

Landscape controls physicochemical properties and nutrient dynamics of a biotite-granite catena in the rainforest zone of Ghana

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ABSTRACT

Soil properties and their interactions serve as essential indicators of soil formation and ecosystem sustainability. However, in tropical ecosystems, limited knowledge exists on nutrient dynamics along toposequences and soil depth under varying land-use. Understanding these spatial and vertical variations is critical for developing sustainable land management practices. Field investigations along a biotite-granite toposequence in Ghana's tropical rainforest were used to assess vertical distributions and interactions of soil physicochemical properties across different landscape positions and land-use systems. Structural equation modeling (SEM) was applied to examine relationships among soil properties and land use. Soils showed marked variability along the toposequence and with depth. Surface layers had sandy loam textures, transitioning to sandy clay loam in subsurface horizons. Bulk density was higher in cultivated soils (1.5 g cm^{-3}) than in forest soils (1.46 g cm^{-3}), reflecting compaction from agricultural activities. Forest soils retained greater soil organic carbon (SOC) and moisture. Soil pH ranged from acidic (5.4) in upper horizons to very strongly acidic (4.6) in deeper layers. Total nitrogen and phosphorus were concentrated in surface horizons, whereas micronutrients, particularly zinc ($< 0.5 \text{ mg kg}^{-1}$), were deficient. SEM indicated significantly lower C:N:P ratios in croplands due to SOC depletion and nutrient imbalance. The study demonstrates that forested landscapes enhance SOC, nutrient availability, and soil health compared to cultivated systems. These findings underscore the importance of conserving natural vegetation and integrating landscape position in designing sustainable soil and nutrient management strategies for tropical agroecosystems.

1. Introduction

Soil is a fundamental component of terrestrial ecosystems, playing a critical role in nutrient cycling, carbon sequestration, and supporting plant growth (Nazir et al., 2024; Smith et al., 2015; Telo da Gama, 2023). It is essential for maintaining agricultural productivity and for ensuring environmental health. The dynamics of soil carbon

sequestration and nutrient cycling are increasingly recognized as pivotal factors in advancing sustainable land management and environmental stewardship (Beheshti et al., 2012). As the global population is projected to reach 9 to 10 billion by mid-century (Nelson et al., 2024; United Nations, 2024), sustainable soil management becomes even more urgent to ensure food security and ecological resilience (Foley et al., 2011; Godfray et al., 2010; Lal, 2008; Smith et al., 2013).

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Tropical soils face significant challenges such as erosion, nutrient leaching, and unsustainable land use, that affect soil health (Montanarella et al., 2016; Powlson et al., 2016). High decomposition rates and nutrient loss further complicate soil fertility in these regions (Don et al., 2011). Food production in such areas is often constrained by low levels of soil organic carbon (SOC), nitrogen, phosphorus, calcium, magnesium, and zinc, coupled with low pH and toxic levels of aluminum and manganese (Sanchez et al., 2003). Furthermore, unsustainable agricultural practices and the prevalence of uncontrolled mining activities have compromised food safety. Addressing these constraints is vital for enhanced soil productivity and climate change mitigation through carbon sequestration (Batjes, 2014; Lal and Stewart, 2018; Martin et al., 2014). Thus, employing sustainable land management practices coupled with different standards of ecosystem restoration is imperative to restore tropical degraded land. For instance, the adoption of restoration standards addresses a series of land degradation issues while reducing CO₂ emission (Nelson et al., 2024; Young et al., 2022).

Topography is one of the cardinal factors that exerts a significant influence on soil properties via the alteration of water movement, erosion, and deposition patterns. Thus, a well-developed catena (a sequence of soils along a slope) offers valuable insights into weathering and pedogenic processes from a variation in common parent material (Lima et al., 2021; Rosemary et al., 2017). These variations result in differences in soil organic matter (SOM), structure, nutrient concentrations, and water retention capacity (Awoonor et al., 2021; Awoonor and Dogbey, 2021). Typically, SOM decomposes rapidly in upland aerobic environments, whereas buildup is observed in lowland anaerobic conditions (Davidson and Janssens, 2006). Furthermore, SOM comprises various pools exhibiting unique physical and biological characteristics that respond differentially to land use and management practices (Von Lützow et al., 2007). Despite the relevance of the catena concept, its detailed application in tropical soil research remains underexplored (Jones et al., 2019). Many studies focus on localized effects of topography over short distances without fully utilising the concept's potential in landscape-scale soil classification and carbon storage assessments. In particular, limited work has examined how soils across a catena (from summit to valley bottom) vary in terms of morphology, fertility, and carbon dynamics within the High Rainforest Zone (HRZ) of Ghana.

