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Distribution and accumulation of trace metals in cultivated Lithomorphic Vertisols of Kaele Far North Cameroon

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Abstract
Lithomorphic Vertisols of Kaélé (Far North Cameroon) are intensively cultivated during the dry season for onion and sorghum production. This study aimed to assess the distribution patterns and controlling factors of trace metal elements (TME) in cultivated Vertisol profiles developed on granite and gneiss. Four soil profiles were described according to the World Reference Base (WRB, 2022), and samples were collected from each master horizon (A–B–C) for physicochemical and geochemical analyses. The soils are clayey to sandy clay loam, moderately to strongly alkaline (pH 6.75–9.70), with moderate to high cation exchange capacity (14.40–39.84 cmol kg^{-1}). Trace metal concentrations followed the order: Ba > Sr > Zn > Cu > Cr > Ni > Pb > Cd. Barium exhibited the highest concentrations (30.42–426.87 mg kg^{-1}). Pearson correlation analysis revealed strong positive relationships between Ba and Ni ($r = 0.95$), Ba and Cu ($r = 0.87$), and Ba and Cr ($r = 0.85$), suggesting similar geochemical behavior. Principal Component Analysis (PCA) indicated that trace metal distribution is mainly controlled by parent material and soil physicochemical properties (clay content, CEC, pH). The results suggest that lithology and soil characteristics play a major role in controlling trace metal distribution in these Vertisols, while anthropogenic influence appears limited. These findings provide baseline data for sustainable soil management in the Sudano-Sahelian region.

Keywords*: Trace metal elements, Lithomorphic vertisols, agricultural activities, Kaele, Far North Cameroon*

Introduction

Trace metal elements (TMEs) are naturally occurring components of soils, derived primarily from the weathering of parent materials and pedogenic processes. They include both essential micronutrients such as Fe, Mn, Cu, and Zn, and potentially toxic elements such as Pb, Cd, Cr, and Ni when present at elevated concentrations. Their distribution in soils is controlled by complex interactions among lithology, mineralogy, climate, soil texture, organic matter content, and redox conditions. In tropical and semi-arid environments, trace metal behavior is strongly influenced by intense weathering processes, seasonal moisture fluctuations, and clay mineral transformations. These factors regulate their mobility, retention, and potential bioavailability. Vertisols are clay-rich soils characterized by high shrink–swell capacity, deep cracking during dry seasons, and strong structural dynamics (Massoura et al., 2006; Yaboki et al., 2021; Gouban Hamadjida et al., 2022). Their mineralogical composition, often dominated by smectites, provides significant adsorption capacity for trace metals (Aminatou Amraou et al., 2023).

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However, seasonal alternation between wet and dry conditions may modify redox potential, influence metal solubility, and redistribute elements within soil profiles. The vertical distribution of trace metals within soil horizons (A–B–C) can reflect both pedogenic differentiation and lithological inheritance (Senesi et al., 1999; Yaboki et al., 2021). Understanding these distribution patterns is essential for distinguishing between natural geogenic enrichment and anthropogenic inputs (Tipping et al., 2006; Traoré et al., 2015). Although many trace metals are naturally present in soils, their accumulation beyond threshold values may pose ecological and human health risks (Salvarredy-Aranguren et al., 2008). In agricultural systems, long-term cultivation, fertilizer application, irrigation practices, and erosion processes may alter trace metal dynamics (Wentao et al., 2012; Tudi et al., 2024; Tiki et al., 2025). In semi-arid regions such as northern Cameroon, increasing agricultural pressure combined with climate variability may modify soil chemical properties and influence trace metal behavior. However, data regarding the distribution and controlling factors of trace metals in cultivated Vertisols of this region remain limited. The Far North region of Cameroon is characterized by lithomorphic Vertisols developed on granitic, metamorphic, and volcanic formations. These soils support intensive cultivation and constitute a major agricultural resource (Basga et al., 2020). Despite their importance, little information exists concerning the vertical distribution of trace metals and the factors controlling their variability. Therefore, the objective of this study was to assess the distribution of trace metal elements in cultivated Lithomorphic Vertisols of Kaélé and to identify the main soil properties influencing their variability.

