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Soil quality evaluation under different agricultural land uses using multiple soil quality indices

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Abstract

Assessing soil quality under agricultural production provides valuable information about the soil's condition and overall health. The study evaluated soil quality across different land uses (cassava, pasture, and maize) using multiple soil quality indices at the Federal University of Agriculture, Abeokuta, Nigeria. Profiles pits were dug at each land use type and described according to WRB guidelines. Soil quality was assessed using physical, chemical, geochemical and ecological (potential ecological risk coefficient and index) indicators. Soil pH (5.60-6.68), OC (0.63-3.03%), TN (0.02-026%), and Av. P (0.76-8.75 mg/kg) showed a decreasing trend with increasing soil depth. Bulk density (1.17-1.42 g/cm^3) and Fe (17.50–65.63%wt) increased with depth, while other metals fluctuated across depths and land uses. Soil quality ranged from low to moderate, with low Av. P and K being the most common limiting factors. Geochemical indicators revealed minor to moderate enrichment for most metals, with Pb (13.884) showing moderate enrichment. Contamination factors indicated low to moderate contamination for most metals, except Pb (5.647), which showed significant contamination. The geoaccumulation index classified most metals as practically uncontaminated, with Ni (0.860) and Pb (1.913) indicating slight to moderate contamination. Ecological risk assessment suggested low potential ecological risk for most metals, but a moderate risk for Pb (28.235). The study concludes that combining different indicators provides a comprehensive evaluation of soil quality, highlighting the impact of agricultural practices on soil health. Regular monitoring and sustainable soil management are recommended to maintain soil quality and mitigate risks associated with heavy metal accumulation in agricultural soils.

Keywords*: Agriculture, Ecological indicators, Geochemical indicators, Land use, Soil health*

Introduction

The ecological system and the production of food and fibre for human use depend on the productivity of agricultural soils. Soils are regarded as non-renewable natural resources because the pace at which they are formed is extremely slow, often imperceptible over a human lifespan (Stockman et al., 2014). They are the foundation of all terrestrial life and cultural legacy (Lal, 2015), and play a crucial role in sustaining life on Earth while mediating many of the environmental challenges occurring around the world (Weil and Brady, 2017). Soils exhibit pronounced spatial and temporal variability arising from the interplay of physical, chemical, biological, and anthropogenic processes that operate at varying intensities and scales (Oyedele et al., 2014; Adebo et al., 2022). Globally, soils display evident problems of degradation (Amundson *et al.*, 2015; FAO, 2017), driven by several threats that undermine their ability to produce goods and services. Consequently, the conditions and sustainability of soils are closely linked to human activeties, societal needs, and environmental health (Yu et al., 2018). Global food security is being threatened because of the decline in soil quality, as approximately 65% of the total arable land has already lost its capacity to support food production (Lal, 2015). Soil quality is a valuable concept for evaluating the condition and changes in soils. It is defined as the soil's ability to perform ecological functions and provide ecosystem services, thus sustaining biological productivity, environmental health, and enhancing plant and animal well-being (Bunemann et al., 2018; Maurya et al., 2020). Assessing soil quality involves measuring the relative changes in soil properties resulting from human management under different land-use systems over time. This assessment can be based on simple visual observations or require detailed laboratory analysis of soil tests (Yu et al., 2018). Soil quality is often evaluated using physical, chemical, and biological characteristics related to soil fertility, which are common parameters for crops. These parameters include particle size, pH, organic matter content, and macro elements such as N, P, and K (Klimkowicz-Pawlas et al., 2019). Similarly, soil quality can be assessed using ecological risks and geochemical indicators. These indicators mainly aim to evaluate the human-made impact on soil quality and can identify the potential effects of trace elements on soil ecology, including the risk of contamination (Kowalska et al., 2018; Fazekašová and Fazekaš, 2020; Kijowska-Strugala et al., 2022). Geochemical indicators (pH, nutrient levels, and heavy metal concentrations) offer a quantitative assessment of soil properties. They provide essential information on soil chemical composition, which influences microbial activity, nutrient availability, and overall fertility (Kabata-Pendias, 2011). In contrast, ecological indicators focus on biological factors such as microbial diversity, plant species composition, and ecosystem resilience functions (Brussaard et al., 2010). Combining these indicators allows for a comprehensive understanding of soil dynamics, including biological interactions and ecosystem functions, alongside chemical variables (Brussaard et al., 2010; Bardgett and van der Putten, 2014). Transforming land for human use, such as in large-scale commercial and subsistence farming, involves extensive clearing of natural vegetation, leading to a decline in soil quality as reflected in its physical and biochemical properties (Veldkamp et al., 2020). The concern for soil sustainability has prompted diverse studies on the impact of land use on soil quality worldwide. Several studies have also been conducted in Nigeria (Oyedele et al., 2014; Osinuga and Oyegoke, 2017; Adedeji et al., 2019); however, many agroecosystems have yet to be assessed. Due to the complex spatial and temporal variability of soil properties, there is a need for site-specific soil quality evaluations that accurately reflect local conditions.This research aims to promote sustainable agricultural practices by optimizing soil fertility and aligning with global efforts to reduce environmental impacts from poor soil management. Additionally, integrating this knowledge provides a strong framework for understanding the complex structure of soil ecosystems, supporting sustainable farming practices, and addressing global environmental challenges. Maintaining and improving soil quality attributes and their relationship with sustainable agriculture is crucial for identifying related problems and developing appropriate solutions to ensure ecosystem sustainability (Delelegn et al., 2017). Therefore, the goals of this study are to characterize soils under various agricultural land uses and evaluate their quality using physical, chemical, geochemical, and ecological indicators.

Materials and Methods

Description of the study area

The study was carried out in the Paddock of the Pasture and Range Department at the Federal University of Agriculture, Abeokuta, Ogun State, Nigeria, as well as at the cassava and maize plots of the Centre of Excellence in Agriculture Development and Sustainable Environment (CEADESE) farm. The area is situated in the northeastern part of Abeokuta, between Latitude 07023'N and Longitude 03026'E (Fig. 1). The study area is located in southwest Nigeria's Precambrian rocks, which are primarily of Basement Complex origin. Schist, quartz, granite, gneiss, and migmatite are the main types of rocks. In the foot slope (valley bottom) areas, plantation crop nurseries and dry season farming were predominant. Climatically, it falls within the derived savannah ecology, characterised by two distinct seasons: a wet season extending from March to November and a dry season from December to early March. The region experiences a mean annual rainfall ranging from 1000 to 1500 mm, mean temperatures of 26–34 °C, relative humidity of 75–95%, and potential evapotranspiration values between 218 and 274 mm (Aiboni, 2001; Osinuga et al., 2020).

Field study

The rigid grid method of soil survey was performed over a land area of 1000 m × 200 m (200,000 m^2) with traverses established at 100 m × 100 m intervals to guide soil sampling. At each sampling point, soil samples were collected from the surface to a depth of 15 cm across the agricultural land use types. Three profiles were dug, one for each land use type: Pedon 1 (cassava), Pedon 2 (paddock), and Pedon 3 (maize). The

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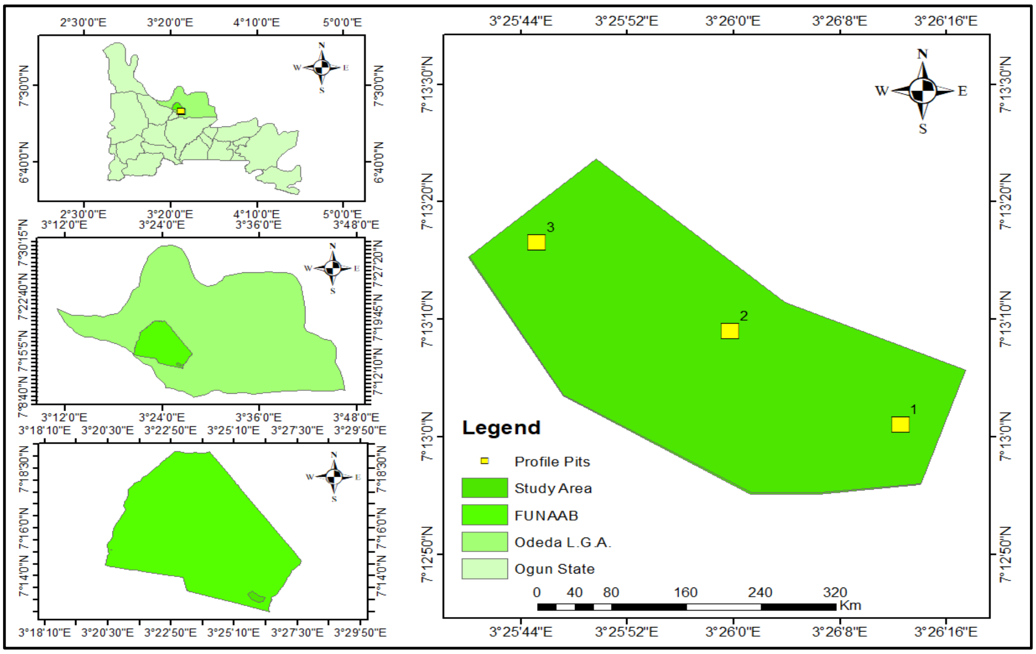

Figure 1
Map of the study area

coordinates of the sampling points and profile pits were recorded using a Global Positioning System (GPS). Distinct soil horizons identified in each profile pit were sampled and properly labelled. Morphological properties of the horizon, such as colour, structure, consistence, texture, root abundance, mottles, and other features, were described following the recommended guidelines for soil description (WRB, 2022). Using the information gathered from the morphological properties, the soils were classified into their appropriate order, suborder, great group, and subgroup in accordance with the guidelines provided by USDA Soil Taxonomy (Soil Survey Staff, 2014) and the FAO classification system (WRB, 2022).

