma cacao*), maize (*Zea mays*), pineapple (*Ananas comosus*), and cassava (*Manihot esculenta*). These activities reflect the significant role of farming in the local economy.

2.2 Experimental design, soil sampling and preparation

2.2.1 Experimental design

The first pedon, classified as Ferralsols, was sampled from an oil palm (*Elaeis oleifera*) plantation managed under a monoculture

system with no fertilizer application or agronomic interventions. This pedon included five distinct horizons: Horizon A (0–16 cm), Horizon B (16–35 cm), Horizon C (35–80 cm), Horizon D (80–120 cm), and Horizon R (120–200 cm). The second pedon, classified as Acrisols, was sampled from a cocoa (*Theobroma cacao*) farm intercropped with maize, reflecting a mixed cropping system. It comprised four horizons: Horizon A (1–50 cm), Horizon B (50–90 cm), Horizon C (90–120 cm), and Horizon D (120–180 cm).

The independent variables were horizon depth and land-use type (monoculture vs. intercropping), while the dependent variables included soil physical properties (e.g., texture), and chemical properties (e.g., pH, organic carbon, and nutrient, heavy metals concentrations). To ensure consistency, soil samples were systematically collected from the center of each horizon, following standardized protocols to minimize variability and maximize reproducibility. Triplicate sampling was conducted within each horizon to account for spatial heterogeneity.

2.2.2 Soil sampling and sample preparation

A total of 27 composite soil samples were collected, with three replicates taken from each horizon across the two representative soil profiles. Each pedon had four exposed sides, and soil from each horizon was sampled from all sides to ensure representativeness. Each composite sample was placed in a labeled bag. The samples then were air-dried, sieved to pass through 2mm to remove larger non-soil particles in preparation for soil analyses.

2.3 Soil physicochemical analysis

Exchangeable bases (Ca^{2+} , Mg^{2+} , K^{+} , and Na^{+}) were extracted with the stirring method using ammonium acetate following the NF X31-108V (2002) standard. The pH and electrical conductivity (EC)

of soil were determined in 1:2 soil: water ratio (22). Organic carbon (OC) content was determined via the Loss on Ignition (LOI) method, involving sequential heating at 450°C for organic matter decomposition and 850°C for carbonate breakdown. Total carbon (C), nitrogen (N), and hydrogen (H) quantification, the Dumas combustion method was employed. Texture analysis, including sand, silt, and clay fractions, was performed using the hydrometer method.

2.4 Total elemental analysis

Soil samples weighing between 50 and 100 milligrams were used for acid digestion. The digestion process involved a stepwise addition of acids: 2 mL of concentrated nitric acid (HNO₃), followed by 1.5 mL of hydrochloric acid (HCl), and finally, 0.5 mL of hydrofluoric acid (HF). The samples were then digested using a microwave digestion system to ensure complete dissolution of the soil matrix.

Elemental analysis was performed using an Agilent 5800 VDV ICP-OES. Data acquisition was conducted in both axial and radial modes, with three replicates measured over a 10-second integration time. To minimize interferences, polyatomic ion interferences were managed using Kinetic Energy Discrimination (KED) mode with helium as the collision gas. Calibration was performed using multi-element standard solutions (CCS4, CCS5, CCS6 from Inorganic Ventures, USA) prepared in 2% HNO₃. Quality control was ensured through the use of certified reference materials, including EnviroMAT Worn Water EUB and EnviroMAT Subterranean Water ES-H-2 (SCP Sciences, France), as well as SRLS-6, a reference material composed of riverine water for trace metal analysis (National Research Council Canada). Reagents used included ultrapure water (18.2 MΩ·cm at 25°C, Milli-Q Reference, Millipore) and high-purity acids (HNO₃ 69%, HCl 37%, TMA-VWR International).

2.5 Data analyses

2.5.1 Weighted mean, trend and specific range

Weighted mean (W), trend (T) and specific range (R) were employed to evaluate the status of metal contaminants in Acrisols and Ferralsols for each profile samples as described by (23).

The weight mean (W) concentration for a profile was obtained by calculating using Equation 1:

$$W = \left[\sum \left[\frac{c \cdot d}{P} \right] \right] \quad (1)$$

Where W = weighted mean, c = concentration of elements in the layer; d = thickness of layer and P = depth of profile

Trend (T) was calculated using Equation 2 to acquire some information on any change in concentration with depth.

$$\begin{cases} T = \frac{(W-S)}{W}, & \text{when } W \text{ is greater than } S \text{ and} \\ T = \frac{W-S}{S}, & \text{when } W \text{ is less than } S. \end{cases} \quad (2)$$

Where (T) denotes the trend, W the weighted mean concentration and (S) the concentration in the surface layer.

The variability of the contaminants was studied by calculating the specific range (R) using Equation 3.

$$R = \frac{(H-L)}{W} \quad (3)$$

Where, R is the specific range, H is the highest and L is the lowest observed concentrations in the profile, and W is the weighted mean.

2.5.2 Quantification of soil contamination level

Although several methods have been developed to measure status of heavy metal pollution, in this study geo-accumulation index, contaminant factor, enrichment factor representing the single group indices whereas multielement pollution load index (PLI) was employed from the total complex indices. Brief description of each index is provided in below:

2.5.3 Index of geo-accumulation

An index of geo-accumulation (*I_{geo}*) was used to determine metal contamination level in soil samples by comparing the current concentrations with background values by calculating using Equation 4 as described in Banat et al. (24),

$$I_{geo} = \log_2 \left[\frac{C_n}{1.5 B_n} \right] \quad (4)$$

where *C_i* is the measured concentration of the examined metal *i* in the soil sample, and *B_n* is the geochemical background concentration or reference value of the metal *i*. Factor 1.5 is used because of possible variations in background values for a given metal in the environment as well as very small anthropogenic influences. The geo-accumulation index (*I_{geo}*) was distinguished into six classes by Buccolieri (25) (Table 1).

2.5.4 Enrichment factor

An element enrichment factor (EF) was calculated to speculate on the origin of elements in the soil samples as described by Reimann and de Caritat, (2005). The formula used to calculate is in Equation 5.