Materials and Methods

Study area

The study was conducted in the Kaélé area, Far North Region of Cameroon. The climate is Sudano-Sahelian, characterized by two distinct seasons: a rainy season extending from June to September, a dry season from October to May (Suchel, 1987). Mean annual rainfall ranges between approximately 700 and 900 mm, with high interannual variability (L'Hote, 2000). The geology of the area is heterogeneous and includes granitic, metamorphic, and volcanic formations. These lithological units are spatially distributed in distinct zones across the study area (Fig. 1). The soils investigated are lithomorphic Vertisols developed on these different parent materials (Nguetnkam et al., 2008).

Experimental design and soil sampling

Four cultivated sites were selected; each located in a different village: DJ: Djidoma - DR: Dramé - BE: Berkédé - NGA: Nord Garey.

At each site, one representative cultivated field of approximately 0.5 ha was selected. In each field, one soil profile was excavated to the parent material. Soil samples were collected by genetic horizons and later grouped into master horizons (A, B, C) for interpretation purposes.

Laboratory analysis

Soil samples were air-dried, sieved (<2 mm), and analyzed for: pH - particle size distribution - organic carbon - soil organic matter (calculated using a single conversion factor of 1.724) - Trace metal concentrations (Fe, Mn, Cu, Zn, Pb, Cd, Cr, Ni) (Runich and Gao,2003).

Particle size distribution was obtained using the Robinson pipette method in accordance with NEN5357 and ISO/DIS 11277. The content in organic matter was calculated by multiplying the OC values with the factor 1.724 (Wakley and Black, 1934). The CEC and exchangeable bases were determined according to the method of Metson, 1956, based on the saturation of the soil by ammonia ions (NH_4^+). This method made it possible to characterize the "soil" reservoir in exchangeable cation and to calculate possible basic amendment inputs. The ICP-AES (Inductive Plasma Atomic Emission Spectrometry) methods (IAO-100 and IAC-100) are designed for the analysis of major and trace elements in non-mineralized geological samples. The trace elements contents in rock samples were obtained by performing the XRF methods (XRF-T02, XRF-T03, XRF-T04, and XRF-W01).

Statistical analysis

Pearson correlation analysis was performed to assess relationships between trace metals and soil physicochemical properties. Principal Component Analysis (PCA) was applied to identify the soil variables that most strongly differentiate the sites. PCA was not used to directly determine the sources of trace metals, but rather to explore patterns of association among variables. The data were analyses statistically using Microsoft Excel 2016 and Xlstat 2019 V21.3. Trace metal elements levels in samples were examined through descriptive statistics (mean, standard deviation, minimum and maximum values). Person's correlation with statistical significance set at a p-value < 0.05, was conducted to segregate the most significant variables.

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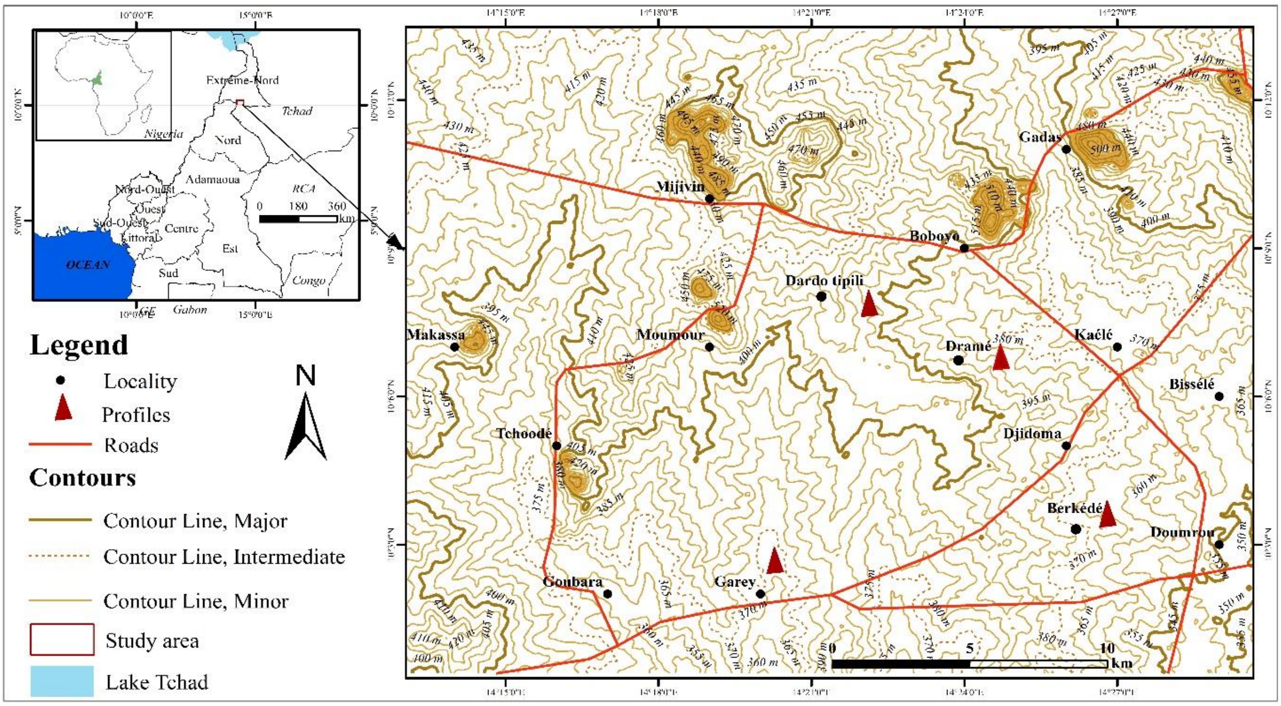