Laboratory soil analysis

The soil samples collected were air-dried, crushed, and passed through a 2 mm sieve. Particle size analysis was determined using the hydrometer method as described by Gee and Bauder (1986). Bulk density (BD) was determined using the core method of Anderson and Ingram (1993), while total porosity of the soils was estimated from the soil BD by assuming that the soil particle density (PD) was 2.65 g cm^{-3}. Soil pH was measured electrometrically in a 1:2 soil-to-water suspension (IITA, 1982). Soil organic carbon was determined using the acid dichromate wet-oxidation procedure of the Walkey and Black method as described by Nelson and Sommers (1996), while total nitrogen was analysed using the micro Kjeldahl digestion method (Nelson, 1983). The available P was extracted using Bray-1 extractant at a 1:5 soil-to-extractant ratio, and its concentration in the extract was determined by the Murphy and Riley (1962) vanado-molybdate blue method using a spectrophotometer at 882 nm wavelength. Exchangeable bases were extracted with neutral normal ammonium acetate. The concentrations of Na^+ and K^+ in the filtrates were determined by a flame photometer, while the EDTA titration quantified Ca^{2+} and Mg^{2+}. Exchangeable acidity was determined titrimetrically following Mclean (1965). The effective cation exchange capacity (ECEC) was expressed as the summation of exchangeable cations and acidity (Summer and Miller 1996). The base saturation was calculated as the percentage ratio of exchangeable bases to the ECEC. The total elemental contents (Fe, Cu, Cr, Ni, Pb, Mo, and Zn) were obtained through laboratory testing of samples using an EDXRF spectrometer (model EX-6600SDD) at the CEADESE laboratory, Federal University of Agriculture, Abeokuta. To ensure the accuracy and precision of the EDXRF analytical results, Certified Reference Material NIST SRM 2711a Montana II Soil was analysed alongside the soil samples (National Institute of Standards and Technology (NIST), 2003). Recovery values for Fe, Cu, Cr, Ni, Pb, Mo, and Zn ranged between 93% and 105%.

Assessment of soil quality

Soil quality was assessed using the direct method by matching the results of both physical and chemical soil properties with the Tropical Soil Quality Index (SQI) following the standard procedures described by Amacher et al. (2007) and Arifin et al. (2012) as presented in Table 1. The geochemical and ecological indicators related to the mobility of trace elements were also assessed. Geochemical indicators like Enrichment Factor (EF), Contamination Factor (CF), and Geo-accumulation Iindex (Igeo), while potential ecological risk coefficient (Er) and potential ecological risk index (RI) were used in this study, as shown in Table 2.

Table 1. *Selected soil properties for Tropical Soil Quality Index (TSQI)*

Parameter	Level	Interpretation
Bulk density (g/cm^3)	> 1.5	Possible adverse effects
	≤ 1.5	Adverse effects unlikely
Coarse fragments (%)	> 50	Possible adverse effects
	≤ 50	Adverse effects unlikely
Soil reaction (pH)	3.01-4.0	Strongly acidic = only highly acid-tolerant plants can survive, and only where organic matter mitigates high extractable Al and metal toxicity
	4.01-5.5	Moderately acidic = growth of acid-intolerant plants may be restricted, depending on extractable Al and metal levels
	5.51-6.8	Slightly acidic = optimal for many plant species, particularly acid-tolerant crops
	6.81-7.2	Near neutral = optimal for most plant species except those preferring acidic soils
	7.21-7.5	Slightly alkaline = suitable for many plants, though deficiencies of P and micronutrients (e.g., Zn) may occur
	7.51-8.5	Moderately alkaline = favoured by plants adapted to alkaline conditions, with possible P and micronutrient deficiencies
	> 8.5	Strongly alkaline = suited only to alkaline-tolerant plants, with possible B and oxyanion toxicities
Total organic carbon (%)	> 5	High = excellent organic carbon accumulation with associated soil health benefits
	1–5	Moderate = generally adequate for soil fertility
	< 1	Low = may indicate organic carbon loss due to erosion or other degradation processes
Total nitrogen (%)	> 0.5	High = excellent nitrogen reserve
	0.1-0.5	Moderate = adequate nitrogen availability
	< 0.1	Low = may indicate depletion of organic nitrogen
Exchangeable Na (cmolkg^{-1})	> 0.65	High = indicates sodic conditions with associated soil structural problems
	≤ 0.65	Moderate = Adverse effects unlikely
Exchangeable K (cmolkg^{-1})	> 1.28	High = excellent K reserve
	0.26-1.28	Moderate = adequate for most crops
	< 0.26	Low = K deficiencies are likely
Exchangeable Mg (cmolkg^{-1})	> 4.2	High = excellent Mg reserve
	0.42-4.2	Moderate = adequate for most crops
	< 0.42	Low = Mg deficiency possible
Exchangeable Ca (cmolkg^{-1})	> 5	High = excellent Ca reserve
	0.5-5	Moderate = adequate for most crops
	0.05-0.5	Low = possible deficiencies
	< 0.05	Very low = severe Ca depletion with increased risk of adverse effects
Exchangeable Acid (cmolkg^{-1})	> 1	High = adverse effects likely, especially for Al-sensitive crops
	0.11-1	Moderate = only Al-sensitive plants likely to be affected
	0.01-0.1	Low = adverse effects unlikely
	< 0.01	Very low = indicates probable alkaline soil conditions
Available P (mg/kg)	> 30	High = excellent P availability in acid soils, though erosion may pose water quality risks
	15-30	Moderate = sufficient for plant growth
	< 15	Low = P deficiencies likely

Source: Modified from Amacher *et al.*, 2007 and Arifin *et al.*, 2012.

Table 2. *Geochemical and Ecological Indicators*

Index	Formula	Explanation	Limit value	Classification
Enrichment factor E_f	$E_f=(Ci/Cref)/(Bi/Bref)$	Ci = content element in soil; Cref = content of Fe in sample; Bi = reference content of element; Bref = reference content of Fe	$EF \le 1$ $1 < EF \le 3$ $3 < EF \le 5$ $5 < EF \le 10$ $10 < EF \le 25$ $25 < EF \le 50$ $EF > 50$	No enrichment Minor enrichment Moderate enrichment Moderately severe enrichment Severe enrichment Very severe enrichment Extremely severe enrichment
Contamination factor C_f	$C_f = Cmi / Cref$	Cmi = element concentration; Cref = reference value of element (background value)	$CF < 1$ $1 \le CF < 3$ $3 \le CF < 6$ $6 \le CF$	Low contamination factor Moderate contamination factor Considerable contamination factor Very high contamination factor
Geoaccumulation index Igeo	$Igeo = \log2(Ci / 1.5B)$	Ci = content of single element in soil; Bn = background value; 1.5 = constant	$Igeo \le 0$ $0 \le Igeo < 1$ $1 \le Igeo < 2$ $2 \le Igeo < 3$ $3 \le Igeo < 4$ $4 \le Igeo < 5$ $5 \le Igeo$	Class 0 — practically uncontaminated Class I — uncontaminated to moderately contaminated Class II — moderately contaminated Class III — moderately to heavily contaminated Class IV — heavily contaminated Class V — heavily to extremely contaminated Class VI — extremely contaminated
Potential ecological Risk coefficient Er	$Er = Tri \times Cfi$	Tr = toxicity response coefficient of element; CFi = contamination factor of single PHE	$Er < 40$ $40 \le Er < 80$ $80 \le Er < 160$ $160 \le Er < 320$ $320 \le Er$	Low potential ecological risk Moderate potential ecological risk Considerable potential ecological risk High potential ecological risk Very high potential ecological risk
Potential ecological risk index RI	$RI = \sum_{i=1}^{n} Er_i$	Eri = potential ecological risk coefficient for a single element; n = number of analysed elements	$RI < 150$ $150 \le RI < 300$ $300 \le RI < 600$ $RI > 600$	Low ecological risk Moderate ecological risk Considerable ecological risk Very high ecological risk

Sources: Gong *et al.* (2008); Kowalska *et al.* (2018); Kulbat and Sokolowska (2019); Gruszecka-Kosowska *et al.* (2019, 2020); Kumar *et al.* (2019).

Statistical Analysis

The soil data were analysed using Descriptive Statistics in IBM SPSS v 27 software. The mean was used to calculate the average distribution of the variables, and Pearson's Correlation Coefficient was used to evaluate the correlations between the variables at the 0.01 and 0.05 probability levels.

Results

Morphological characteristics of the soils

The soils were characterised by very dark greyish brown (10YR3/2) to greyish brown (10YR5/2) colour on the surface overlaid with dull brown (10YR3/3) to yellowish brown (5YR5/4) colour at the subsurface (Table 3). The soil texture consisted of loamy sand (LS) at the surface horizons overlaid by sandy loam (SL) and sandy clay (SC) subsurface horizons. The soil structure ranged between weak medium granular and weak friable crumb at the surface horizons and moderate medium to strong coarse subangular blocky at the subsurface horizons. Soil consistency was non-sticky loose soft to slightly sticky friable soft at surface horizons, while at the subsurface horizons it was slightly sticky friable soft to very sticky fine hard. Horizon boundaries were generally smooth and clear. The root abundance at the surface horizons was many common medium to coarse pores overlying very fine to fine pores. Mottles were prominent and distinct, with varying amounts of iron and manganese (plinthite) concretions present in the last horizon of paddock and maize profiles. The soils were generally classified as Lixisols and Alfisols according to the World Reference Base and USDA Soil Taxonomy, respectively, because Bt horizons are present, clay illuviation is evident, soil structures are subangular, and sandy loam surface over sandy clay loam subsurface. The cassava pit was classified as Rhodic Lixisol (Typic Haplustalf), pasture profile as Endogleyic

Table 3. *Morphological characteristics of the soils*

Horizon Designation	Depth (cm)	Elevation (m)	Colour Matrix	Textural Class	Structure	Consistency	Horizon Boundary	Root Abundance	Concretions
Cassava									
A_p	0-18	133	10YR4/3, db	LS	w, me, gr	ns, lo	sm, cl	me, c	n
B_e	18-42		10YR5/3, b	LS	m, co, sab	ns, fr	sm, cl	f, c	n
B_{t1}	42-70		5YR4/4, rb	SL	m, me, sab	ss, fr	sm, cl	f, fe	n
B_{t2}	70-146		7.5YR5/6, sb	SCL	m, co, sab	ss, fr	-	f, fe	n
Pasture									
A_p	0-16	124	10YR3/2, vdgb	LS	w, f, cr	ns, lo	sm, cl	co, m	n
AB	16-62		10YR3/3, b	LS	m, me, sab	ns, fr	sm, cl	me, c	n
B_t	62-118		5YR4/4, rb	SL	m, me, sab	ss, fr	sm, cl	f, fe	n
B_r	118-150		5YR5/3, rb	SL	m, me, sab	ss, f	-	vf, f	m, Fe/Mn
Maize									
A_p	0-25	121	10YR5/2, gb	LS	w, me, cr	ns, lo	sm, cl	co, c	n
B_{t1}	25-80		5YR4/8, yr	SCL	w, me, sab	ss, fr	sm, cl	f, fe	n
B_{t2}	80-130		5YR5/4, yb	SC	m, me, sab	s, f	-	vf, fe	f, Fe/Mn

Colour: db = dark brown, vdgb = very dark greyish brown, gb = grayish brown, rb = redish brown, b = brown, yr = yellowish red, yb = yellowish brown – Textural Class (TC): SL = Sandy loam, SCL = Sandy clay loam, SC = Sandy clay - Structure: w = weak, m = moderate, s = strong, f = fine, me = medium, co = coarse, cr = crumb, gr = granular, sab = sub-angular blocky – Consistency: ns = non-sticky, ss = slightly sticky, s = sticky, lo = loose, f = firm, fr = friable, so = soft – Horizons Boundary: sm = smooth, wv = wavy, ir = irregular, ab = abrupt, cl = clear, di = diffuse - Roots: vf = very fine, f = fine, me = medium, co = coarse (size), fe = few, c = common, m = many (concentration) - Mottles and Concretions: n = none, f = few, vm = very many, Fe/Mn = Iron and Manganese.