Tropical soils represent significant carbon reservoirs, accounting for approximately 55% of global terrestrial carbon stocks, with estimates of SOC ranging from 2.3 to 21.7 kg m⁻² at 1 m depth (Cerri et al., 2019). These stocks are influenced by biogeochemical interactions among CNP cycles (Cleveland and Liptzin, 2007). Nitrogen fixation and mineralization often depend on phosphorus availability, illustrating the strong stoichiometric relationships between nutrients (Cleveland et al., 2006; Fairhurst, 2012). However, few studies have assessed these nutrient interactions along toposequences in tropical ecosystems, particularly with soil depth and land-use systems in the Global South, especially Ghana. Several studies (Bufebo et al., 2021; Dessalegn et al., 2014; Miheretu and Yimer, 2018) confirm that nutrient accumulation, e.g., SOC, total nitrogen (TN), available phosphorus (AP), and cation exchange capacity (CEC), tends to increase downslope due to deposition processes. On the other hand, upland soils exhibit lower nutrient concentrations, higher decomposition rates, and greater susceptibility to erosion. Guan et al. (2015) and Yang et al. (2024), further noted that the conversion of forest to cropland reduces SOC contents in tropical lowlands. Moreover, unbalanced fertilizer applications, particularly of nitrogen-phosphorus-potassium (NPK) combinations, can deplete micronutrients like zinc, copper, and manganese, adversely affecting crop yields (Dimkpa et al., 2023; Stewart et al., 2020).

In the HRZ of Ghana, smallholder farmers depend heavily on highly weathered, nutrient-depleted soils for subsistence agriculture across these diverse landscapes, yet there is a lack of detailed investigation into how land-use types and landscape positions affect soil properties, especially below surface layers. Current studies rarely assess vertical distributions of soil properties down to 1 m depth relative to catena

positions across different land uses, particularly in tropical biotite-granite landscapes. Such in-depth investigations are essential for understanding nutrient stock trends and the pedological processes that drive them, which are crucial for optimizing soil fertility and enhancing carbon sequestration. Furthermore, understanding the spatial variability of soil properties across toposequences can guide more effective and site-specific land management practices. Acrisols and Nitisols, for example, are common in the HRZ, often showing clay accumulation in the B horizon (Curi et al., 2023). These characteristics make them particularly susceptible to erosion when vegetation cover is disturbed. Relief influences drainage and erosion potential, driving key differences in soil structure, nutrient contents, and carbon dynamics (Sharon Anderson, 2005; Tan et al., 2004). In this context, we hypothesise that (i) landscape position significantly influences variations in most soil attributes along a toposequence, and therefore physico-chemical soil properties may differ depending on land use type, elevation, and soil depth, compared with native forest and secondary forest; (ii) micro- and macronutrients, along with their stoichiometric ratios, can vary laterally and with depth along the toposequence.

Thus, the study aims to address a critical knowledge gap by investigating the influence of various land-use regimes and catena positions on soil morphological, physical, and chemical qualities in the HRZ of Ghana. A thorough comprehension of these dynamics would facilitate the establishment of site-specific strategies for sustainable land use, improve soil fertility through integrated soil fertility management (ISFM), and different standards of ecosystem restoration for restoring ecological integrity within tropical agroecosystems.

2. Materials and method

2.1. Study area

The study was conducted in the Wassa East District of Ghana, covering an area of 1289 km², located between latitudes 5° 5' 10.0" N and 5° 29' 42.0" N and longitudes 1° 54' 13.0" W and 1° 23' 45.0" W (Fig. 1).

The region experiences a tropical humid climate, according to the Köppen classification, with annual precipitation ranging from 1500 to 2150 mm. Temperatures vary between 23 °C and 29 °C, with relative humidity averaging 90% at night and 75% during the afternoon (Christiansen and Awadzi, 2000; Hammond et al., 2022). The district is characterized by a bimodal rainfall pattern, which supports the moist evergreen forests that dominate the landscape. The study area is classified as a moist (humid) or wet (wetter) evergreen forest subtype.