TABLE 1 Classification of soil quality based on *I_{geo}* values.

Class	Values	Soil quality
0	$I_{geo} \leq 0$	Uncontaminated
1	$0 < I_{geo} \leq 1$	from uncontaminated to moderately contaminated
2	$1 < I_{geo} \leq 2$	moderately contaminated
3	$2 < I_{geo} \leq 3$	from moderately to strongly contaminated
4	$3 < I_{geo} \leq 4$	strongly contaminated
5	$4 < I_{geo} \leq 5$	from strongly to extremely contaminated
6	$I_{geo} > 5$	extremely contaminated

$$EF = \frac{\left(\frac{C_i}{C_{ie}}\right)_S}{\left(\frac{C_i}{C_{ie}}\right)_{RS}} \quad (5)$$

where C_i is the content of element i in the soil samples, and C_{ie} is content of immobile element in the soil sample. So $(C_i/C_{ie})_S$ is the heavy metal to immobile element ratio in the soil samples, and $(C_i/C_{ie})_{RS}$ is the heavy metal to immobile element ratio in the selected reference sample (26). The immobile element selected for this study is Fe (27). According to (28), five contamination categories were used to identify sources of contaminants. These are of the enrichment factor: $EF < 2$, depletion to mineral enrichment; $2 \leq EF < 5$, moderate enrichment; $5 \leq EF < 20$, significant enrichment; $20 \leq EF < 40$, very high enrichment; and $EF > 40$, extremely high enrichment.

2.5.5 Assessment of soil metals risk

Risk Index (RI) was used to assess the degree of heavy metal pollution in soils according to the toxicity of metals and the response of the environment (29). RI values for soil samples were computed stepwise, viz, the first step was the calculation of the risk quotient (Q) for each analysed metal that exceeded the limit risk values. In the second step, the RI was determined from the summation QERI as expressed in Equation 6.

$$\begin{cases} Q_{ERI} = \frac{A_{ci}}{R_{ci}} \\ RI = \sum Q_{ERI} \end{cases} \quad (6)$$

Where:

Aci: concentration of metal i in the soil sample,

Rci: reference (background) concentration of metal i ,

QERI: risk quotient for metal i , and

RI: Risk Index calculated as the sum of all QERI values.

The RI values were rated as low risk < 30 ; moderate: $30 < RI < 60$; considerable risk: $60 < RI < 120$; high risk: $> 120 < \text{very high risk}$.

2.5.6 Soil quality index calculations

To assess soil quality variations across horizons, SQI was computed using principal component analysis (PCA). Because numeric values of the soil indicators are on very different scales of magnitude and even on different units, standardization was employed to make sure that comparability across variables are possible (30). Principal component loadings of each soil type were used to derive the SQI using Equation 7.

$$SQI = \sum (\text{standardized variable} \times PC \text{ loading}) \quad (7)$$

2.6 Statistical data analyses

Statistical analyses were conducted to examine relationships among elemental concentrations and soil properties. An independent t-test was used to correlate the results of soil indices. Pearson's correlation coefficients were calculated to assess the strength and direction of these relationships, with statistical significance set at $p < 0.05$. A heatmap was generated in R using

the ggplot2 and reshape2 packages to visually represent the correlations. Furthermore, PCA was performed using the FactoMineR and factoextra packages in R to identify patterns and reduce data dimensionality. To ensure comparability across variables, the dataset was standardized using z-scale transformation prior to PCA.

3 Results and discussion

3.1 Statistical evaluation of metal contaminants in Acrisols and Ferralsols

The comparative analysis of nutrient and trace element concentrations in Acrisols and Ferralsols highlights distinct patterns of distribution, variability, and trends, which are reflective of their contrasting pedogenic processes (Table 2).

Acrisols exhibit a weighted average Al concentration of 11,626.4 mg/kg, with a negative trend ($T = -0.2$) and a narrow range ($R = 0.39$), indicating progressive leaching and depletion. In contrast, Ferralsols show a slightly lower Al concentration (10,110.61 mg/kg) but greater variability ($R = 0.57$) and a more pronounced negative trend ($T = -0.31$). Fe is the most abundant element in both soils, with Acrisols displaying a significantly higher concentration (115,130.8 mg/kg) than Ferralsols (63,223.63 mg/kg). However, the positive trend in Ferralsols ($T = 0.82$) suggests ongoing Fe enrichment, likely due to sesquioxide accumulation, whereas Acrisols exhibit a weaker trend ($T = 0.12$), indicating less translocation (31). The dominance of Fe and Al in these soils reflects intense tropical weathering, leading to Fe oxide accumulation and aluminosilicate formation. Zn is present in moderate amounts, while trace elements like As, Cd, and Co appear in lower concentrations. The similarity in weighted averages between Acrisols and Ferralsols suggests that both soils undergo comparable pedogenic processes, shaped by tropical climatic conditions and parent material influences.

Elemental distribution patterns reveal that highly symmetrical elements such as Al, Cd, Mo, and Ti exhibit low T and R values across both soils, indicating a uniform distribution. For instance, Cd in Acrisols has a T value of 0.17 and R of 0.50, whereas in Ferralsols, T remains at 0 and R at 1. Conversely, asymmetrical elements such as Fe, Ba, and Ni display higher T and R values, particularly in Ferralsols, signifying greater variability. Ba in Ferralsols ($T = 0.79$, $R = 1.25$) contrasts sharply with its lower values in Acrisols ($T = -0.06$, $R = 0.31$). Moderate symmetrical elements like Zn and As exhibit intermediate T and R values, suggesting localized variations in distribution. These patterns reflect stable pedogenic processes for some elements, while others indicate more dynamic redistribution through leaching and mineral dissolution (32).

Ferralsols contain significantly higher concentrations of Ba (450.65 mg/kg), Fe, Sr, and Cr, with Sr showing a highly significant difference ($p < 0.01$). Acrisols have higher concentrations of Zn (30.22 mg/kg), Cu, Mn, and Mo, with Mo and Zn showing very highly significant differences ($p < 0.001$). Acrisols also exhibit greater variability in Co (4.6 mg/kg, $T = -0.46$,

TABLE 2 Elemental concentrations and statistical comparison between Acrisols and Ferralsols: weighted averages, trends, range, t-Statistics, p-values, and significance.