Lixisol (Oxyaquic Haplustalf), and maize pit as Ferric Lixisol (Typic Haplustalf) based on the colour matrix, argic horizon, clay accumulation, and iron concretions.

Physical Characteristics of the Soils

The physical characteristics of the representative profiles across different agricultural land uses are shown in Table 4. The particle size distribution revealed that the soils had a high sand content (>590 g/kg), which decreased with depth, and ranged from 594 to 864 g/kg. Silt contents were generally low, with no clear pattern across the profiles, ranging from 16 to 86 g/kg across land uses. In contrast, the clay content increased with depth, ranging from 110 to 360 g kg^{-1}, with an

Table 4. *Physical characteristics of the soils*

Horizon Designation	Depth (cm)	Sand	Silt	Clay	SCR	BD (g/cm^3)	Ksat. (cm/hr)	Porosity (%)	Textural Class
			(g/kg).						
Profile 1									
A_p	0-18	864	16	120	0.13	1.18	2.94	43.65	LS
B_e	18-42	844	26	130	0.20	1.23	1.58	45.42	LS
B_{t1}	42-70	774	46	180	0.26	1.29	1.49	47.68	SL
B_{t2}	70-146	714	66	220	0.30	1.33	1.21	49.06	SCL
Profile 2									
A_p	0-16	854	36	110	0.36	1.17	1.97	43.28	LS
AB	16-62	844	26	130	0.21	1.22	1.47	44.91	LS
B_t	62-118	774	86	140	0.62	1.34	1.04	4969	SL
B_r	118-150	734	66	200	0.33	1.36	0.89	50.20	SL
Profile 3									
A_p	0-25	834	36	130	0.27	1.27	1.63	47.05	LS
B_{t1}	25-80	614	86	300	0.29	1.39	1.08	51.33	SCL
B_{t2}	80-130	594	46	360	0.13	1.42	0.67	52.58	SC
	Mean	767.64	48.73	183.64	0.28	1.29	1.45	47.71	
	SEM	16.13	4.23	13.86	0.03	0.01	0.10	0.53	
	SD	92.66	24.27	79.64	0.15	0.08	0.60	3.06	

SCR = Silt Clay Ratio - BD = Bulk Density - Ksat. = Saturated Hydraulic Conductivity - LS= Loamy Sand - SL = Sandy Loam – SCL = Sandy Clay Loam - SC = Sandy Clay - SEM = Standard Error of Mean - SD = Standard Deviation.

overall mean of 183.64 g kg⁻¹. The silt-to-clay ratio ranged from 0.13 to 0.36, suggesting low weathering intensity. Soil texture ranged from loamy sand (LS) to sandy loam (SL) in the upper horizons, and between sandy loam (SL) and sandy clay loam (SCL) in the lower horizons. Bulk density increased with soil depth across the land uses and ranged from 1.17 to 1.42 g/cm³. Statistical analysis showed significant differrences ($p<0.05$) in the mean profile bulk density across the evaluated agricultural lands (Table 3). Saturated hydraulic conductivity (Ksat) values ranged from 0.67 to 2.94 cm/hr across all profiles. Ksat decreased with depth, and the average profile Ksat was significantly affected by agricultural practices ($p<0.05$). Soil porosity increased with depth, following the trend of bulk density. The lowest porosity recorded was 43.28%, and the highest was 52.58% at the first horizon of pasture land and the fourth horizon of maize land. These values were statistically significant ($p<0.05$).

Chemical characteristics of the soils

The chemical characteristics of the soils are depicted in Table 5. Soil reactions in water suspension ranged from slightly acid to neutral (5.60 – 6.68), and strongly acid to moderately acid (3.68 – 5.05) in KCl. In all the profiles, the surface horizons exhibited higher pH values than the subsurface horizons. The soil's electrical conductivity (EC) was low (12 – 44 µS/cm), and the soil salinity ranged from 6% to 30%. A high level of significant differences ($p<0.05$) was observed among the mean values. The organic carbon (OC) content of the soils ranged from low (0.63%) to very high (3.03 %) and decreased down the profile in all the pedons. The total nitrogen (TN) content of the soils ranged from very low (0.02%) to medium (0.26%). The available phosphorus (P) of the soils ranged from very low (0.83 mg/kg) to medium (8.75 mg/kg), with a mean value of 3.11 mg/kg, and decreased with depth. The exchange site of the soils was dominated by calcium (Ca), magnesium (Mg), and sodium (Na), while potassium (K) had values lower than them. The values were 0.45 – 3.57 cmol/kg, 0.38 – 1.07 cmol/kg, 0.38 – 0.67 cmol/kg, and 0.04 – 0.20 cmol/kg for Ca, Mg, Na, and K, respectively. The mean profile exchangeable acidity (EA) ranged from 0.04 cmol/kg to 0.08 cmol/kg and was irregularly distributed in all profiles. Effective cation exchangeable capacity (ECEC) of the soils ranged from very low to low, ranging from 1.51 cmol/kg to 4.96 cmol/kg across the assessed profiles, with significant differences ($p<0.05$) among the profiles. In addition, the base saturation (BS) was consistently high, being greater than 50%, and its value ranged from 95.51% to 99.11% with a mean value of 97.64%.

Table 5. *Chemical characteristics of the soils*

Horizon	Depth	pH	pH	EC	Salinity	OC	TN	Avail-P	Ca	Mg	Na	K	Al+H	ECEC	BS
Designation	cm	H_2O	KCl	µS/cm	%	%	%	mg/kg	.cmol/kg						%
Cassava															
A_p	0-18	6.68	5.05	40	30	2.34	0.15	8.75	3.57	0.53	0.67	0.07	0.04	4.88	99.11
B_e	18-42	6.50	4.98	20	10	2.20	0.11	7.80	1.97	0.47	0.41	0.06	0.04	2.95	98.65
B_{t1}	42-70	6.51	4.90	20	11	1.93	0.08	4.12	2.13	0.44	0.43	0.06	0.05	3.11	98.39
B_{t2}	70-146	6.41	4.67	20	10	1.13	0.04	1.75	0.63	0.34	0.43	0.09	0.07	1.56	95.51
Pasture															
A_p	0-16	6.06	4.48	28	14	3.03	0.26	2.23	2.55	0.45	0.38	0.07	0.07	3.52	98.01
AB	16-62	5.81	4.43	39	20	2.46	0.15	2.10	1.82	0.55	0.45	0.08	0.06	2.96	97.98
B_t	62-118	5.79	4.30	16	08	1.60	0.07	1.55	2.26	1.07	0.41	0.12	0.08	3.94	98.05
B_r	118-150	5.60	3.68	24	12	0.87	0.03	0.76	0.89	0.38	0.43	0.08	0.08	1.86	95.68
Maize															
A_p	0-25	6.30	4 84	41	21	2.66	0.18	2.29	4.05	0.40	0.41	0.05	0.06	4.96	98.79
B_{t1}	25-80	6.11	4.45	44	22	1.36	0.06	2.04	1.93	1.07	0.43	0.20	0.08	3.71	97.84
B_{t2}	80-130	5.62	4.44	12	06	0.63	0.02	0.83	0.45	0.46	0.50	0.04	0.06	1.51	96.04
	Mean	6.13	4.56	27.64	14.64	1.84	0.11	3.11	2.02	0.56	0.45	0.08	0.06	3.18	97.64
	SEM	0.06	0.07	1.92	1.49	0.13	0.01	0.46	0.19	0.04	0.01	0.008	0.01	0.20	0.24
	SD	0.34	0.38	11.04	8.54	0.75	0.02	2.62	1.09	0.25	0.08	0.05	0.02	1.16	1.38

OC = Organic Carbon - TN = Total Nitrogen - Avail-P = Available Phosphorus - BS = Base Saturation - SEM = Standard Error of Mean – SD = Standard Deviation.

Heavy metal concentrations

The concentrations of various metals (Cu, Cr, Fe, Ni, Pb, Mn, Zn) across the different agricultural (cassava, pasture, and maize) land uses are presented in Table 6. Heavy metal contents (%wt) in the soil profiles were Cu (0.034 – 0.084), Cr (0.025 – 0.065), Fe (17.50 – 65.63), Mn (0.34 – 1.89), Ni (0.089 – 0.128), Pb (0.034 – 0.096), and Zn (0.037 – 0.143). The overall abundance followed the order: Fe > Mn > Ni > Zn > Pb > Cu > Cr. The profiles showed increasing Fe content with depth, with the highest at B_t (65.53) horizon under maize land use and the lowest at A_p (17.50) at cassava land use. The remaining heavy metal fluctuate with the profiles across the agricultural land uses, with surface horizons having the highest values for Mn only, while other metals had the highest values at the last horizons, except for Pb under pasture, which had the highest value at the surface horizon.