The native vegetation consists of wet and moist evergreen zones, as well as deciduous forests. The district has several national forest reserves, including Subri River (375 km²), Pra Suhyen (204 km²), and the Ben East and West Block Forest Reserves, which contain remnants of virgin forest (DPCU, 2017). The native vegetation is predominantly characterized by deciduous evergreen forests, typical of the High Forest Zone. The *Celtis-Triplochiton* (Cannabaceae-Malvaceae) and *Triplochiton* (Ochnaceae-Malvaceae) forest associations dominate the northern and southern parts of the Wassa East District, respectively (Taylor, 1960). Tree species in the area include *Cynometra ananta* Hutch. and Dalziel, *Lophira alata* Banks ex Gaertn., and *Tarrietia utilis* Sprague, forming the distinctive *Cynometra* – *Lophira* – *Tarrietia* association (Hall and Swaine, 1976; Hammond et al., 2022; Mooney, 1961). Agriculture is the primary livelihood for about 60% of the population engaged in small-scale rain-fed crop production plots less than 2 ha (Pauw, 2021). Farmers use predominantly slash-and-burn farming methods. Key crops grown include tree crops (e.g., cocoa, oil palm, and rubber), food crops (e.g., maize, cassava, cocoyam, and plantain). Cocoa, the leading cash crop, occupies around 40% of the land.

In this study, we grouped the major land uses (Fig. 2) (i) Forest: Woodland with native trees higher than 5 m and dense canopy occupying more than 0.5 ha. Notable forest reserves are Subri River Forest Reserve, Pra Suhyen Forest Reserve, Ben West Block and the Ben East