Element	Acrisols			Ferralsols			T-statistic	P-value	Significance
	Weighted Average	Trend (T)	Range (R)	Weighted Average	Trend (T)	Range (R)			
Al	11626.4	−0.2	0.39	10110.61	−0.31	0.57	0.971	0.356	ns
As	8.31	−0.01	0.33	7.68	0.61	1.61	0.242	0.818	ns
Ba	58.85	−0.06	0.31	450.65	0.79	1.25	−3.368	0.020	*
Cd	0.02	0.17	0.5	0.01	0	1	1.732	0.114	ns
Co	4.6	−0.46	1.22	1.72	0.76	1.1	2.336	0.057	ns
Cr	121.37	−0.32	0.71	250.19	0.71	0.87	−2.543	0.042	*
Cu	25.72	−0.22	0.46	14.16	0.68	1	3.024	0.013	*
Fe	115130.8	0.12	0.45	63223.63	0.82	1	2.983	0.015	*
Hg	0.03	−0.21	0.67	0.03	0.66	1	0.000	1.000	ns
Mn	163.78	−0.4	1.05	31.54	0.16	1.04	3.648	0.013	*
Mo	2.27	−0.02	0.22	0.56	0.48	1.13	10.315	0.000	***
Ni	21.82	0.03	0.17	57.79	0.86	1.54	−1.976	0.105	ns
Pb	12.93	0.17	0.45	11.33	0.66	0.81	0.689	0.510	ns
Se	2.11	0.18	0.68	0.47	0.53	1.74	4.819	0.001	**
Sr	7.07	−0.2	0.48	112.21	0.68	1.15	−3.982	0.010	*
Ti	6461.21	−0.02	0.64	4603.48	0.15	0.5	1.855	0.102	ns
Zn	30.22	−0.02	0.26	3.93	0.85	2.53	9.666	0.000	***

*p < 0.05 (.).
**p < 0.01 (highly significant).
***p < 0.001 (very highly significant).
ns, not significant (p ≥ 0.05).

R = 1.22) compared to Ferralsols (1.72 mg/kg, T = 0.76, R = 1.1) The higher trace metal content in Ferralsols may be attributed to parent material differences, as soils derived from mafic crystalline rocks generally contain elevated trace metal concentrations. In sedimentary soils, trace metal levels are strongly influenced by sediment type (33).

While tropical rainforest conditions tend to homogenize soil mineralogy, mainly leaving quartz, kaolinite, gibbsite, goethite, and hematite, variations in trace metal concentrations can still be linked to parent rock composition (33, 34).

Based on the t-test, several elements show significant differences between Acrisols and Ferralsols. Ferralsols have significantly higher concentrations of Ba, Cr, and Sr (p < 0.05), while Acrisols contain significantly higher levels of Cu, Fe, Mn, Mo, Zn, and Se, with Mo, Zn, and Se showing highly significant differences (p < 0.01). Elements such as Al, As, Cd, Co, Hg, Ni, Pb, and Ti do not show significant variation between the two soil types (p > 0.05). These differences can be explained by the distinct mineralogical and geochemical characteristics of the soils, Ferralsols, often formed on mafic parent material, tend to accumulate Ba, Cr, and Sr due to their association with resistant minerals and specific geochemical weathering patterns (35). Meanwhile, Acrisols, which typically develop under more

intense weathering and leaching, can retain higher levels of trace metals such as Cu, Fe, Mn, Mo, Zn, and Se through strong adsorption to sesquioxides and organic matter (36). Elements showing no significant difference are likely more uniformly distributed in the parent material or have geochemical behaviors that lead to stable baseline concentrations across soil types.

3.2 Soil pollution hazard assessment using geo-accumulation indices

Some studies have been carried out to determine the long-term behavior of chemical elements in soils (37, 38) However, many questions remain in tropical soil about the mobility of trace metals, probably caused by the scarcity of long-term studies in these regions. The results presented in the previous section did not provide sufficient information on vertical viability. Here, the geochemical features along the soil profiles allow a much more accurate analysis. The comparison of elemental concentrations and geo-accumulation indices (Igeo) between Acrisols and Ferralsols highlights distinct patterns of natural enrichment and potential contamination across the two soil types (Table 3).

TABLE 3 Geo-accumulation (Igeo) index classes for potentially toxic elements in Acrisols and Ferralsols.

Eléments	Acrisols, ppm				Ferralsols, ppm				t-statistic	p-value	significance
	Igeomean	Igeomax	Igeomin	Soil quality	Igeomean	Igeomax	Igeomin	Soil quality			
<i>Al</i>	−3.22	−2.9	−3.44	uncontaminated	−3.42	−2.89	−3.62	Uncontaminated	0.460	0.672	ns
<i>As</i>	−0.38	−0.2	−0.71	uncontaminated	−0.49	0.5	−1.85	Uncontaminated	0.263	0.815	ns
<i>Ba</i>	−3.89	−3.66	−4.11	uncontaminated	−0.95	−0.41	−3.22	Uncontaminated	−2.71	0.108	ns
<i>Cd</i>	−4.71	−4.13	−4.71	uncontaminated	−5.71	−4.71	−5.71	Uncontaminated	2.23	0.106	ns
<i>Co</i>	−1.57	−0.69	−2.26	uncontaminated	−2.99	−2.56	−5.02	Uncontaminated	2.28	0.0995	ns
<i>Cr</i>	0.58	1.13	0.17	From uncontaminated to moderately contaminated	1.63	1.85	−0.14	Moderately contaminated	−0.707	0.535	ns
<i>Cu</i>	−0.54	−0.19	−0.83	uncontaminated	−1.41	−1	−3.03	Uncontaminated	2.00	0.164	ns
<i>Fe</i>	1.56	1.89	1.24	Moderately contaminated	0.7	0.94	−1.77	From uncontaminated to moderately contaminated	1.81	0.201	ns
<i>Hg</i>	−2.17	−1.75	−2.75	uncontaminated	−2.17	−1.75	−3.75	Uncontaminated	0.494	0.657	ns
<i>Mn</i>	−2.33	−1.6	−3.06	uncontaminated	−4.71	−3.99	−5.44	Uncontaminated	4.01	0.016	*
<i>Mo</i>	0.64	0.73	0.41	From uncontaminated to moderately contaminate	−1.38	−0.66	−2.33	Uncontaminated	4.16	0.0467	*
<i>Ni</i>	−0.39	−0.26	−0.51	uncontaminated	1.02	1.76	−1.84	Moderately contaminated	−0.636	0.589	ns
<i>Pb</i>	−1.14	−0.79	−1.42	uncontaminated	−1.33	−1.13	−2.91	Uncontaminated	1.14	0.355	ns
<i>Se</i>	1.85	2.27	1.25	From moderately to strongly contaminated	−0.32	0.77	−1.7	From uncontaminated to moderately contaminated	2.85	0.0746	ns
<i>Sr</i>	−5.67	−5.34	−6.05	Uncontaminated	−1.68	−1.13	−3.31	Uncontaminated	−5.32	0.0226	*
<i>Ti</i>	0.57	1.14	0.31	Moderately contaminated	0.08	0.37	−0.4	From uncontaminated to moderately contaminated	1.98	0.12	ns
<i>Zn</i>	−1.57	−1.45	−1.85	uncontaminated	−4.52	−2.9	−5.41	Uncontaminated	3.57	0.0654	ns