Table 6
Heavy Metals contents of the soils

Horizon Designation	Depth cm	Cu	Cr	Fe	Mn	Ni	Pb	Zn
		wt%.						
Cassava								
A_p	0-18	0.039	0.025	17.50	1.54	0.114	0.036	0.08
B_e	18-42	0.041	0.039	19.27	1.07	0.089	0.043	0.047
B_{t1}	42-70	0.034	0.035	18.60	0.91	0.094	0.047	0.037
B_{t2}	70-146	0.076	0.056	64.74	1.03	0.113	0.078	0.123
Pasture								
A_p	0-16	0.047	0.057	23.67	1.89	0.127	0.056	0.073
AB	16-62	0.045	0.065	24.20	1.40	0.101	0.047	0.057
B_t	62-118	0.069	0.059	42.77	1.11	0.124	0.053	0.123
B_r	118-150	0.084	0.062	46.40	1.12	0.124	0.034	0.143
Maize								
A_p	0-25	0.048	0.044	20.50	1.50	0.113	0.096	0.073
B_{t1}	25-80	0.038	0.048	21.63	1.08	0.089	0.083	0.047
B_{t2}	80-130	0.060	0.063	65.53	0.34	0.128	0.081	0.087
	Mean	0.053	0.050	33.16	1.185	0.111	0.060	0.081
	SEM	0.002	0.002	3.120	0.068	0.003	0.004	0.006
	SD	0.016	0.013	17.92	0.389	0.015	0.021	0.036

SEM = Standard Error of Mean - SD = Standard Deviation.

Correlation Analysis of Soil Properties

The correlation matrix (Table 7) shows the degree of association among selected soil properties. The results indicate a strong negative correlation between sand and clay (r = -0.972, p < 0.01) as well as sand and silt (r = -0.603, p < 0.01). Sand showed a significant negative correlation (r = -0.902, p < 0.01) with bulk density (BD), while showed a significant positive correlation (r = 0.732, p < 0.01) with saturated hydraulic conductivity (Ksat.). The BD showed a strong negative correlation with Ksat. (r = -0.842, p < 0.01), organic carbon (OC) (r = -0.889, p < 0.01), and total nitrogen (TN) (r = -0.876, p < 0.01). Soil pH was positively correlated with available phosphorus (Avail-P) (r = 0.741, p < 0.01) and negatively correlated with Cu (r = -0.559, p < 0.05). Additionally, pH showed positive correlations with OC and negatively correlated with Fe and Zn. The OC showed strong positive correlations with total nitrogen (TN) (r = 0.896, p < 0.01) and Mn (r = 0.839, p < 0.01). The TN showed a strong positive correlation with Mn (r = 0.905, p < 0.01) and negatively correlated with Fe (r = 0.718, p < 0.01).

Assessment of Soil Quality Indices

The soil quality assessment results are shown in Tables 8 and 9 for both physical and chemical Soil Quality Indicators (SQIs). The soil bulk density (BD) in all the profiles was less than 1.5 g/cm^3 and was rated to have no adverse effects (NAE) for plant root growth and development. The pH (H_2O) decreased with depth across the land uses, with values ranging from 5.60 to 6.68, and thus was rated slightly acidic and neutral. The organic carbon (OC) contents decreased with depth,

Table 7. *Pearson's correlation analysis of soil properties*

	Sand	Silt	Clay	BD	Ksat.	pH	EC	OC	TN	Avail-P	Cu	Fe	Mn	Zn
Silt	-0.630**													
Clay	-0.972**	0.428												
BD	-0.902**	0.731**	0.827**											
Ksat.	0.732**	-0.659**	-0.651**	-0.842**										
pH	0.428*	-0.391	-0.378	-0.504*	0.682**									
EC	0.276	-0.232	-0.250	-0.369	0.490*	0.246								
OC	0.851**	-0.597*	-0.808**	-0.889**	0.728**	0.446*	0.491*							
TN	0.798**	-0.612**	-0.742**	-0.876**	0.828**	0.375	0.550*	0.896**						
Avail-P	0.506*	-0.587*	-0.409	-0.570*	0.742**	0.741**	0.184	0.366	0.442*					
Cu	-0.295	0.470*	0.200	0.478*	-0.541*	-0.559*	-0.483*	-0.611**	-0.480*	-0.505*				
Fe	-0.617**	0.424*	0.589*	0.652**	-0.636**	-0.502*	-0.638**	-0.782**	-0.718**	-0.550*	0.811**			
Mn	0.774**	-0.349	-0.794**	-0.805**	0.701**	0.288	0.604**	0.839**	0.905**	0.243	-0.260	-0.616**		
Zn	-0.163	0.442*	0.055	0.335	-0.295	-0.437*	-0.360	-0.478*	-0.288	-0.354	0.907**	0.680**	-0.087	
Pb	-0.490*	0.280	0.485*	0.437*	-0.346	-0.034	0.145	-0.149	-0.270	-0.502*	-0.005	0.269	-0.211	-0.078

BD = Bulk Density - Ksat. = Saturated Hydraulic Conductivity - EC = Electrical Conductivity - OC = Organic Carbon - TN = Total Nitrogen - Avail-P = Available Phosphorus. - * Significant at the 0.05 level - ** Significant at the 0.01 level.

across the land uses, with values ranging from 5.60 to 6.68, and thus was rated slightly acidic and neutral. The organic carbon (OC) contents decreased with depth, having values that ranged from 0.63 to 3.03% and were rated low to moderate. The total nitrogen (TN) decreased with depth, with the values ranging from 0.02 to 0.26% and was evaluated as low to moderate. Available P was generally rated low, having values <15 mg/kg across all the land uses. The exchangeable K was rated low across all the agricultural land uses, with the values that ranged from 0.04 to 0.20 cmol/kg. The Ca and Mg were rated low to moderate, with moderate being dominant in all the fields, with the values ranging from 0.45 to 3.57 cmol/kg and 0.38 to 1.07 cmol/kg, respectively. The enrichment factor (E_f) derived from heavy metal contents is given in Figure 2. The ranges of E_f values were Cu (1.648 – 4.215), Cr (0.474 – 1.471), Mn (0.261 – 4.435), Ni (1.872 – 6.986), Pb (2.172 – 13.884), and Zn (0.999 – 3.439). The E_f value of Pb was higher, and a lower value for Cr was observed

Table 8. *Assessment of Soil Quality Indices*

Land Use Type	Horizon Depth	Standard Ratings	Present Field Condition	Remark	Standard Ratings	Present Field Condition	Remark	Standard Ratings	Present Field Condition	Remark	Standard Ratings	Present Field Condition	Remark
			BD (g/cm^3)			pH (H_2O)			Org. C (%)			TN (%)	
Cassava													
A_p	0-18	≤ 1.5	1.18	NAE	5.51-6.8	6.68	SA	1-5	2.34	Moderate	0.1-0.5	0.15	Moderate
B_e	18-42	≤ 1.5	1.23	NAE	4.01-5.5	6.50	SA	1-5	2.20	Moderate	0.1-0.5	0.11	Moderate
B_{t1}	42-70	≤ 1.5	1.29	NAE	5.51-6.8	6.51	SA	1-5	1.93	Moderate	< 0.1	0.08	Low
B_{t2}	70-146	≤ 1.5	1.33	NAE	5.51-6.8	6.41	SA	1-5	1.13	Moderate	< 0.1	0.04	Low
Pasture													
A_p	0-16	≤ 1.5	1.17	NAE	5.51-6.8	6.06	SA	1-5	3.03	Moderate	0.1-0.5	0.26	Moderate
AB	16-62	≤ 1.5	1.22	NAE	5.51-6.8	5.81	SA	1-5	2.46	Moderate	0.1-0.5	0.16	Moderate
B_t	62-118	≤ 1.5	1.34	NAE	5.51-6.8	5.79	SA	1-5	1.60	Moderate	< 0.1	0.07	Low
B_r	118-150	≤ 1.5	1.36	NAE	5.51-6.8	5.60	SA	< 1	0.87	Low	< 0.1	0.03	Low
Maize													
A_p	0-25	≤ 1.5	1.27	NAE	5.51-6.8	6.30	SA	1-5	2.66	Moderate	0.1-0.5	0.18	Moderate
B_{t1}	25-80	≤ 1.5	1.39	NAE	5.51-6.8	6.11	SA	1-5	1.36	Moderate	< 0.1	0.06	Low
B_{t2}	80-130	≤ 1.5	1.42	NAE	5.51-6.8	5.62	SA	< 1	0.63	Low	< 0.1	0.02	Low

NAE: No Adverse Effects - SA: Slightly Acid

Table 9. *Assessment of Soil Quality Indices*

Land Use Type	Horizon Depth	Standard Ratings	Present Field Condition Av. P (cmol kg^{-1})	Remark	Standard Ratings	Present Field Condition K (cmol kg^{-1})	Remark	Standard Ratings	Present Field Condition Ca (cmol kg^{-1})	Remark	Standard Ratings	Present Field Condition Mg (cmol kg^{-1})	Remark
Cassava													
A_p	0-18	< 15	8.75	Low	< 0.26	0.07	Low	0.5-5.0	3.57	Moderate	0.42-4.2	0.53	Moderate
B_e	18-42	< 15	7.80	Low	< 0.26	0.06	Low	0.5-5.0	1.97	Moderate	0.42-4.2	0.47	Moderate
B_{t1}	42-70	< 15	4.12	Low	< 0.26	0.06	Low	0.5-5.0	2.13	Moderate	0.42-4.2	0.44	Moderate
B_{t2}	70-146	< 15	1.75	Low	< 0.26	0.09	Low	0.5-5.0	0.63	Moderate	< 0.42	0.34	Low
Pasture													
A_p	0-16	< 15	2.23	Low	< 0.26	0.07	Low	0.5-5.0	2.55	Moderate	0.42-4.2	0.45	Moderate
AB	16-62	< 15	1.55	Low	< 0.26	0.08	Low	0.5-5.0	1.82	Moderate	0.42-4.2	0.55	Moderate
B_t	62-118	< 15	0.76	Low	< 0.26	0.12	Low	0.5-5.0	2.26	Moderate	0.42-4.2	1.07	Moderate
B_r	118-150	< 15	2.10	Low	< 0.26	0.08	Low	0.5-5.0	0.89	Moderate	< 0.42	0.38	Low
Maize													
A_p	0-25	< 15	2.29	Low	< 0.26	0.05	Low	0.5-5.0	4.05	Moderate	< 0.42	0.40	Low
B_{t1}	25-80	< 15	2.04	Low	< 0.26	0.20	Low	0.5-5.0	1.93	Moderate	0.42-4.2	1.07	Moderate
B_{t2}	80-130	< 15	0.83	Low	< 0.26	0.04	Low	0.05-0.5	0.45	Low	0.42-4.2	0.46	Moderate