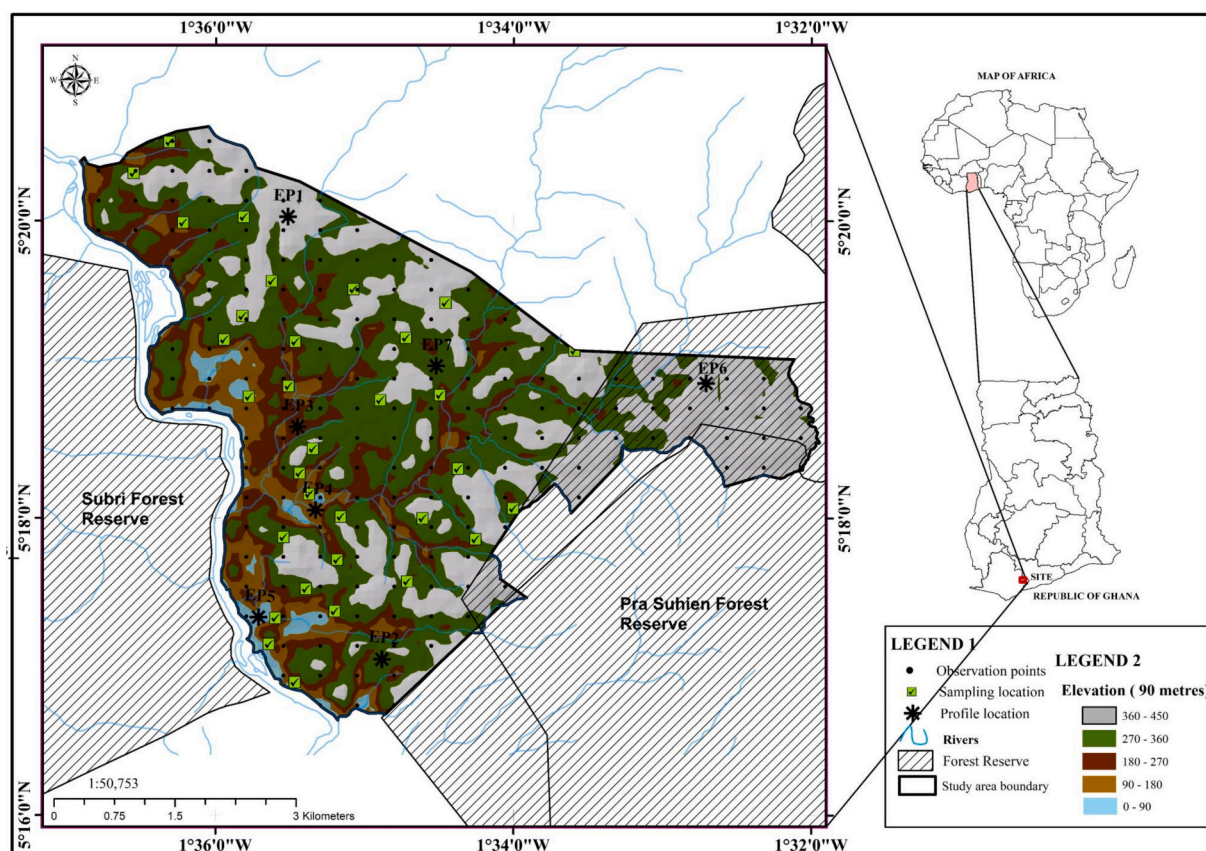


Fig. 1. Study area with observation points, sampling locations and sampled soil profiles.



Fig. 2. Five representative land use types selected for this study: (a) Forest, (b) Cropland (maize farm), (c) Cocoa plantation, (d) Riverine Mixed Thicket, and (e) Swampy Thicket.

Block Forest Reserves, (ii) Cocoa plantation: Commercial farms of the tropical evergreen tree (*Theobroma cacao* L.) cultivated for cocoa beans, (iii) Maize farm: arable and planted to maize, (iv) Riverine thicket: Riverine thickets and woodland vegetation types that occur as natural climax communities on the banks of the seasonal and main rivers (Subri, Butre, Abetumaso, Brempong etc.). These streams and rivers follow

dentritic and radial patterns, and (v) Swampy thicket: All forms of water bodies in the study area, i.e., river networks, streams, lagoons, stagnant waterbodies, etc. (Fig. 2).

Table 1

Physical and chemical properties of Cape Coast Biotite Granite.

Physical composition of Cape Coast granite	
Property	Scaling
Hardness	6–7 on Moh's scale
Density	2.6–2.8 kg cm ³
Compressive strength	140–210 N mm ⁻²
Modulus of rupture	15–25 N mm ⁻²
Water absorption	0.1–0.6%
Average wear	< 1%
Porosity	Quite low
Weather impact	Resistant
Chemical composition of Cape Coast granite	
Property	Scaling
Silica (SiO ₂)	70–75%
Al ₂ O ₃	10–15%
CaO + MgO	< 0.5%
FeO + Fe ₂ O ₃	2–4%
Alkalis	4–6%
TiO ₂	< 0.5%
Loss on ignition (LOI)	< 0.5%

The images (a) and (b) represents the predominant parent material (i.e., Cape Coast Biotite granite) in the study area. Source: (Gyamera et al., 2014).

2.2. Geology, drainage, and soils of the study area

The study area encompasses three major geological formations: (i) Granite, (ii) Lower Birimian, and (iii) Tertiary sands (Schlüter, 2006). Granite intrusions within the Lower Birimian formation have resulted in extensive areas dominated by biotite-rich granite, particularly within the Cape Coast Complex (Tables 1), (Ahn, 1961a, 1961b). The Cape Coast granite dominates over 50% of the district's geological landscape.

The elevation varies from 200 to 1800 m a.s.l. and is characterized by distinct upper, middle, and lower slopes. The region can be categorized into three primary physiographic zones: lowlands (< 700 m a.s.l.), midlands (700–1400 m a.s.l.), and highlands (1400–1800 m a.s.l.). These variations in elevation play a significant role in influencing soil formation, drainage patterns, and land use potential, with each zone presenting unique challenges and opportunities for sustainable land management. The area lies within the watershed of the Bonsa and Pra rivers, and the landscape is crossed by numerous tributaries, creating expansive areas of swampy vegetation that pose significant challenges to accessibility. The rivers primarily originate from the Akwapim ranges and flow southward toward the sea, following dendritic and radial drainage patterns. Major rivers and streams within the study district include the Pra, Subri, Butre, Suhien etc. (DPCU, 2017). The undulating terrain, in conjunction with the tropical climate, has resulted in the formation of the *Kumasi-Asuansi-Akroso-Nta/Ofin compound soil*