Figure 1. *Location of the study area*

Results and Discussion

Soil morphology description and classification

The morphological description shows that, the profiles of the Vertisols in the study area are of A-B-C type (Aydinalp, 2010) (Fig. 2). Only the NGA profile is formed on metamorphic material (gneiss); the three others (DJ, DR and BE) are formed from igneous material (granite).

The DJ profile was developed on granite. From the top to the bottom, the following horizons were noted:

• 0-80 cm: Ap horizon, yellow (10YR8/8); sandy clay loam, angular blocky, slightly moist, very few to few mineral concentrations, many roots, very common mottles, low and common porosity, many clay mineral (coating), common biological activity (termites, artefacts, burrows, insects …), calcareous nodules; presence of slickensides; gradual boundary with the underlying horizon.

• 80-130 cm: Bfe horizon, grayish brown (10YR5/2); clay loam; common mottles; hard and soft; angular blocky; slightly moist; high porosity; few biological activities; calcareous nodules; presence of slickensides; gradual and smooth boundary with the underlying horizon.

• 130-160 cm: C horizon, dark gray (10YR4/1); clay loam; angular blocky; hard; few coatings; low porosity; common and distinct mottles, few coating, calcareous nodules; slickensides; few biological activity, Few/distinct clay minerals and sesquioxide; clear boundary whith the parent material.

• >160: R (parent material).

The DJ profile described, is classified as Duric cromic vertisol (grumic, hypereutric, mollic).

The DR profile was developed on granite. From the top to the bottom, the following horizons were noted:

• 0-30 cm: Ap horizon, dark gray (7.5YR4/1); clay loam, angular to subangular blocky, slightly moist, many roots, common mottles, medium porosity, many artefacts, gradual boundary with the underlying horizon.

• 30-60 cm: BtCa horizon, light brownish gray (10YR6/2); sandy clay; few mottles; hard and soft; subangular blocky; slightly moist; few coatings; high porosity; presence of calcareous nodules; few biological activities; Clear and smooth boundary with the underlying horizon.

• 60-160 cm: C horizon, light reddish grey (2.5YR7/1); sandy loam; few and distinct mottles; few coatings; biological activity, abrupt boundary.

• >160 cm: R, Parent material (granite).

The DR profile was classified as Duric cromic vertisol (grumic, hypereutric, mollic).

The BE profile was developed on granite. From the top to the bottom, the following horizons were noted:

• 0-40 cm: Ap horizon; dark gray (7.5YR4/2); clay loam; very few mottles; hard; firm; sligly sticky; angular blocky; few coatings; many roots; common biological

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activities; gradual boundary with the underlying horizon.

• 40 – 60 cm: Bcw horizon, sandy clay loam; grayish brown (10YR5/2); common mottles; hard and soft; subangular blocky; slightly moist; high porosity; common biological activities (termites, burrows, artefacts, other insects); many clays mineral and sesquioxide; presence of slickensides; hight porosity; clear and smooth boundary with the underlying horizon.