PAE: Possible Adverse Effects - NAE: No Adverse Effects

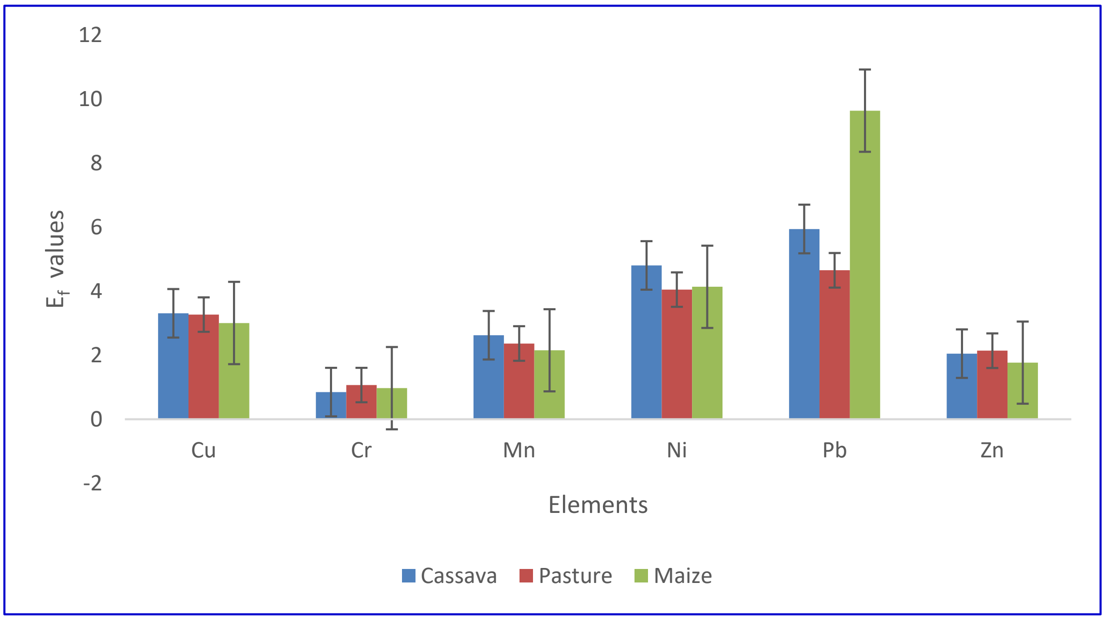

Figure 2
Enrichment factor (E_f)

compared with other heavy metals in the soil samples across the various land uses. Minor enrichment was observed for Cr and Zn, moderate enrichment for Cu and Mn, and moderately severe enrichment for Ni and Pb. Soils under maize showed severe enrichment with Pb when compared with other land uses. The results of the contamination factor (C_f) are presented in Figure 3. The ranges of C_f values were Cu (1.214 – 3.000), Cr (0.272 – 0.707), Fe (0.347 – 1.300), Mn (0.340 – 1.890), Ni (1.894 – 2.702), Pb (2.000 – 5.647), and Zn (0.552 – 2.134). The higher value of $C_{f,}$ irrespective of land use, was observed for Pb, and a lower value for Cr. The C_f values ranged from 0.272 to 5.647 across the agricultural lands. The results identified low (CF<1) to moderate (1≤CF<3) contamination for cassava, pasture, and maize lands for all the metals, and considerable (3≤CF<6) contamination for Pb. The geoaccumulation index (I_{geo}) values were depicted in Figure 4 and ranged as follows: Cu (-0.305 – 1.000), Cr (-2.465 – -1.086), Fe (-2.111 – -1.086), Mn (-2.141 – 0.333), Ni (0.336 –

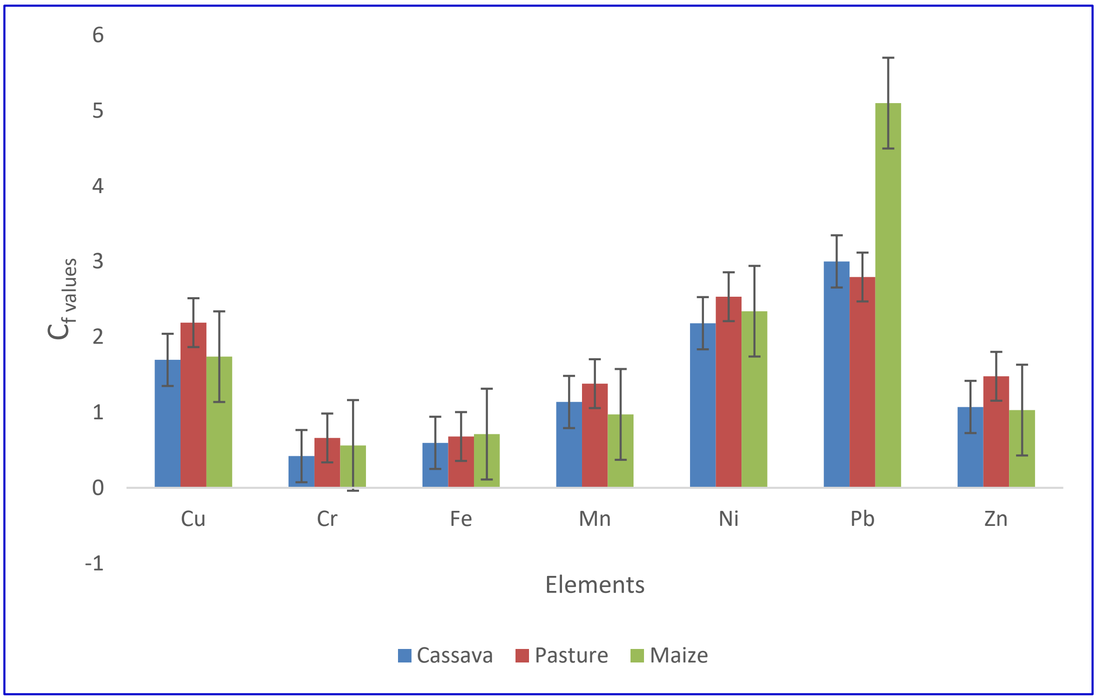

Figure 3 *Contamination factor (C_f)*

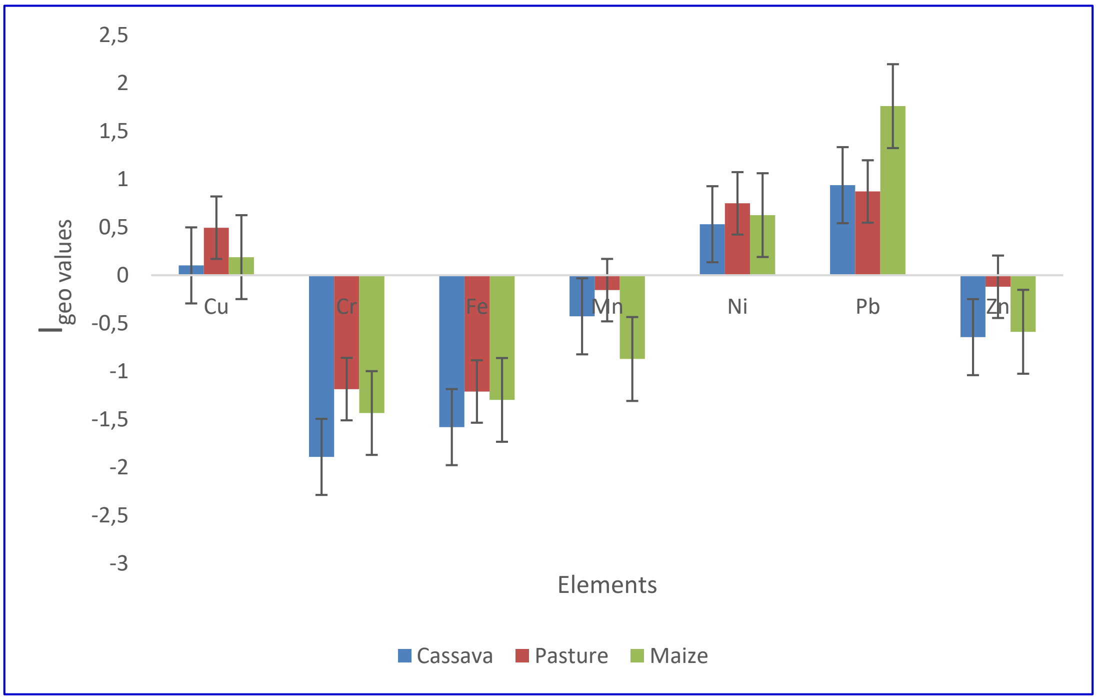

Figure 4 *Geoaccumulation index (I_{geo})*

0.860), Pb (0.415 – 1.913), and Zn (-1.442 – 0.509). The I_{geo} results indicated a contamination class of 0 (not contaminated) for nearly all the analysed heavy metals in the agricultural lands. Only Ni and Pb for all the examined agricultural lands were categorised as contamination class I (uncontaminated to moderately contaminated) and contamination class II (moderately contaminated), respectively (Table 5). The potential ecological risk coefficient (Er) values for all the metals assessed were below 40 (Er<40) (Table 10), indicating low potential ecological risk (Table 2). The order of the mean Er values was Pb > Ni > Cu > Mn> Zn > Cr. In general, the potential ecological risk index (RI) values for the heavy metals in the studied soils ranged between 12.022 and 192.353, implying low ecological risk (PERI<150) for the majority of the metals, except for Pb, posing a moderate ecological risk (150<RI<300).