association, which represents the most extensive catena or soilscape in Ghana's tropical high rainforest zone (Table 2). The predominant soil association is the *Kumasi-Asuansi* (Acrisol) upland soil association typically found on summits and upper slopes, *Akroso series* (Nitisols) found on the middle slope position and *Nta/Ofin* (Gleysols) association occupying lower slopes and valley bottoms (Taylor, 1960; Adjei-Gyapong and Asiamah, 2002; Krasilnikov et al., 2009; IUSS Working Group WRB, 2022). The soil moisture and temperature regime are udic and isohyperthermic, respectively (Soil Survey Staff, 2022).

2.3. Study design, soil profile description and sampling

We undertook extensive sampling of physico-chemical properties of soil profiles across elevation gradients ranging from 50 to 1200 m above sea level along a 1.8 km transect spanning both cultivated (croplands) and uncultivated (native forest) land use systems. Soil profile locations were strategically selected based on elevation, slope, and predominant land use to effectively capture variability across different topographic positions. This approach allowed for a detailed assessment of how these factors influence soil properties. Consequently, seven (7) profiles were dug in five (5) land use representative sites (Fig. 2; Table 2), measuring 2 m length × 1 m width × 1.5 m depth, were excavated. These sites corresponded to distinct topographic positions: summit, upper slope, middle slope, lower slope, and valley bottom. Profiles EP-1 and EP-2 were on summit and upper slope, Profile EP-3 on the midslope, and Profiles EP-4 and EP-5 on the lower slope or valley bottom (Fig. 3; Table 2).

A comprehensive site description was carried out for each pedon following the guidelines outlined in the *FAO Guidelines for Soil Description* (FAO, 2006). In the field, soil horizons were carefully identified and delineated based on their distinct physical and chemical properties, ensuring precise classification and characterization for further analysis. For each soil profile, detailed descriptions were conducted, including horizon boundaries (distinctness and topography), soil matrix colours (using the *Munsell colour system notation*) (Munsell Colour (Firm), 2012), root distribution, soil structure, consistency, coatings, and the presence of mineral concretions, all following standardized procedures (FAO, 2006). Soil sampling was conducted on 7 soil profiles with 34 soil samples from different soil horizons. Profiles EP-1 and EP-2 were dug on Acrisols, EP-3 on Nitisols, and EP-4 and EP-5 on Gleysols (IUSS Working Group WRB, 2022). However, two profiles were excluded because EP-6 fell in the Pra Suhien Forest Reserve and EP-7 was dug in a disputed cocoa plantation. After removing profiles EP-6 and EP-7 constituting 10 soil samples, the remaining 24 samples belonging to 5 soil profiles were studied, (Figs. 1 and 2). This sampling approach ensured a well-detailed and accurate representation of both disturbed and undisturbed soil properties for detailed analysis (Stoops, 2003). Each sample was

Table 2

Description and classification of representative soil profiles.

Site characteristics	Profile EP-1	Profile EP-2	Profile EP-3	Profile EP-4	Profile EP-5
GPS coordinates	5° 18' 53.96" N 1° 35' 20.50" W	5° 18' 1.64" N 1° 35' 34.20" W	5° 20' 7.84" N 1° 35' 42.46" W	5° 18' 17.9" N 1° 35' 18.63" W	5° 18' 42.65" N 1° 35' 24.49" W
Land use	Forest	Cocoa plantation	Maize farm	Riverine thicket	Swampy thicket
Physiographic position	Summit to Upper Slope	Upper slope	Middle to Lower slope	Lower to Valley Bottom	Flat Valley Bottom
Slope	2–3%	0–2%	1–2%	0–1%	0–1%
Drainage	Well-drained	Moderately well drained	Moderately to Imperfectly drained	Poor-drained	Poorly-drained
Depth	> 150 cm	> 150 cm	> 150 cm	> 150 cm	< 150
Groundwater depth	–	–	–	130 cm	85 cm
Parent material	Granite (Biotite)	Granite (Biotite)	Sandy colluvium associated with biotite schist	Mixed coarse sandy colluvial-alluvial drift	Sandy alluvium associated with granite rock
Soil Classification System:					
Ghanaian	Kumasi series	Asuansi series	Akroso series	Nta series	Ofin series
WRB	Acrisol	Acrisol	Nitisol	Gleysol	Gleysol

Source: (Adjei-Gyapong and Asiamah, 2002; Effland et al., 2009; IUSS Working Group WRB, 2022).