• 60 – 160 cm: Btg horizon; sandy clay; (10YR5/2); common distinct and medium mottles; angular blocky; hard; sticky; firm; fines roots, few biological activities; presence of slickenside; few clays mineral; low porosity; gradual and smooth boundary with the underlying horizon.

• 160 -220 cm: C horizon; sandy clay; pale red (2.5YR7/2); very few coarse fragments; common, fine and distinct mottles; subangular blocky; low porosity; few biological activities; abrupt boundary with the parent material.

• > 220 cm: R (parent material).

The described Vertisol (BE profile) is classified as Duric cromic vertisol (grumic, hypereutric, mollic).

The NGA profile was developed on gneiss. It is 305 cm thick, poorly drained and exhibit desiccations cracks at surface during dry season. 5 horizons are observed and from top to bottom, the following organization was described:

• 0-70 cm: Ap horizon, grey 5YR6/1, clay loam, strong, hard, angular blocky, slickensides, dry, fine roots, very few and fine mottles, very few coarse fragments, many roots, common and high porosity common biological activity (termites, artefacts, burrows, other insects), gradual boundary with the underlying horizon.

• 70-135 cm: BtCa horizon; grayish brown 10YR5/2; clayey; common mottles; compact, angular blocky; slightly moist; high porosity; calcareous nodules; presence of slickensides; biological activity; gradual boundary with the underlying horizon.

• 135-205 cm: Bt horizon; yellow 10YR7/6; sandy clay; sub-angular blocky; hard and firm; low porosity; slightly moist; common and distinct mottles; few coatings; calcareous nodules; presence of slickensides; few biological activities; gradual boundary with the underlying horizon.

• 205-305 cm: C horizon; pale red 2.5YR7/2; sandy loam; very few mottles; weak and granular; friable; dry; high and common porosity; presence of clay mineral; very few fine roots; artefacts; Abrupt boundary.

•>305 cm: R parent material): gneiss.

The NGA profile was classified as pellic Vertisol (ochric, grumic, gilgaic).

Vertical distribution of trace metals

Trace metal concentrations varied among sites and along soil profiles. When data were grouped according to master horizons (A, B, C), clearer distribution patterns emerged. In most profiles, Fe and Mn concentrations tended to increase with depth, particularly in B and C horizons (Tab1.a). This trend may reflect their lithological inheritance and the influence of parent material. Iron and manganese oxides are known to accumulate in subsurface horizons due to pedogenic processes and redox fluctuations (Tab 1.a). Conversely, Cu and Zn showed relatively higher concentrations in A horizon at certain sites, which may be related to organic matter accumulation and surface biological activity. Organic matter has a strong affinity for Cu and Zn through complexation mechanisms, which can explain their enrichment in topsoil (Gourban Hamadjida et al., 2022) (Tab 1.b).

Potentially toxic elements such as Pb, Cd, Cr, and Ni displayed variable vertical patterns depending on the site. In some profiles, relatively uniform distributions suggest a predominantly geogenic control. In others, slight enrichment in surface horizons may indicate limited anthropogenic influence or surface retention mechanisms (Sigh et al., 2006; Amraou et al., 2021).

The absence of sharp concentration peaks in specific horizons suggests that no strong localized contamination source is present (Tab.1.a).

Mechanistic explanation

The variability of trace metal concentrations among sites can be explained by a combination of lithological and pedogenic factors (Temga et al., 2019; Yaboki et al., 2021). Parent material composition likely plays a major role, especially for elements such as Cr and Ni, which are commonly associated with mafic or metamorphic rocks rock (Vriend et al., 1985). Differences between granitic and metamorphic substrates may partly account for site-to-site variability (Yerima et al., 2003; Yerima et al., 2009; Aydinalp, 2010; Yerima et al., 2013). Clay content also appears to influence trace metal distribution. Vertisols are characterized by high smec-tites content, providing numerous adsorption sites (Fig.3). Higher clay percentages may therefore enhance metal retention capacity (Nguetnkam et al., 2008) (Tab.2). Soil pH is another key factor controlling metal mobility. Slightly acidic to neutral conditions generally favor metal adsorption onto clay minerals and