ns = not statistically significant (p > 0.05); * = statistically significant (p ≤ 0.05).

The contrasting contamination profiles observed between Acrisols and Ferralsols are shaped by both their inherent mineralogical composition and anthropogenic influences. Acrisols generally exhibit higher contamination levels for most trace elements, as reflected by their less negative or even positive Igeo values, suggesting significant deviation from natural geochemical baselines. For instance, (Al) in Acrisols has a weighted mean concentration of 11,626.4 ppm with an Igeo mean of (−3.22), while (Cd), although present at a very low concentration of 0.02 ppm, has a higher Igeo mean (−4.71) than in Ferralsols, indicating relatively greater enrichment. These patterns likely stem from the acidic, siliciclastic nature of Acrisols' parent materials, such as granite or gneiss which typically have lower native metal contents and reduced capacity for trace metal retention.

In contrast, Ferralsols tend to display more negative Igeo values, indicative of lower contamination levels and concentrations closer to natural background thresholds. However, certain exceptions are notable. (Cr) in Ferralsols reaches a mean of 250.19 ppm (Igeo = 1.63), surpassing levels found in Acrisols (121.37 ppm; Igeo = 0.58), and nickel (Ni) also shows substantial enrichment (57.79 ppm; Igeo = 1.02 vs. 21.82 ppm; Igeo = −0.39 in Acrisols). These enrichments may be attributed to the mineralogical origin of Ferralsols, which often develop from mafic or ultramafic rocks such as basalt or amphibolite. Such parent materials contain Fe and Mn-oxides like goethite, hematite, and lithiophorite, which have high sorption capacities and can strongly retain trace metals (39).

Beyond lithological factors, anthropogenic activities also contribute to differential contamination. Agricultural practices, particularly fertilizer and pesticide application are known to introduce metals such as Zn, Cu, and Mo into the soil (40, 41). This may explain the comparatively elevated Mo concentrations in Acrisols (2.25 ppm; Igeo = −1.52). Additionally, small scale mining and industrial emissions, common in parts of Western Ghana, further exacerbate contamination, particularly for elements like Pb, Cd, and Hg. Acrisols, being more weathered and having lower oxide buffering capacities, may be especially vulnerable to these inputs (42).

T-test analyses confirm statistically significant differences between soil types for Mn ($p = 0.016$), Mo ($p = 0.0467$), and Sr ($p = 0.0226$). Mn and Sr are more abundant in Ferralsols, consistent with their mineral origin and higher retention capacity, while Mo enrichment in Acrisols likely reflects anthropogenic influence.

Although t-test analyses revealed no statistically significant differences ($p > 0.05$) for most elements between Acrisols and Ferralsols (e.g., Al, As, Cd, Co, Cu, Fe, Fe, Hg, Ni, Pb, Se, Ti), this suggests that the two soil types share similar geochemical backgrounds and contamination levels for these trace elements. Consequently, variability in elemental concentrations is likely influenced more by localized environmental factors or soil profile heterogeneity than by soil classification per se. These findings emphasize the need for integrated soil management approaches that consider a suite of physicochemical properties alongside site-specific conditions to accurately assess contamination risks and support sustainable land-use practices in tropical regions.

3.3 Sources of potentially toxic elements

EF and QRET were used to assess the potential sources and ecological risks of elements in Acrisols and Ferralsols (32). As shown in Table 4, all EF values for both soil types are below 2, classifying them within the “depletion to minimal enrichment” category as defined by (28). This indicates that the elements examined are primarily of natural origin, with no significant anthropogenic contributions.

Selenium (Se) exhibits EF values of 1.33 in Acrisols and 0.85 in Ferralsols, both consistent with natural background levels. Although Se can be influenced by environmental factors such as wet atmospheric deposition (43–45), the current data do not support anthropogenic enrichment in the study area (46). Further highlight that Se concentrations tend to be higher in regions receiving over 700 mm of annual rainfall, which may explain some of the observed variability.

Despite the uniformly low EF values, QRET analysis highlights Se (QRET = 5.41), Mo (2.34), and Cr (2.25) as predominant contributors to ecological risk in Acrisols, while Cr (4.63) and Ni (3.04) lead risk scores in Ferralsols. These elevated QRET values reflect inherent geochemical characteristics rather than external contamination. Cr and Ni enrichments in Ferralsols are primarily lithogenic: these soils form on mafic to ultramafic parent materials (e.g. peridotite, serpentinite) rich in Fe–Mg minerals and iron oxides, which naturally concentrate Cr and Ni through weathering and oxide formation (47). Iron oxides such as goethite and hematite possess high sorptive capacity, immobilizing trace metals even under tropical conditions. Se and Mo accumulation in Acrisols, though also tied to parent geology, may be further enhanced by agricultural inputs, particularly phosphate fertilizers known to supply Mo and Se to soils, where their ecotoxicological weight elevates risk potential despite low enrichment factors (48).