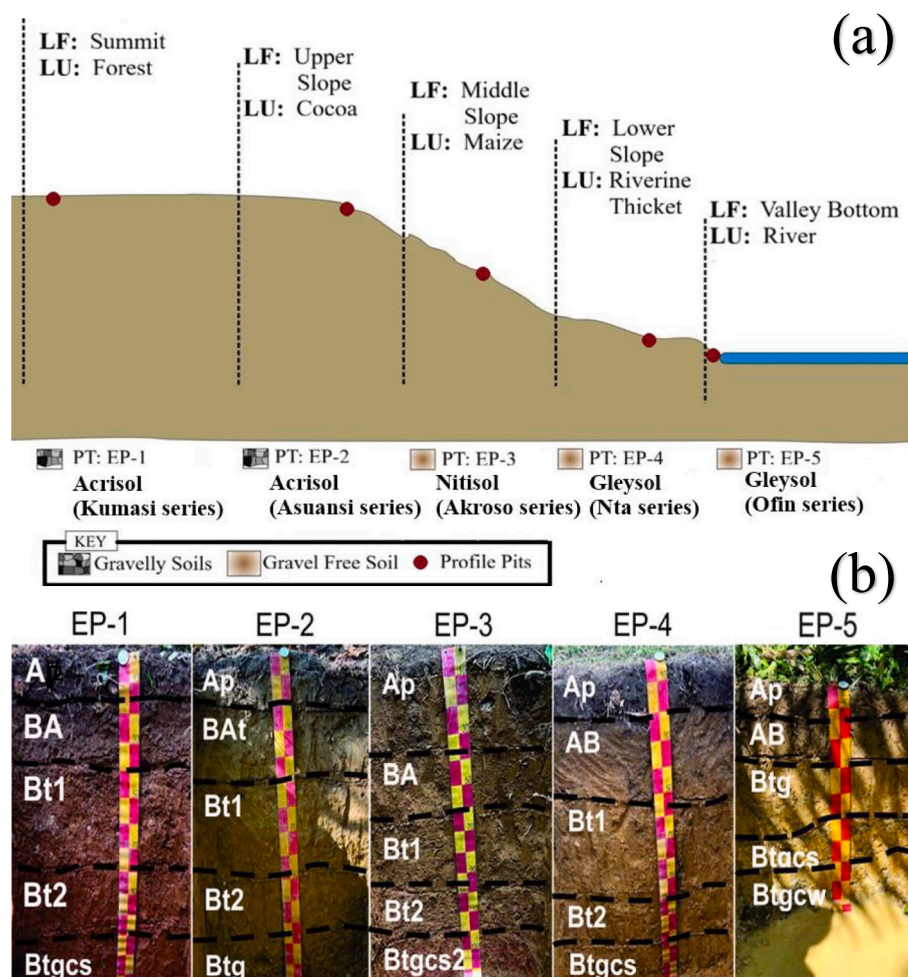


Fig. 3. (a) Topographical transects and profile pit sampling point locations for the study site (not drawn to scale. The blue line represents a stream in the valley bottom. (b) From left to right: Acrisol (EP-1), Acrisol (EP-2), Nitisol (EP-3), Gleysol (EP4) and Gleysol (EP-5) are the five genoforms used to illustrate the pedons along the Cape Coast biotite-granite toposequence in the High Rainforest Zone of Ghana. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

properly labelled and transported to the laboratory for further analysis, ensuring the integrity of the samples for accurate physical and chemical testing.