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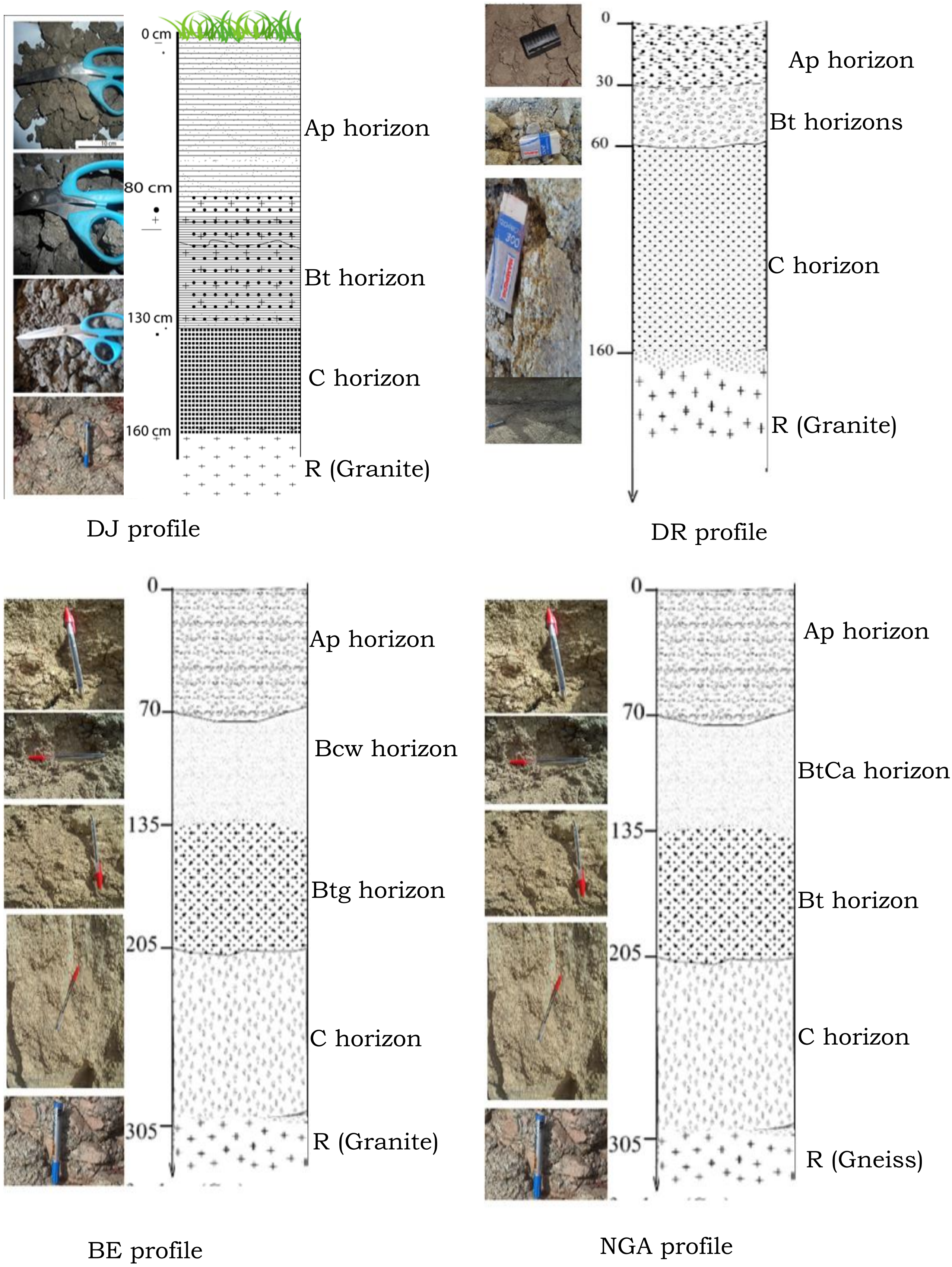

Figure 2. *Vertisols profiles in the study area*

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Table 1a. *Physico-chemical characteristics of vertisols of Kaele*