Table 10
Potential Ecological Risk Coefficient (Er) and Index (RI)

Horizon Designation	Depth (cm)	Cu	Cr	Mn	Ni	Pb	Zn
Profile 1				Er			
A_p	0-18	6.964	0.543	1.540	12.128	10.588	1.194
B_e	18-42	7.321	0.848	1.070	9.468	12.647	0.701
B_{t1}	42-70	6.071	0.761	0.910	10.000	13.824	0.552
B_{t2}	70-146	13.571	1.217	1.030	12.021	22.941	1.836
Profile 2							
A_p	0-16	8.393	1.239	1.890	13.511	16.471	1.090
AB	16-62	8.036	1.413	1.400	10.745	13.824	0.851
B_t	62-118	12.321	1.283	1.110	13.191	15.588	1.836
B_r	118-150	15.000	1.348	1.120	13.191	10.000	2.134
Profile 3							
A_p	0-25	8.571	0.957	1.500	12.021	28.235	1.090
B_{t1}	25-80	6.786	1.043	1.080	9.468	24.412	0.701
B_{t2}	80-130	10.714	1.370	0.340	13.617	23.824	1.299
	Mean	9.432	1.093	1.181	2.352	3.497	1.208
				RI			
		103.750	12.022	12.990	129.362	192.353	13.284

Discussion

The study results showed the significant impact of agricultural activities on some soil morphological, physical, and chemical properties. The soils under cassava, pasture, and maize cultivation are generally Lixisols according to WRB (2022) and Alfisols according to USDA Soil Taxonomy (Soil Survey Staff, 2014). These classifications indicate moderately developed tropical soils with appreciable fertility and subsurface clay accumulation suitable for agricultural production. The differences in soil physical properties between cassava and pasture land uses can be attributed to variations in soil management practices, organic matter content, and nutrient cycling. The higher sand content and lower clay content in the pasture Ap horizon may imply a higher danger of soil erosion, whereas cassava soils' rising clay concentration with depth may suggest more pronounced soil compaction (Morgan, 2005). The high percentage of sand in all the lands reflects the observed high infiltration rate (Senjobi, 2007; Basil et al., 2019). The soils' poor water-holding capacity, caused by their coarse texture, increased their erodibility, which has been exposed by crop production and livestock grazing. The silt/clay ratio data indicated that the soils were composed of weakly weathered parent materials. Van Wambeke (1962) reported that old parent materials usually have silt/clay ratios below 0.15, while silt/clay ratios above 0.1 indicates young parent materials. Bulk density above 1.65g/cm3 can inhibit root growth and water movement (Aminu et al., 2013). This increase in bulk density with depth is attributed to organic matter depletion and tillage practices. Tillage activities and surface soil disturbance are expected to deplete organic matter and cause soil degradation (Bahrami et al., 2010). The percentage of soil organic carbon content was higher in the topsoil layer than in the deeper layer. The findings of this study are consistent with earlier research (Nguyen, 2008; Basil *et al.*, 2019), which found that SOC is low when compared to average levels of SOC classification by Amacher et al. (2007) and Arifin et al. (2012). The low level of basic cations in agricultural fields is due to the long-term effect and continual nitrogen uptake by plants. The findings show that weathering severity, agriculture, and the use of inorganic acid-forming fertilisers all have an impact on cation distribution and depletion (Owusu-Bennoah et al. 2000). The low results for these basic cations could be related to poor OM and clay activity (Osinuga et al., 2020). Pedons have low ECEC levels, frequently less than 6 cmol/kg (Defoer et al., 2000). As a result, the calculated ECEC depends on soil pH and organic matter. There is no concern regarding soil sodicity or alkalinity based on the current level of basic cations, as it will not affect the world food supply or increase environmental challenges (Osinuga et al., 2024). In agricultural soils, levels of heavy metals are of critical importance due to their accumulation in food chains and adverse effects on the entire ecosystem. Soil contamination with heavy metals increases the risk of exposure to these metals in livestock and humans, and absorption by edible plants. In this study, seven metals (Cu, Cr, Fe, Mn, Ni, Pb, and Zn) were assessed, and their levels were found to be within world averages for agricultural soils (Kabata-Pendias and Mukherjee, 2007). However, since metal uptake by plants from soil is greater at low soil pH, the high pH observed in the studied soils may have a mitigating effect (Afonne et al., 2022). The Pb level was higher than that of other metals. Lead is a common element naturally present in the Earth's crust and used in various industrial applications, such as fertilizers and pesticides for agriculture. It can enter the soil through these processes (Hernberg, 2000; Salminen et al., 2013). Exposure to these metals can cause a range of health issues, including kidney, nervous, and respiratory problems, disturbances in calcium metabolism, increased blood pressure, and fertility issues (Nelson et al., 2011; Salminen et al., 2013). Elevated levels of these metals often result from poor waste disposal into river systems and the use of fertilizers and other agricultural additives (Kumar et al., 2023). Agricultural practices, especially the use of fertilizers and pesticides, can lead to increased levels of these metals in the soil over time, which potentially pose risks to soil health and crop productivity. Variations in metal levels across different land uses could be due to natural processes and diverse anthropogenic sources (Salminen et al., 2013). The correlation analysis revealed significant interrelation-ships among soil properties, emphasizing the dominant influence of soil texture and organic matter on soil quality, hydraulic behaviour, nutrient dynamics, and heavy metals enrichment. The inverse relationship among the soil particles reflects the compositional nature of soil separates and is consistent with findings by Weil and Brady (2017) and Osinuga et al. (2024), who reported that increases in one particle fraction necessarily reduce others within a fixed soil mass. The negative relationships between BD and Ksat. confirm that soil compaction reduces pore space and restricts water movement, while well-structured soils enhance infiltration and permeability (Zhang and Schaap, 2019; Reynolds et al., 2020). Organic carbon exhibited a negative correlation BD and positive correlations Ksat. This indicates that increased organic matter improves soil structure, reduces compaction, and enhances water movement. Similar findings have been reported by Minasny and McBratney (2018) and Voltr et al. (2021), who emphasized the structural benefits of soil organic matter. Furthermore, the positive correlation of OC with TN and avail-P highlights the central role of organic matter in nutrient cycling and availability. Organic matter serves as a reservoir for nitrogen and phosphorus and enhances microbial activity, leading to improved nutrient mineralization (Lal, 2020; Lehmann et al., 2020). Soil quality assessment using SQIs is a more pragmatic, realistic, and sensible tool for evaluating and monitoring soil health (Rachman, 2019), and can serve as a guide to predict soil potentials and productivity (Karlen et al., 2006; Kiani et al., 2017). Furthermore, Bünemann et al. (2018) reported that soil quality assessment is a type of soil evaluation that describes soil using multiple concepts. The results of bulk density show no adverse effect on growth and development. However, the majority of the indicators (organic carbon, total nitrogen, available phosphorus, and exchangeable bases) revealed low to moderate quality. In a similar study by Arifin et al. (2016) in dryland farms at Lombok, West Nusa Tenggara, low levels of organic carbon and nitrogen were found. Similarly, Martunis et al. (2016) reported low levels of organic carbon, nitrogen, and available phosphorus in some dryland farming areas in Aceh Besar. Geochemical indicators are used to quantify the degree of anthropogenic impact on soil contamination by trace elements (Kowalska et al., 2018). The enrichment factor (Ef) is a normalization factor often used as an indicator to assess the presence and severity of anthropogenic contamination in sediments or aquatic habitats. In this study, iron (Fe) was used as a normaliser for several reasons. Firstly, it is not significantly affected by diagenetic processes and strong redox effects in sediments, which make it highly immobile. Secondly, it is one of the most abundant naturally occurring metals in the Earth's crust and does not exist in a dissolved form; therefore, its anthropogenic sources are considered very few (Ho et al., 2012; Mohammed et al., 2021). The degree of anthropogenic impact on soil contamination by trace elements is measured using geochemical indicators (Kowalska et al., 2018). A normalization factor called the enrichment factor (Ef) is frequently used as an index to determine whether anthropogenic contamination is present and its severity in sediments or aquatic environments. Iron (Fe) was employed as a normalizer in this investigation for various reasons. Firstly, it is extremely immobile due to strong redox effects in sediments and diagenetic processes. Secondly, its anthropogenic origins are extremely rare because it is one of the most prevalent naturally occurring metals in the Earth's crust and does not exist in a dissolved state (Ho et al., 2012; Mohammed et al., 2021). Lead has a higher Ef than other metals, suggesting significant contamination. The distribution of heavy metals was under minimal to moderate conditions, and most of the metal enrichment in the soils may be due to the natural weathering processes and agricultural practices. The contamination factor (C_f) is a simple and lovely indicator to assess the degree of contamination of heavy metals in soils. The quality of aquatic systems and sediments near industrial and urban areas can also be monitored and evaluated using this index (Hakanson, 1980; Shen et al., 2019). The average contamination values of the metals showed low levels of contamination for Cr (0.546) and Fe (0.658), moderate contamination levels for Cu (1.886), Mn (1.181), Ni (2.352), and Zn (1.208), and considerable levels of contamination for Pb (3.497) only. Thus, the level of contamination can be from both the natural sources and agricultural activities (Anu et al., 2019; Chaudhari et al., 2024). The geoaccumulation index (Igeo) is an indicator used to assess the temporal variation of trace elements by comparing the current metal concentrations in sediments with the geochemical background (Anu et al., 2019). This index has been frequently utilised in trace elements research worldwide (Loska et al., 2003; Yaqin et al., 2008). According to the Igeo classification system of Muller (1981), the Igeo results indicated a contamination class of 0 (practically not contaminated) for nearly all the metals except for Ni, which has a contamination class of 1 (uncontaminated to moderately contaminated), and Pb has a contamination class of II (moderately contaminated). Ecological indicators such as microbial diversity and plant species composition were crucial in understanding the biological aspects of soil quality. The potential ecological risk coefficient (Er) and potential ecological risk index (RI) are the ecological risk assessment indices used in the current study. All other metals posed low ecological risk (ER <40). Kumar et al. (2020) in their research reported Er value below 40 for elements such as Cr, Mn, Ni, Cu, and Zn. This was also the result obtained in this study, indicating low ecological risk associated with heavy metals. The RI values indicated low ecological risk (RI<150) for all the heavy metals assessed, except for Pb, which revealed moderate ecological risk. This finding supported the work of Anu et al. (2019). Overall, the results indicate the need for careful monitoring and management of soil quality in agricultural areas to prevent excessive accumulation of heavy metals, especially Pb, and ensure sustainable agricultural practices.

Conclusions

The soils of the study sites were characterised and assessed using physical, chemical, geochemical, and ecological soil quality indicators. The findings highlight the significant variations in nutrient elements and heavy metal concentrations across different land uses, emphasising the impact of human activities on soil fertility and quality. The application of Soil Quality Indices (SQIs) has proven to be a valuable tool for assessing soil quality, providing a systematic and comparative evaluation of soil health across different land uses, reflecting the impact of agricultural practices on soil quality. The soils were classified as “low to medium” in quality, with the most common limiting factors being low levels of available phosphorus and exchangeable potassium. Also, the distribution and enrichment of heavy metals in the soils of the study area depend on the lithogenic and anthropogenic factors. Most of the heavy metals’ enrichments were due to the natural weathering process, atmospheric deposition, and agrochemical usage. Heavy metals, viz. Ni and Pb were found to be highly enriched, while others were less enriched in the soils. Therefore, regular soil testing programs should be conducted at intervals of 2-3 years to monitor soil quality, detect early signs of soil degradation and contamination, and identify areas that need improvement. Adoption and promotion of soil management practices like crop rotation, use of organic amendments (compost and biochar), and planting of cover crops to enhance soil fertility, increase microbial diversity and ecosystem resilience, and reduce contamination risks, with the attendant toxicity to man. Land use managers and policymakers should prioritise soil conservation and fertility management to ensure long-term soil health and productivity.