Despite their classification as geogenic based on EF values, potential anthropogenic contributions, especially from agriculture or nearby mining activities, cannot be fully excluded and may contribute locally to the observed elemental load. The overall Risk Index (RI) indicates a low ecological risk for both soil types, with Acrisols (RI = 22.66) slightly higher than Ferralsols (RI = 17.76). This variation is mainly attributed to naturally elevated concentrations of certain elements rather than anthropogenic contamination. These results highlight the necessity of differentiating between inherent geochemical background levels and pollution sources when assessing soil quality and guiding land management strategies.

Although EF values suggest predominantly geogenic origins for Cr, Ni, and Pb, it remains essential to compare these concentrations against established environmental and toxicological benchmarks. In Ferralsols, the Cr concentration (250.19 mg/kg) exceeds the U.S. EPA residential soil screening level of 100 mg/kg, while Ni (57.79 mg/kg) slightly surpasses the recommended threshold of 50 mg/kg (49). Pb concentrations (maximum 35.33 mg/kg) remain well below the threshold of 400 mg/kg for residential soils (49) and the FAO/WHO permissible limit of 100 mg/kg for agricultural

TABLE 4 Classification and comparative analysis of elemental enrichment factors (EF) and quality risk evaluation (QRET) in Acrisols and Ferralsols.

Element	EF			Class	QRET	
	Acrisols	Class	Ferralsols		Acrisols	Ferralsols
Al	0.04	N	0.077	N	0.16	0.14
As	0.26	N	0.588	N	1.15	1.07
Ba	0.02	N	0.291	N	0.1	0.78
Cd	0.01	N	0.020	N	0.06	0.03
Co	0.11	N	0.073	N	0.51	0.19
Cr	0.51	N	1.933	N	2.25	4.63
Cu	0.24	N	0.226	N	1.03	0.57
Fe	1.00	N	1.000	N	4.43	2.43
Hg	0.08	N	0.143	N	0.33	0.33
Mn	0.07	N	0.031	N	0.3	0.06
Mo	0.54	N	0.300	N	2.34	0.58
Ni	0.27	N	1.053	N	1.15	3.04
Pb	0.15	N	0.259	N	0.68	0.6
Se	1.33	N	0.85	N	5.41	1.21
Sr	0.01	N	0.179	N	0.03	0.47
Ti	0.54	N	0.715	N	2.23	1.59
Zn	0.12	N	0.033	N	0.5	0.07
					RI=22.66	17.76

soils (50). These findings suggest a moderate ecological concern for Cr and Ni in Ferralsols, while Pb poses minimal risk. As such, localized geochemical monitoring remains advisable to support sustainable land management.

3.4 Potentially toxic elements as affected by the Soil quality index

To ensure a reliable Soil Quality Index (SQI) for Acrisols and Ferralsols under oil palm and cocoa cultivation, multiple soil parameters reflecting fertility, structure, and nutrient status were evaluated. These included pH, exchangeable cations (Ca^{2+} , Mg^{2+} , K^{+} , Na^{+}), organic carbon, and soil texture. Soils exhibited acidic pH values (4.8–5.9), consistent with Dabin’s classification of low-fertility soils (pH 4.75–5.1) (51) (Table 5). Exchangeable Ca^{2+} was the dominant cation but declined with depth due to leaching, while Mg^{2+} , K^{+} , and Na^{+} remained relatively stable. Organic carbon concentrations were highest in the surface layers and decreased sharply with depth, reflecting limited organic matter inputs. Texturally, Acrisols ranged from sandy clay to sandy clay loam, whereas Ferralsols exhibited greater variation, including loam and sandy loam. In both soils, clay content increased with depth, indicating processes of clay illuviation.

SQI was computed using 13 selected soil attributes (Table 5). For Ferralsols, the first principal component (PC1), which accounted for the highest variance (55.66%) (Figure 2A), was used in the SQI calculation. In Acrisols, both PC1 (47.29%) and PC2 (39.63%) were included, as together they explained the majority of variability in the dataset (Table 6, Figure 2B).

In Ferralsols, the surface horizon (0–16 cm) exhibited the lowest SQI (–2.65), likely due to leaching and nutrient depletion. The middle horizons (35–80 cm and 80–120 cm) showed improved SQI values (–0.63 and 0.21, respectively), reflecting moderate nutrient retention, while the deeper horizon (120–200 cm) has the highest SQI value (1.78). In Acrisols, the top horizon (1–50 cm) had the lowest SQI (–2.84), suggesting severe nutrient leaching. However, the middle horizons (50–90 cm and 90–120 cm) displayed the higher SQI values (–1.17 and 0.11, respectively), indicating optimal nutrient retention and soil quality. The deepest horizon (120–180 cm) exhibited a higher SQI (3.89), consistent with the ferrasols pedon, showcasing a better fertility at greater depths.

In Ferralsols, SQI values range from –2.65 to 1.78, with mostly negative values indicating poor soil quality due to low organic carbon (OC), and clay content. This low organic carbon content can be attributed to the low amount of organic materials applied to the soil and to the complete removal of the biomass in the field, as it was observed by Pansu (52). The increase at 80–120 cm (SQI = 1.78) can be

TABLE 5 Chemical and granulometric properties of the studied soils with corresponding SQI for each horizon.