Parameters	DJ1	DJ2	DJ3	DJR	BE1	BE2	BE3	BER	DR1	DR2	DRR	NGa1	NGa2	NGaR
Clay (%)	19.51	22.69	25.72	14.44	30.36	16.14	14.44	14.44	35.00	38.00	14.44	37.00	36.00	35.00
Sand (%)	60.21	48.63	48.3	34.00	35.87	57.31	49.32	34.00	45.00	40.00	34.00	34.00	34.00	34.00
Silt (%)	20.28	28.68	25.98	20.28	33.76	26.55	36.24	20.28	20.00	22.00	20.28	29.00	30.00	36.00
OM (%)	3.57	2.39	2.55	1.33	4.59	4.59	4.80	1.33	1.33	2.22	1.33	2.49	2.58	2.38
OC (%)	1.78	2.19	1.27	1.27	2.29	2.29	2.40	1.27	0.77	1.29	1.27	1.45	1.50	1.50
TN (%)	0.59	0.50	0.35	0.29	0.31	0.31	0.29	0.29	0.50	0.40	0.29	0.18	0.51	0.39
Ca (cmol.kg-1)	0.24	0.26	0.32	0.22	0.34	0.22	3.15	0.22	10.88	11.08	0.22	15.08	9.68	11.14
Mg (cmol.kg-1)	16.00	12.14	19.68	1.12	29.26	24.34	54.45	1.12	1.32	1.12	1.12	1.92	1.92	1.90
K (cmol.kg-1)	0.84	0.08	0.03	0.00	0.00	0.14	0.14	0.00	0.07	0.07	0.00	0.19	0.13	0.25
Na (cmol.kg-1)	0.19	0.03	0.05	0.03	0.05	0.03	0.03	0.03	0.09	0.09	0.03	0.61	0.36	0.36
CEC (cmol.kg-1)	21.63	14.4	24.4	14.4	36.8	24.00	21.6	14.4	23.04	25.92	14.4	39.84	33.28	36.38
pH	6.75	6.77	6.75	6.75	7.6	8.19	8.34	6.75	9.70	9.60	6.75	9.40	9.60	9.50
SiO2	4.29	2.71	4.61	3.46	3.69	3.38	3.18	2.99	3.91	3.2	5.67	3.07	3.19	1.89
Cr (mgkg-1)	8.87	12.72	11.94	7.82	11.14	10.06	13.42	4.78	11.29	12.67	3.83	22.05	18.38	12.12
Ni (mgkg-1)	10.00	6.4	8.5	6.4	9.3	8.1	9.9	4.3	7.9	8.70	3.00	19.6	17.90	20.60
Cu (mgkg-1)	3.7	5.5	10.5	3.3	6.2	5.3	5.8	4.2	5.5	5.70	5.90	18.8	23.80	29.50
Zn (mgkg-1)	24.2	31.4	21.8	64.4	44.00	22.7	26.2	22.5	26.4	33.3	11.70	63.3	44.80	96.60
Sr (mgkg-1)	50.18	54.8	42.43	109.8	53.12	47.84	60.7	187.55	58.44	67.41	62.3	170.26	181.81	178.48
Ba (mgkg-1)	132.26	193.89	118.9	78.51	161.1	130.33	147.71	33.57	159.11	161.86	30.42	426.87	369.32	391.24
Pb (mgkg-1)	4.91	5.65	4.64	5.75	3.86	3.9	4.41	2.45	5.61	5.11	3.65	6.52	5.17	3.63
Cd (mgkg-1)	0.026	0.013	0.029	0.08	0.016	0.021	0.019	0.05	0.77	0.80	0.014	0.043	0.052	0.034

Table 1b. *Descriptive statistical analysis*

Parameters	min	max	mean	SD	Skewness	Kurtosis	CV (%)
Clay (%)	14.44	38	25.22	9.69	0.09	-1.89	94.04
Sand (%)	34	60.21	42.04	9.35	0.78	-0.7	87.52
Silt (%)	20	36.24	26.38	6.06	0.43	-1.23	36.8
OM (%)	1.33	4.8	2.67	1.25	0.65	-0.78	1.56
OC (%)	0.77	2.4	1.61	0.49	0.38	-0.88	0.24
TN (%)	0.18	0.59	0.37	0.11	0.45	-0.53	0.01
Ca (cmol.kg-1)	0.22	15.08	4.5	5.63	0.77	-1.25	31.75
Mg (cmol.kg-1))	1.12	54.45	11.95	15.73	1.72	3.09	247.68
K (cmol.kg-1)	0.03	0.84	0.14	0.21	3.1	10.5	0.04
Na (cmol.kg-1)	0.03	0.61	0.14	0.17	1.79	2.65	0.03
CEC (cmol.kg-1)	14.4	39.84	24.6	8.91	0.42	-1.04	79.52
pH	6.75	9.7	8.03	1.29	0.22	-1.93	1.68
SiO2	50.73	74.52	64.43	6.45	-0.52	0.22	41.66
Cr (mgkg-1)	3.83	22.05	11.5	4.74	0.57	1.08	22.49
Ni (mgkg-1)	3	20.6	10.04	5.45	1.03	0.1	29.75
Cu (mgkg-1)	3.3	29.5	9.55	8.29	1.67	1.64	68.74
Zn (mgkg-1)	11.7	96.6	38.09	22.89	1.48	2.11	523.96
Sr (mgkg-1)	42.43	187.55	94.65	57.95	0.86	-1.23	3358.6
Ba (mgkg-1)	30.42	426.87	181.07	125.98	1.01	0.03	15872.82
Pb (mgkg-1)	2.45	6.52	4.66	1.08	-0.29	-0.12	1.17
Cd (mgkg-1)	0.013	0.8	0.18	0.31	1.76	1.38	0.1