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Author contributions. Olufemi Adewale Osinuga conceptualized and designed the study. Other authors, aside from Olufemi Adewale Osinuga, sourced funds, prepared materials, and collected data. Olufemi Adewale Osinuga analysed the data. Kaothar Iretomiwa Shittu and Barakat Ireyimika Adewale wrote the first draft of the manuscript. Olufemi Adewale Osinuga wrote the final manuscript, which all authors read and approved.

References

ADEBO B.O., AWETO A.O., OGEDENGBE K. (2020) Assessment of soil quality under different agricultural land use systems: a case study of the Ibadan farm settlement. International Journal of Plant and Soil Science*,* 32(4): 89-104. https://doi.org/10.9734/ijpss/2020/v32i430275

ADEDEJI O.H., OLAYINKA O.O., TOPE-AJAYI O.O. (2019) Spatial distribution and health risk assessment of soil pollution by heavy metals in Ijebu-Ode, Nigeria. Journal of Health and Pollution*,* 9(22): 1-15. https://doi.org/10.5696/2156-9614-9.22.190601

AFONNE O.J., CHUKWUKA J.U., IFEDIBA E.C., OBI, E. (2022) Pollution indices of heavy metal contaminants in typical agrarian soil samples in Ihiala, South-East Nigeria. Health and Environment*,* 3(1): 176-185. https://doi.org/10.25082/HE.2022.01.005

AIBONI V.U. (2001) Characteristics and classification of soils of a representative topography location in UNAAB. ASSET Series A*,* 1(1): 35-50.

AMACHER M.C., O'NEILL K.P., PERRY C.H. (2007) Soil Vital Signs: A New Soil Quality Index (SQI) for Assessing Forest Soil Health. Research Paper RMRS-RP-65WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 12pp. https://doi.org/10.2737.RMRS-RP-65

AMINU Z., YAKUBU M., MOHAMMED A.A., KUMAR N. (2013) Impact of land use on soil quality in Suleja, Niger State. Indian Journal of Land Science*,* 2(2): 1-7. ISSN: 2277-1743 (Print) ISSN: 2278-7879 (Online)

AMUNDSON R., BERHE A.A., HOPMANS J.W., OLSON C., SZTEIN A.E., SPARKS D.L. (2015) Soil science. Soil and human security in the 21st century. Science, 348(6235): 1261071. https://doi.org/10.1126/science.1261071

ANDERSON J.M., INGRAM J.S.I. (1993) Tropical soil biology and fertility: a handbook of methods. CAB International, Wallingford. ISBN 0 85198 821 0.

ANU J., ANOOP P.P., RAJESH R., JOSE M., ANGEL M., ANU G. (2019) Spatial variation of trace element concentration and contamination assessment in the coral reef sediments of Lakshadweep Archipelago, Indian Ocean. Marine Pollution Bulletin*,* 146: 106-116. https://doi.org/10.1016/j.marpolbul.2019.06.003

ARIFIN A., KARAM D.S., SHAMSHUDDIN J., MAJID N.M., RADZIAH O., HAZANDY A.H., ZAHARI I. (2012) Proposing a suitable soil quality index for natural, secondary and rehabilitated tropical forests in Malaysia. African Journal of Biotechnology, 11(14): 3297-3309. https://doi.org/10.5897/AJB11.2903

ARIFIN Z., SUSILOWATI L.E., KUSUMA B.H. (2016). Perubahan indeks kualitas tanah di lahan kering akibat masukan pupuk anorganik-organik. Jurnal Agroteksos, 26(2): 1–17.

BAHRAMI A., EMADODIN I., ATASHI M.R., BORK H.R. (2010) Land use change and soil degradation: a case study, North of Iran. Agriculture and Biology Journal of North America, 1(4): 600-605. ISSN Print: 2151-7517.

BARDGETT R.D., VAN DER PUTTEN W.H. (2014).Belowground biodiversity and ecosystem functioning. Nature, 515(7528): 505–511. https://doi.org/10.1038/nature13855

BASIL E.C., SENJOBI B.A., OYEGOKE C.O., FABUNMI T.O. (2019). Effects of different land uses on soil quality and degradation in Abeokuta, Ogun State, Nigeria. Nigerian Journal of Soil Science, 29: 87-101. ISSN-1597-4488

BRUSSAARD L., CARON P., CAMPBELL B., LIPPER L., MAINKA S., RABBINGE R., DIDIER D., PULLEMAN M.M. (2010) Reconciling biodiversity conservation and food security: scientific challenges for a new agriculture. Current Opinion in Environmental Sustainability, *2*(1-2): 34-42. https://doi.org/10.1016/j.cosust.2010.03.007

BUNEMANN E.K., BONGIORNO G., BAIC Z., CREAMERB R.E., DEYNB G.D., GOEDEB R.D., FLESKENSD L., GEISSEND V., KUYPERB T.W., MADERA P., PULLEMANB M., SUKKELF W/., GROENIGENB J.W.V., BRUSSAARD L. (2018) Soil quality – a critical review. Soil Biology and Biochemistry, 120: 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030

CHAUDHARI U., KUMARI D., TYAGI, T., MITTAL S., SAHOO P.K. (2024) Geochemical Signature and Risk Assessment of Potential Toxic Elements in Intensively Cultivated Soils of South-West Punjab, India. Minerals, 14: 576. https://doi.org/10.3390/min14060576

DELELEGN Y.T., PURAHONG W., BLAZEVIC A., YITAFERU B., WUBET T., GORANSSON H., GODBOLD D.L. (2017) Changes in land use alter soil quality and aggregate stability in the highlands of northern Ethiopia. Scientific Report, 7(1): 1–12. https://doi.org/10.1038/s41598-017-14128-y

FAZEKAŠOVÁ D., FAZEKAŠ J. (2020) Soil quality and heavy metal pollution assessment of iron ore mines in Nizna Slana (Slovakia). Sustainability, 12(6): 2549. https://doi.org/10.3390/ su12062549

FOOD AND AGRICULTURE ORGANIZATION (FAO). (2017) The impact of land use and soil management on soil health. FAO. https://www.fao.org/3/bl813e/bl813e

GEE G., BAUDER J.W. (1986) Particle Size Analysis. In: Klute, A., Ed., Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods, 2nd Edition, American Society of Agronomy, Inc., Madison, 383-411. https://doi.org/10.2136/sssabookser5.1.2ed.c15

GRUSZECKA-KOSOWSKA A., BARAN A., MAZUR-KAJTA K., CZECH T. (2019) Geochemical fractions of the agricultural soils of southern Poland and the assessment of the potentially harmful element mobility. Minerals, 9(11): 674. https://doi.org/10.3390/min9110674

GRUSZECKA-KOSOWSKA A., BARAN A., WDOWIN M., MAZUR-KAJTA K., CZECH T. (2020) The contents of the potentially harmful elements in the arable soils of southern Poland, with the assessment of ecological and health risks: a case study. Environmental Geochemistry and Health, 42(2): 419–442. https://doi.org/10.1007/s10653-019-00372-w

GONG Q., DENG J., XIANG Y., WANG Q., YANG L. (2008) Calculating pollution indices by heavy metals in ecological geochemistry assessment and a case study in parks of Beijing. Journal of China University of Geoscience, 19: 230–241. https://doi.org/10.1016/S1002-0705(08)60042-4

HAKANSON L. (1980) An ecological risk index for aquatic pollution control: a sedimentological approach. Water Research, 14: 975–1001. https://doi.org/10.1016/0043-1354(80)90143-8

HERNBERG S. (2000) Lead poisoning in a historical perspective. American Journal of Industrial Medicine, 38: 244-254. http://dx.doi.org/10.1002/1097-0274(200009)38:3<244::AID-AJIM3>3.0.CO;2-F

HO H.H., SWENNEN R., CAPPUYNS V., VASSILIEVA E., VAN TRAN T. (2012) Necessity of normalization to aluminum to assess the contamination by heavy metals and arsenic in sediments near Haiphong Harbor, Vietnam. Journal of Asian Earth Sciences, 56: 229–239. http://dx.doi.org/10.1016/j.jseaes.2012.05.015

INTERNATIONAL INSTITUTE OF TROPICAL AGRICULTURE (IITA) (1982) Laboratory manual for soil and plant analysis. IITA, Ibadan, Nigeria. Manual Series, 1: 70

KABATA-PENDIAS A., MUKHERJEE A.B. (2007) Trace elements from soil to human, Springer Berlin Heidelberg, New York. https://doi.org/10.1007/978-3-540-32714-1

KARLEN D.L., HURLEY E.G., ANDREWS S.S., CAMBARDELLA C.A., MEEK D.W., DUFFY M.D., MALLARINO A.P. (2006) Crop rotation effects on soil quality at three northern corn/soybean belt locations. Agronomy Journal, 98(3): 484–495. https://doi.org/10.1016/S00167061(03)00039-9

KIANI M., HERNANDEZ-RAMIREZ G., QUIDEAU S.A., SMITH E.G., JANZEN H.H., LARNEY F.J., PUURVEEN D. (2017) Quantifying sensitive soil quality indicators across contrasting long-term land management systems: Crop rotations and nutrient regimes. Agriculture, Ecosystems and Environment, 248: 123-135. https://doi.org/10.1016/J.AGEE.2017.07.018

KIJOWSKA-STRUGALA M., BARAN A., SZARA-BAK M., WIEJACZKA L., PROKOP P. (2022) Soil quality under different agricultural land uses as evaluated by chemical, geochemical and ecological indicators in mountains with high rainfall (Darjeeling Himalayas, India). Journal of Soils and Sediments, 22: 3041–3058. https://doi.org/10.1007/s11368-022-03274-0

KLIMKOWICZ-PAWLAS A., MALISZEWSKA-KORDYBACH B., SMRECZAK B. (2019) Triad-based screening risk assessment of the agricultural area exposed to the long-term PAHs contamination. Environmental Geochemistry and Health, 41: 1369–1385. https://doi.org/ 10.1007/s10653-018-0220-y