Pedon	Depth (cm)	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	pH (H ₂ O)	pH (KCl)	OC	Clay	Sand	Silt	Textural class	Al ₂ O ₃	Fe ₂ O ₃	EC	SQI
		Cmol(c) kg ⁻¹ soil						%					%		µScm ⁻¹	
<i>Ferralsols</i>	0–16	5.1	1.2	2.1	0.9	5.1	4.4	0.76	2	82	16	Loamy sand	4.99	1.58	104	–2.65
	16–35	3.7	0.9	0.9	0.9	5.1	4.5	0.95	4	66	30	Sandy loam	10.74	5.11	108	–0.63
	35–80	3.8	1.3	0.8	0.9	4.9	4.5	1.05	26	52	22	Sandy clay loam	15.22	7.41	121	0.21
	80–120	3.4	1.2	0.5	0.8	5.9	4.7	1.06	24	46	30	Clay loam	14.29	10.11	101	1.78
	120–200	2.9	0.9	0.5	1.1	5.1	4.6	0.05	20	38	42	Loam	19.15	8.17	115	1.28
<i>Acrisols</i>	1–50	4.4	2.2	0.6	0.9	5.6	4.3	2.40	18	70	12	Sandy loam	19.56	15.16	81	–2.84
	50–90	3.5	2.1	0.5	0.8	5.1	4.2	2.40	40	46	14	Sandy clay	24.27	17.75	116	–1.17
	90–120	3.1	2.7	0.5	0.9	5.2	4.5	2.41	38	48	14	Sandy clay	19.74	15.23	112	0.11
	120–180	2.9	3.6	0.6	0.9	4.8	4.5	2.26	22	62	16	Sandy clay loam	19.75	24.8	117	3.89

Soil indicators with the strongest correlations in PCA, along with those showing the greatest variation in the descriptive analysis, were selected for SQI construction (Figure 2). The variance explained by each PCA component served as the basis for determining the weighting factors of each indicator. Thus, the assigned weights for selected indicators reflected the variance explained by their respective components (Table 6).

linked to improved cation retention at this depth, but the overall trend suggests nutrient depletion due to intense weathering and leaching.

Acrisols, in contrast, exhibit a wider SQI range (–2.84 to 3.89), with the surface horizon showing the lowest value (–2.84), likely due to high leaching, acidic pH, and relatively lower clay content. However, deeper layers (50–120 cm) show positive SQI values, which can be attributed to higher Mg²⁺ and clay content, enhancing nutrient retention and soil structure (53). The deeper horizon (120–180 cm) records a very positive SQI (3.89), possibly due to increased biological activity. Given that the soils of tropical regions are highly degraded, the quantities of exchangeable cations are limiting factors in agricultural productivity (54). As a result of this, the acidification of soil upper layers is observed (55). On the other hand, Lal & Stewart (56) suggest that continuous and intensive cultivation practices can explain the deterioration of the soil aggregates, combined with the low return of plant biomass to the soil in cultivated land. These SQI trends align with

the advanced weathering and pedogenic characteristics of tropical soils, where surface horizons are often nutrient-depleted due to leaching, while subsurface horizons may exhibit some degree of nutrient accumulation, particularly in Acrisols.

A t-test was performed to assess whether the Soil Quality Index (SQI) differs significantly between Ferralsols and Acrisols. The mean SQI values were nearly identical for Ferralsols (–0.0020) and Acrisols (–0.0025), with variances of 3.07 and 8.19, respectively. The t-statistics (–0.0003) and degrees of freedom (4.75) indicate a reliable estimate, while the high p-value (0.9998) and the 95% confidence interval ([–4.26, 4.26]), which includes zero; confirm there is no statistically significant difference in SQI between the two soil types. Thus, any observed variation is likely due to chance.

3.5 Correlation of soil properties and potentially toxic elements

Principal component analysis (PCA) provides a clear differentiation between Acrisols and Ferralsols based on their elemental compositions and soil properties (Figure 3). The first two principal components (PC1 and PC2) represent 70.78% of the total variance, with PC1 accounting for 45.15% and PC2 contributing 25.63%. This spatial distinction suggests that the two soil types have distinct compositional profiles.

For Acrisols, the clustering of elements such as Ti, Co, Cd, Hg, Pb, Fe, Mn, Zn, Mo, Se, and total C, H, and N within the ellipse indicates that these parameters strongly contribute to their characterization. The similar lengths of their arrows suggest comparable levels of influence on PC1 and PC2. In contrast, Ferralsols are characterized by elements like Sr, Ba, Ti, Ni, Cr, and soil properties such as pH (KCl), conductivity, and CEC. The arrows for Sr, Ba, and pH (KCl) are the longest in this cluster,

TABLE 6 Principal component analysis (PCA) results for Ferralsols and Acrisols.

Soil Type	PC1	PC2	PC3	PC4
Ferralsols				
Eigenvalue	7.24	3.29	1.87	0.60
Proportion of variance	55.66%	25.30%	14.42%	4.62%
Cumulative variance	55.66%	80.96%	95.38%	100.00%
Acrisols				
Eigenvalue	6.14724	5.15234	1.70042	–
Proportion of variance	47.29%	39.63%	13.08%	–
Cumulative variance	47.29%	86.92%	100.00%	–

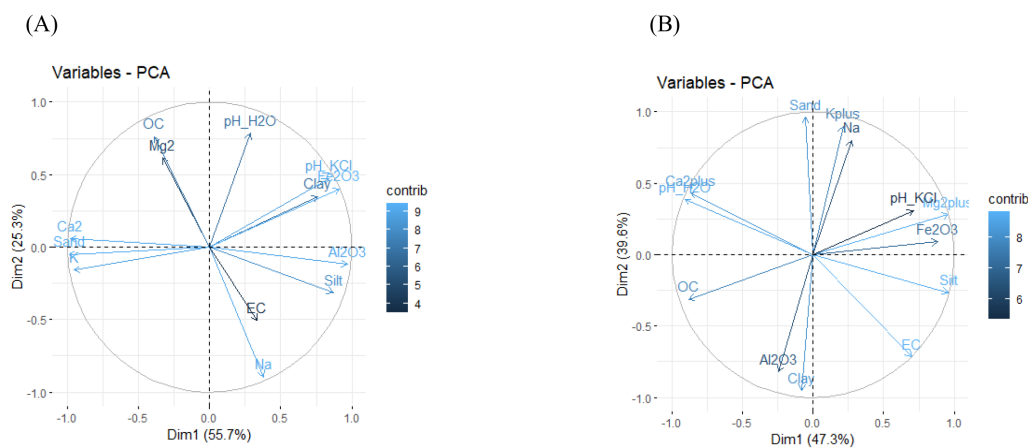


FIGURE 2

PCA of Ferralsols (A) and Acrisols (B), with the dimensions expressed as percentages used for SQI calculations.

highlighting their dominant role in defining the variability within Ferralsols. The large spread of the Ferralsols ellipse along the x-axis implies greater variability in their elemental and physicochemical composition compared to the Acrisols. The unique positioning and long upward arrow of Al distinguishes it as a critical variable contributing to the separation along PC2. This implies that Al concentrations vary significantly between the two soil types and play a pivotal role in distinguishing their profiles.