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Table 2. *Pearson correlation for the soil physicochemical properties. Correlation is significant at the 0.05 level.*

Clay	Sand	Silt	OM	OC	TN	Ca	Mg	K	Na	CEC	pHw	SiO2	Cr	Ni	Cu	Zn	Sr	E
1																		
-0.3	1																	
0.26	-0.08	1																
-0.1	0.52	0.61	1															
-0.3	0.43	0.62	0.86	1														
0.22	0.43	-0.17	-0.04	-0.06	1													
0.83	-0.36	0.2	-0.21	-0.4	0.01	1												
-0.36	0.52	0.54	0.85	0.77	-0.13	-0.39	1											
-0.03	0.53	-0.07	0.28	0.16	0.51	-0.006	0.08	1										
0.62	-0.32	0.31	-0.05	-0.17	-0.06	0.76	-0.34	0.3	1									
0.76	-0.25	0.61	0.35	0.09	-0.11	0.65	0.01	0.1	0.74	1								
0.78	-0.22	0.33	0.04	-0.19	0.06	0.91	-0.16	-0.06	0.58	0.67	1							
-0.46	0.41	-0.56	0.03	-0.06	0.01	-0.6	0.21	0.03	-0.63	-0.5	-0.58	1						
0.69	-0.07	0.53	0.24	0.12	-0.007	0.7	0.05	0.04	0.74	0.72	0.65	-0.55	1					
0.67	-0.23	0.6	0.17	0.02	0.02	0.73	-0.1	0.27	0.89	0.85	0.68	-0.76	0.78	1				
0.61	-0.42	0.56	-0.05	-0.13	0.01	0.64	-0.27	0.05	0.78	0.71	0.58	-0.76	0.59	0.89	1			
0.45	-0.49	0.46	-0.09	-0.07	-0.15	0.51	-0.28	0.03	0.61	0.57	0.42	-0.76	0.4	0.73	0.71	1		
0.27	-0.67	0.16	-0.37	-0.31	-0.2	0.48	-0.5	-0.06	0.65	0.34	0.34	-0.77	0.29	0.58	0.67	0.6	1	
0.74	-0.26	0.59	0.1	0.02	0.06	0.77	-0.18	0.15	0.89	0.81	0.7	-0.78	0.85	0.95	0.87	0.7	0.55	
0.41	0.08	-0.06	-0.12	-0.15	0.18	0.44	-0.17	0.1	0.4	0.17	0.29	-0.09	0.64	0.29	0.07	0.2	-0.09	0.4
0.49	-0.01	-0.39	-0.33	-0.52	0.27	0.5	-0.32	-0.16	-0.1	-0.006	0.53	0.09	0.04	-0.12	-0.18	-0.12	-0.18	-0.