KOWALSKA J.B., MAZUREK R., GĄSIOREK M., ZALESKI T. (2018) Pollution indices as useful tools for the comprehensive evaluation of the degree of soil contamination–a review. Environmental Geochemistry and Health, 40: 2395–2420. https://doi.org/10.1007/s10653-018-0106-z

KULBAT E., SOKOŁOWSKA A. (2019) Methods of assessment of metal contamination in bottom sediments (case study: Straszyn Lake, Poland). Archives of Environmental Contamination and Toxicology, 77: 605–618. https://doi.org/10.1007/s00244-019-00662-5

KUMAR A., CABRAL-PINTO M., KUMAR M., DINIS P.A. (2020) Estimation of risk to the eco-environment and human health of using heavy metals in the Uttarakhand Himalaya, India. Applied Sciences, 10(20): 7078. https://doi.org/10.3390/app10207078

KUMAR V., TYAGI S.K., KUMAR K., PARMAR R.S. (2023) Heavy metal-induced pollution in the environment through waste disposal. International Journal of Research Publication and Reviews, 4(7): 1205-1210. ISSN 2582-7421

LAL R. (2015) Restoring soil quality to mitigate soil degradation. Sustainability, 7(5): 5875– 5895. https://doi.org/10.3390/su7055875

LAL R. (2020) Soil organic matter and water retention. Agronomy Journal, 112(5): 3265–3277. https://doi.org/10.1002/agj2.20282

LEHMANN J., BOSSIO D.A., KÖGEL-KNABNER I., RILLING M.C. (2020) The concept and future prospects of soil health. Nature Reviews Earth and Environment, 1, 544–553. https://doi.org/10.1038/s43017-020-0080-8

LOSKA K., WIECHULA D., BARSKA B., CEBULA E., CHOJNECKA, A. (2003) Assessment of arsenic enrichment of cultivated soils in Southern Poland. Polish Journal of Environmental Studies, 2: 187–192. eISSN: 2083-5906 ISSN: 1230-1485

MARTUNIS L., SUFARDI S., MUYASSIR M. (2016) Analisis indeks kualitas tanah di lahan kering Kabupaten Aceh Besar Provinsi Aceh. Jurnal Budidaya Pertanian, 12(1): 34–40. ISSN: 1858-4322

MAURYA S., ABRAHAM J.S., SOMASUNDARAM S., TOTEJA R., GUPTA R., MAKHIJA S. (2020) Indicators for assessment of soil quality: a mini-review. Environmental Monitoring and Assessment, 192(9): 1–22. https://doi.org/10.1007/s10661-020-08556-z

MCLEAN E.O. (1965) Exchangeable acidity. In C A. Black (Ed.), Methods of soil analysis, Part 2. American Society of Agronomy, Madison, WI., pp.1093-1104. 35

MINASNY B., MCBRATNEY A.B. (2018) Limited effect of organic matter on soil available water capacity. European Journal of Soil Science, *69*(1): 39-47. https://doi.org/10.1111/ejss.12475

MOHAMMAD A.M., BHASKARA RAO K., DHANAMJAYA RAO E.N., REDDY K.S.N. (2021) Major and trace elements' concentration in recent clastic sediments from part of the eastern coast of India: an assessment of metal pollution. Environmental Earth Sciences, 80: 341. https://doi.org/10.1007/s12665-021-09627-1

MORGAN R.P.C. (2005) Soil erosion and conservation. 3rd ed. Blackwell Publishing. (Chapter 2: Soil Properties of Erosion). ISBN 1-4051-1781-8.

MULLER G. (1981) The heavy metal pollution of the sediments of Neckars and its tributary: a stocktaking. Chemiker-Zeitung, 105: 157–164.

MURPHY J., RILEY J.P. (1962) A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta, 27: 31-36. http://dx.doi.org/10.1016/S0003-2670(00)88444-5

NELSON D.W. (1983) Determination of nitrogen in soil and plant tissue. In R. D. Bremner and A.M Blackmer (Eds.), Methods of soil analysis, Part 2. American Society of Agronomy, Madison, WI., pp.561-579.

NELSON D.W., SOMMERS L.E. (1996) Total carbon, organic carbon and organic matter. In D.L. Sparks (Eds.) Methods of soil analysis. Part 3. Chemical methods. SSSA Book Ser. 5. SSSA, Madison, WI., pp.961-1010.

NELSON L.S., LEWIN N.A., HOWLAND M.A., HOFFMAN R.S., GOLDFRANK L.R., FLOMENBAUM N.E. (2011) Goldfrank's toxicologic emergencies, 9th edition, McGraw Hill, New York. Academic Emergency Medicine, 18(10): e85. ISBN: 978-0-07-160594-6

NGUYEN V.L. (2008) Use of GIS modelling in assessment of forestry land´s potential in Thua Thien Hue province of Central Vietnam (PhD dissertation). Germany: Göttingen University.

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST). (2003). SRM 2711a: Montana II Soil Moderately Elevated Trace Element Concentrations. Gaithersburg, Maryland, USA.

OSINUGA O.A., OYEGOKE C.O. (2017) Impact of land use and agrochemicals on quality potential of wetland soils of Odeda Farm Institute, Eweje, Ogun State, Nigeria. Agriculture, Forestry and Fisheries, 6(3): 82-88. https://doi.org/10.11648/j.aff.20170603.13

OSINUGA O.A., AIBONI V.U., OYEGOKE C.O. (2020) Classification and suitability evaluation of soils along a toposequence for rice production in Alabata, southwest Nigeria. Agro-Science, 19(4): 43-50. https://dx.doi.org/10.4314/as.v19i4.8

OSINUGA O.A., ADEKOLA E.A., AKANDE O.O., OBRUTU I., OLUTIMI M.S. (2024) Properties and micronutrients status of hydromorphic soils overlying Ewekoro formation in Ogun State, Nigeria. Arabian Journal of Geosciences, 17: 197. https://doi.org/10.1007/s12517-024-11999-0

OWUSU-BENNOAH E., AWADZI T.W., BOATENG E., KROGH L., BREUNING-MADSEN H., NBORGGARD O.K. (2000) Soil properties of a toposequence in the moist semideciduous forest zone of Ghana. West African Journal of Applied Ecology, 1: 1–10. https://doi.org/10.4314/wajae.v1i1.40565

OYEDELE A.O., DENTON O.A., OLAYUNGBO A.A., OGUNREWO O.M. (2014) Spatial assessment of soil quality indicators under different agricultural land uses. IOSR Journal of Agriculture and Veterinary Science, 7(8): 41-48. https://doi.org/0.9790/2380-07814148

RACHMAN L.M. (2013) Esensi dan kebutuhan terhadap penetapan kualitas tanah. Lokakarya Nasional Dan Seminar Forum Komunikasi Perguruan Tinggi Pertanian Indonesia, 749–763.

RACHMAN L.M. (2019) Urgensi indeks kualitas tanah plus sebagai instrumen untuk penilaian dan monitoring kualitas tanah. Jakarta (Unpublished).

REYNOLDS W.D., NURSE R.E., PHILLIPS L.A., DRURY C.F., YANG X.M., PAGE E.R. (2020) Characterizing mass–volume–density–porosity relationships

DOI: 10.60923/issn.2281-4485/24769

in a sandy loam soil amended with compost. Canadian Journal of Soil Science, 100: 289–301. https://doi.org/10.1139/cjss-2019-0149

SALMINEN R., SPIJKER J., VIJVER M., ECKELMAN M., SELINUS O., POST-HUMA L., DE ZWART D., VAN DE MEENT D. (2013) Metals in the environment. In: Environmental risks and challenges of anthropogenic metals flows and cycles. A report of the Working Group on the Global Metal Flows to the International Resource Panel, United Nations Environment Programme, New York, 31-55pp.

SENJOBI B.A. (2007) Comparative assessment of the effect of land use and land type on soil degradation and productivity in Ogun state, Nigeria. Published Ph.D. Thesis submitted to the Department of Agronomy, University of Ibadan, Ibadan. 161pp.

SHEN F., MAO L., SUN R., DU J., TAN Z., DING M. (2019) Contamination evaluation and source identification of heavy metals in the sediments from the Lishui River Watershed, southern China. International Journal of Environmental Research and Public Health, 16(3): 336–351. https://doi.org/10.3390/ijerph16030336

SOIL SURVEY STAFF. (2014). Keys to Soil Taxonomy. USDA Natural Resources Conservation Service. 12th edition, 372pp.

STOCKMAN U., MINASNY B., MCBRATNEY A.B. (2014) How fast does soil grow? Geoderma, 216: 48e61. https://doi.org/10.1016/j.geoderma.2013.10.007

SUMMER M.E., MILLER W.P. (1996) Cation exchange capacity and exchange coefficients. In D. L. Sparks (Ed.), Methods of Soil Analysis, Part 3. Soil Science Society of America, Madison, WI., pp.1201-1229.

VAN WAMBEKE A.R. (1962) Criteria for classifying tropical soils by age. Journal of Soil Science, 13: 124-132.

VELDKAMP E., SCHMIDT M., POWERS J.S., CORRE M.D. (2020) Deforestation and reforestation impacts on soils in the tropics. Nature Reviews, 1(11): 590–605. https://doi.org/10. 1038/s43017-020-0091-5

VOLTR V., MENŠÍK L., HLISNIKOVSKÝ L., HRUŠKA M., POKORNÝ E., POSPÍŠILOVÁ L. (2021) The Soil Organic Matter in Connection with Soil Properties and Soil Inputs. Agronomy,11: 779. https://doi.org/10.3390/agronomy11040779

WEIL R.R., BRADY N.C. (2017). The nature and properties of soils. 15th Edition, Pearson Education, 695-709. ISBN: 978-0133254488

WORLD REFERENCE BASE (WRB). (2022) World reference base for soil resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria. 234pp.

YAQIN J., YINCHANG F., JIANHUI W., TAN Z., ZHIPENG B., CHIQING D. (2008). Using geoaccumulation index to study source profiles of soil dust in China. Journal of Environmental Science, 20(5): 571–578. https://doi.org/10.1016/S1001-0742(08)62096-3

YU P., HAN D., LIU S., WEN X., HUANG Y., JIA H. (2018) Soil quality assessment under different land uses in an alpine grassland. Catena, 171: 280-287. https://doi.org/10.1016/j. catena.2018.07.021

ZHANG Y., SCHAAP M.G. (2019) Estimation of saturated hydraulic conductivity with pedotransfer functions: A Review. Journal of Hydrology, 575: 1011-1130. https://doi.org/10.1016/j.jhydrol.2019.05.058