2.4. Characterization of hydro-physicochemical parameters of the soils

Soil samples were air-dried and sieved through a 2-mm sieve and later analyzed for their physical, chemical, and morphological parameters. Soil moisture content was determined using the gravimetric method (Gardner, 1986). Total porosity was calculated from bulk density, assuming an average particle density (PD) of 2.65 g cm^{-3} . Water

the soil with water through capillary action using the KR box (Baruah and Barthakur, 1997). Plant available water capacity (AWC) was calculated as the difference between field capacity and wilting point (Kara and Bolat, 2008). Infiltration rates were measured in triplicates for each soil unit using a double-ring infiltrometer (Landon, 2014). Soil colour was determined using the Munsell Colour Chart (Munsell Colour (Firm), 2012). Particle size distribution and bulk density (BD) were measured using the hydrometer (Bouyoucos, 1962) and the core methods, respectively (Blake and Hartge, 2018). The Clay Contrast Index (CCI) (Young, 1976) and Saturation of the Exchange Complex (SEC) with cations were also calculated using Eqs. 1 and 2.

$$CCI = \frac{\text{Clay Content of Subsurface Horizon} - \text{Clay Content of Surface Horizon}}{\text{Clay Content of Surface Horizon}} \times 100 \quad (1)$$

holding capacity (HC) was determined using a ceramic pressure plate apparatus after a 10-day equilibration period. It was calculated as the difference in gravimetric water content between field capacity (-10 kPa) and permanent wilting point (-1500 kPa), with soil samples dried at 105°C for three days. Additionally, HC was measured by equilibrating

$$SEC = \left(\frac{\sum \text{Exchangeable Cations}}{CEC} \right) \times 100 \quad (2)$$

Soil pH was determined in a soil-to-water suspension using a 1:2.5 (w/v) ratio (Thomas, 1996). Exchangeable acidity was measured via titration with a 0.025 M NaOH solution (Pansu and Gautheyrou, 2006). Organic carbon content was determined using the Walkley-Black wet combustion method, which involves the oxidation of organic matter with 0.07 mol L⁻¹ potassium dichromate in the presence of concentrated sulfuric acid (Jackson, 1958). Total nitrogen (TN) was measured via the Kjeldahl method, employing a semi-automatic distillation unit (Velp Scientifica UDK 139) (Bremner, 2018). These methods provide precise assessments of key soil organic matter components, essential for understanding nutrient dynamics and soil fertility.

Available phosphorus (AP) was quantified colourimetrically using the Bray and Kurtz (1945) method. Exchangeable potassium (Ex. K) and sodium (Ex. Na) were analyzed using the Jenway PFP7 flame photometer after extraction with ammonium acetate buffered to pH 7 (Motsara and Roy, 2008). Exchangeable magnesium (Ex. Mg) and calcium (Ex. Ca) and Cation Exchange Capacity (CEC) were determined using the EDTA titrimetric method, following extraction with a 1 M ammonium acetate solution buffered at pH 7 (Thomas, 1982). Effective cation exchange capacity (ECEC) was calculated by summing basic cations and exchangeable acidity (Juo and Franzluebbers, 2003). Available micronutrients (i.e., copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn), were extracted using the diethylene triaminepentaacetic acid (DTPA) method (Lindsay and Norvell, 1978). Carbon (C), nitrogen (N) and phosphorus (P) stocks (kg m⁻²) in the different horizons of each pedon was calculated using Eq. 3.

$$C_t(\text{kg/m}^2) = BD_i \times d_i \times OC_i \times a \quad (3)$$

where C_t = i th layer of C, N, or P stock (kg m⁻²), BD_i = bulk density of the i th layer (kg m⁻³), OC = the carbon content (%), N = nitrogen content (%), available phosphorus content (mg kg⁻¹), d_i = thickness of the i th layer (cm), and a is the conversion factor of 10 from kg m⁻² to t ha⁻¹.

2.5. Calculations and statistical analysis

Data quality was assessed by testing for homogeneity and normality prior to statistical analyses. Pearson's correlation analysis was applied to examine relationships among soil physical and chemical properties, with statistical significance evaluated at $p \leq 0.05$. To elucidate interrelationships among soil attributes along the toposequence, multivariate statistical approaches were considered most appropriate for data interpretation. Principal component analysis (PCA) was employed to explore the structure of relationships among soil variables and to reduce data dimensionality. The PCA was considered effective when a limited number of principal components accounted for the majority of the total variance. Separate PCA models were developed for the summit-upper slope, upper slope-middle slope, lower slope-valley bottom, and the entire summit-valley bottom sequence. The resulting component score equations used to derive the composite soil quality index (CSQI) for each landscape position are presented in Eqs. (4)–(7).