The differentiation highlighted by the PCA between the soil types reflects the distinct geochemical and pedological processes influenced by their environmental conditions and parent materials. For Acrisols, the enrichment in trace elements like Ti, Co, Cd, Hg, Pb, Fe, Mn, Zn, Mo, and Se can be attributed to the weathering of parent rocks rich in these trace elements, limited leaching due to relatively lower pH or water movement, or anthropogenic inputs.

The clustering of organic components, including total carbon C, H, and N, could indicate higher organic matter content or organic-mineral associations typical of Acrisols, which often form in areas with moderate weathering and vegetation cover.

In contrast, Ferralsols, characterized by higher variability in properties like Sr, Ba, pH (KCl), conductivity, and CEC, reflect their formation under intense weathering conditions common in tropical regions. These soils are often derived from deeply weathered parent material such as basalt or granites, leading to the accumulation of resistant minerals like aluminum oxides and iron oxides. The dominance of Ba and Sr may suggest the retention of these elements in secondary minerals or the influence of specific rock types, while the strong influence of pH (KCl) and CEC reflects the soil's physicochemical properties influenced by clay mineralogy, organic matter interactions, and nutrient exchange dynamics. The

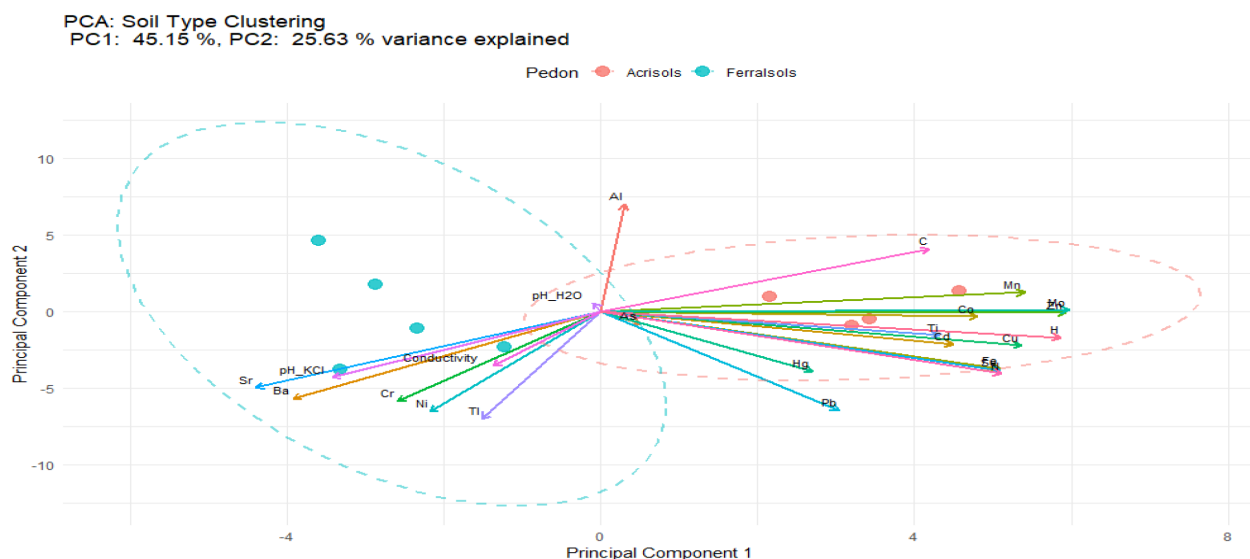


FIGURE 3

Factor map illustrating soil pedon clusters and associated soil parameter.

prominent role of Al, as indicated by its distinct and long arrow, suggests that Al may be a significant marker of Ferralsols formation, likely due to the dominance of kaolinite and gibbsite, which are common in these soils (57).

3.6 Pearson correlation analysis

The Pearson correlation matrix between elements, indices and soil attributes is presented in (Figure 4), in the form of a matrix heatmap. The tricolor heatmap shows dark red boxes with strong positive, dark blue boxes with strong negative, and white boxes with intermediate correlation.

The revised Pearson correlation heatmap highlights significant associations between elemental concentrations and key soil physicochemical properties, offering insights into the mechanisms controlling trace metal behavior in Acrisols and Ferralsols. Strong positive correlations were observed between Fe_2O_3 and several trace metals, including Cd ($r = 0.71$), Co ($r = 0.53$), Cu ($r = 0.76$), Pb ($r = 0.74$), Se ($r = 0.91$), and Zn ($r = 0.84$), underscoring the critical role of iron oxides in the adsorption and immobilization of potentially toxic elements. These associations reflect the high affinity of iron oxides for metal binding, which helps reduce metal mobility and bioavailability in tropical soils.

Similarly, Al_2O_3 displayed strong correlations with metals such as Cd ($r = 0.62$), Co ($r = 0.57$), Cu ($r = 0.81$), Fe ($r = 0.83$), Hg ($r = 0.71$), Mo ($r = 0.69$), and Zn ($r = 0.76$), suggesting that aluminum oxides also contribute significantly to trace element retention. The high surface area and reactive hydroxyl groups of Al_2O_3 likely facilitate the formation of inner-sphere complexes with metal ions, enhancing their sorption and stabilization.