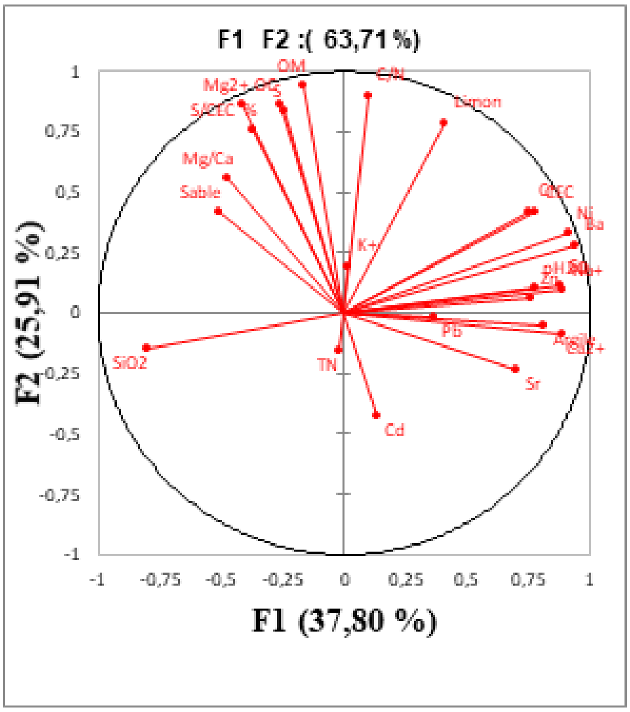

Figure 3. *The principal component analysis*

iron oxides, reducing their mobility (Temga et al, 2019; Yaboki et al., 2021). In contrast, localized pH variations may influence the solubility of Cd and Zn (Yaboki et al., 2021; Gouban Hamadjida et al., 2022). Seasonal redox fluctuations in Vertisols may also affect Fe and Mn behavior, leading to periodic dissolution and re-precipitation processes that indirectly influence the mobility of associated trace metals (Yaboki et al., 2021). Pearson correlation analysis supports these interpretations, showing significant relationships between trace metals and clay content, organic matter, and Fe–Mn oxides (Table 1.b).

Agricultural and environmental implications

Although trace metal concentrations remain below international threshold values, their vertical distribution patterns indicate strong interactions with soil properties (Yerima and al., 2013; Basga and al., 2020). Given the intensive cultivation in the study area, long-term monitoring is recommended to detect possible accumulation trends (Tab.3). The current levels suggest predominantly natural control rather than anthropogenic contamination (Tab.3).

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Table 3. *Varimax-rotated factor loadings of the soil properties*

	Factors	
	F1	F2
Clay	**0.65**	0.002
Sand	0.25	0.17
Silt	0.16	**0.62**
OM	0.02	**0.88**
OC	0.06	**0.74**
TN	0.0003	0.02
C/N	0.009	**0.81**
Ca^{2+}	**0.78**	0.01
Mg^{2+}	0.17	**0.74**
Mg/Ca	0.22	**0.31**
K^+	0.0002	0.03
Na^+	**0.79**	0.008
S	0.05	**0.7**
CEC	**0.6**	0.17
S/CEC %	0.13	**0.57**
pH_{H2O}	**0.6**	0.01
SiO_2	**0.63**	0.02
Cr	**0.56**	0.17
Ni	**0.82**	0.1
Cu	**0.76**	0.01
Zn	**0.57**	0.003
Sr	**0.49**	0.055
Ba	**0.87**	0.078
Pb	0.13	0.0003
Cd	0.01	0.18
Total	**9.44**	**6.47**
(%) of variance	**37.79**	**25.91**
cumulative%	**37.79**	**63.7**

Conclusion

This study evaluated the vertical distribution and soil controls of trace metal elements (Fe, Mn, Cu, Zn, Pb, Cd, Cr, and Ni) in cultivated Lithomorphic Vertisols of Kaélé, Far North Cameroon. The results showed moderate variability among sites, with generally neutral to alkaline pH conditions and relatively homogeneous clay content. Trace metal distribution along soil profiles revealed distinct patterns according to master horizons. Iron and manganese tended to increase in subsurface horizons, reflecting pedogenic redistribution processes. Copper and zinc showed relative enrichment in surface horizons, likely associated with organic matter interactions. Chromium and nickel exhibited higher concentrations at the Nord Garey site, suggesting lithological influence as a major controlling factor. The absence of pronounced surface accumulation and the fact that all concentrations remain below international threshold values indicate that trace metal levels are predominantly controlled by natural soil-forming factors rather than anthropogenic contamination. Overall, soil properties such as pH, clay content, and mineralogical composition play a key role in regulating trace metal distribution and mobility in these Vertisols. Under current conditions, the risk of trace metal mobility appears limited; however, continued monitoring is recommended to ensure sustainable soil management under increasing agricultural pressure and climatic variability.

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