Organic carbon (OC) showed strong correlations with Fe_2O_3 ($r = 0.79$), Al_2O_3 ($r = 0.78$), and Mg^{2+} ($r = 0.80$), indicating the

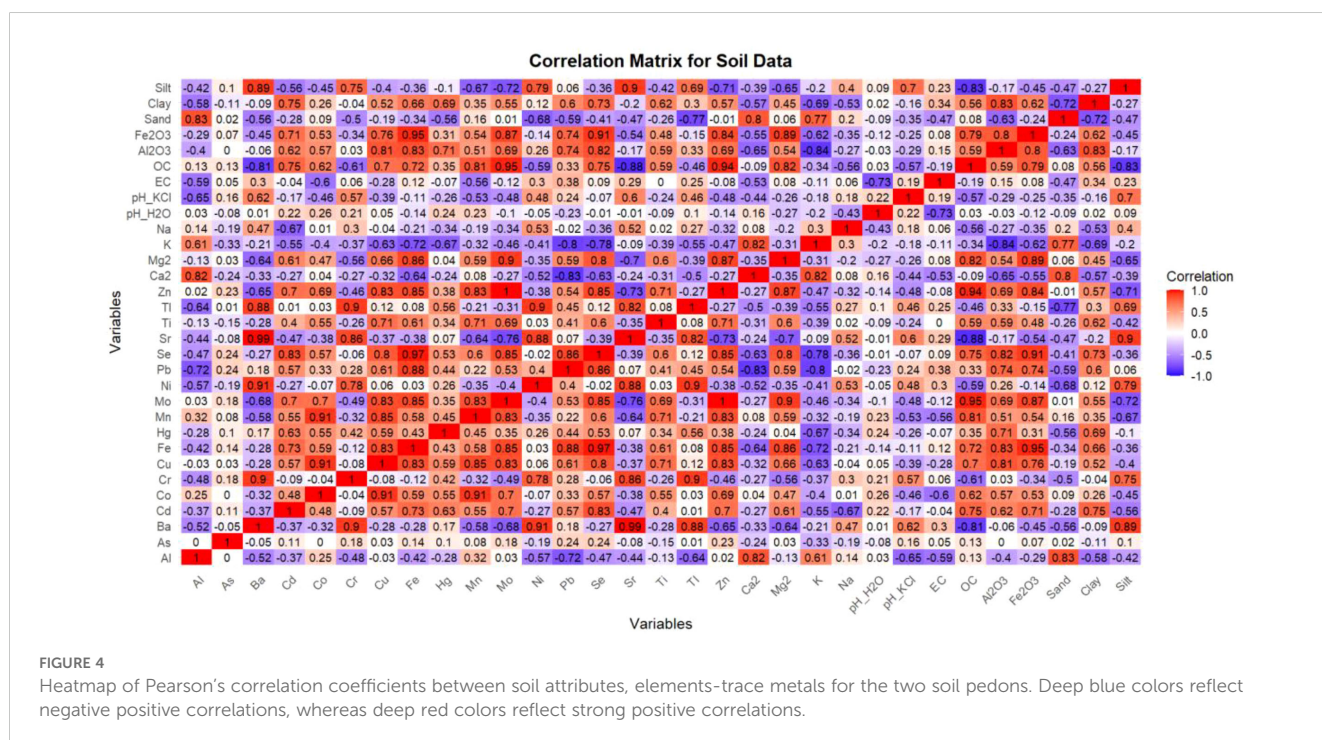
synergistic role of soil organic matter and oxides in metal complexation. These interactions may promote organo-mineral associations that further stabilize trace metals. Additionally, clay content correlated moderately with both Fe_2O_3 ($r = 0.62$) and OC ($r = 0.60$), suggesting that fine-textured soils enhance the retention capacity for trace elements due to increased surface area and cation exchange potential.

Exchangeable bases such as Ca^{2+} and Mg^{2+} also demonstrated notable correlations with elements including Zn, Cu, Se, and K, reflecting their involvement in metal mobility and nutrient dynamics. Ca^{2+} , in particular, showed strong positive correlations with Al ($r = 0.82$), K ($r = 0.82$), and sand content ($r = 0.80$), suggesting its role in ion exchange and soil structural processes.

Overall, the correlation analysis underscores that trace element distribution in these soils is predominantly governed by intrinsic factors such as oxide content, organic matter, and texture, rather than contamination indices. These findings reinforce the need to assess geochemical interactions using independent variables for more robust interpretations.

4 Conclusion

This study presents a detailed comparative analysis of the geochemical behavior, contamination potential, and soil quality of Acrisols and Ferralsols within a tropical environment. Distinct elemental distribution patterns were identified, with Ferralsols exhibiting elevated concentrations of Ba, Zn, Cu, and Fe, accompanied by lower (SQI) values in surface horizons (-2.65 to 1.78), likely reflecting enhanced leaching and organic matter depletion. Conversely, Acrisols demonstrated higher nutrient retention, particularly in subsurface horizons (SQI: -2.84 to 3.89), and showed moderate enrichment of elements such as Se, Mo, Fe,



and Ti. Pearson correlation analysis, revealed significant positive relationships between heavy metal concentrations and soil physicochemical properties, including organic carbon, clay content, (Al_2O_3), and (Fe_2O_3). These correlations confirm the pivotal role of mineralogy and soil texture in modulating metal mobility and retention. The evidence indicates that Ferralsols are more susceptible to nutrient depletion and potential quality degradation due to their susceptibility to intense weathering and leaching, despite their higher oxide content, which influences metal retention. In contrast, Acrisols demonstrate greater resilience through improved nutrient conservation and buffering capacity but may be prone to moderate accumulation of specific trace elements. From a land management perspective, these findings suggest that Acrisols possess a comparatively higher agricultural sustainability potential, contingent upon regular monitoring of trace metal accumulation, while Ferralsols necessitate targeted soil conservation measures, including organic amendments and erosion control. Tailored management strategies that consider these soil-specific geochemical dynamics are essential to optimize crop productivity and minimize ecological risks in tropical agroecosystems.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MM: Validation, Methodology, Formal Analysis, Data curation, Writing – review & editing, Conceptualization, Software, Writing – original draft, Investigation. AB: Validation, Supervision, Writing – review & editing. FK: Writing – review & editing, Supervision, Resources, Project administration, Validation.

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