$$CSQI_{(S-UPS)} = 0.997(Silt) + 0.972(PS) + 0.932(BS) + 0.841(Sand) + 0.630(Mn) \quad (4)$$

$$CSQI_{(UPS-MS)} = 0.999(PS) + 0.983(BS) + 0.954(Mn) + 0.892(Sand) \quad (5)$$

$$CSQI_{(LS-VB)} = 0.996(Fe) + 0.992(Mn) + 0.978(PS) + 0.953(BS) + 0.841(Clay) \quad (6)$$

$$CSQI_{(S-VB)} = 0.960(Silt) + 0.847(BS) + 0.826(Mn) + 0.768(PS) + 0.569(Clay) \quad (7)$$

To further investigate causal relationships among soil physico-chemical properties (i.e., macronutrients, micronutrients, and CNP stoichiometric ratios), a Bayesian structural equation modeling (SEM)

Table 3

Classification of the pedons according to the World Reference Base for Soil Resources.

Profile	WRB RSG	Ghanaian System	Principal and Supplementary qualifiers	Major Criterion
EP-1	Acrisols	Kumasi series	Ferric, loamic, cutanic, differentic, ochric, profundic, raptic	Low-activity clays, low base status
EP-2		Asuansi series	Ferric, aric, loamic, cutanic, differentic, ochric, profundic	
EP-3	Nitisol	Akroso series	Acric, aric, ferric, ochric	Low activity clays, P fixation, Fe oxide, strongly structured
EP-4	Gleysols	Nta series	Reductigleyic, aric, clayic, stagnic	Prolonged wetness (saturated with groundwater for long enough to develop redoximorphic features)
EP-5		Ofin series	Stagnic, aric, clayic, ochric	

Abbreviation: IGSC: Ghana Interim Soil Classification System. Source: (Adjei-Gyapong and Asiamah, 2002; Krasilnikov et al., 2009; Schad, 2023; IUSS Working Group WRB, 2022).

approach was applied using IBM SPSS Amos 23. Both direct and indirect effects of soil attributes on CNP relationships were quantified using standardized path coefficients (λ). Model performance and goodness-of-fit were evaluated using the chi-square (χ^2) test ($p > 0.05$) and approximation (RMSEA < 0.05), following the criteria proposed by (Hooper et al., 2007). Classification of pedons and genetic horizons was conducted using hierarchical cluster analysis (Young and Hammer, 2000) to identify vertical differentiation within soil profiles. This approach grouped individual horizons into hierarchical clusters based on similarity, allowing smaller, more homogeneous groups to be nested within broader categories. The resulting dendrograms were used to visualize similarities among soil horizons and to highlight heterogeneity between groups. Overall, the multivariate statistical framework adopted in this study enabled robust assessment of interactions among soil properties and their role in environmental differentiation along the toposequence. All statistical analyses and graphical outputs were generated using OriginPro 2022, IBM SPSS Statistics 20, and IBM SPSS Amos 23.

3. Results

3.1. Soil types and their morphology

The landscape and physiographic characteristics of the profile locations, along with their corresponding land uses, are presented in Table 2. Although the soils were classified with two classification systems, the WRB reference soil group names will be used from this point. Generally, the profiles were deep (> 100 cm) with the water table at 120 cm depth in EP-4 (Gleysol). An exception was pedon EP-5 (Gleysol) that had a relatively shallow depth of 85 cm where the water table was encountered (Tables 2). Soil horizons were well-developed with notable variations reflecting the landform. For instance, Pedons EP-2 (Acrisol) and EP-4 located on the upper and middle-to-lower slopes had relatively shallow A horizons (5 and 7 cm, respectively), compared to slightly thick ones (10 to 14 cm) for EP-1 (Acrisol), EP-3 (Nitisol) and EP-5 (Tables 3 and 4; Fig. 3). The upper horizons of the pedons predominantly had dark brown to yellowish colours (10YR 3/3 to 10YR 3/6), compared to yellowish-brown to olive-yellow hues (2.5YR to 10YR) for subsurface horizons. Chromas were mostly 4 or higher.

As expected, EP-4 and EP-5 being exposed to groundwater table fluctuations exhibited gleyic colour patterns in the profiles. These poorly drained soils were characterized by grey-coloured B-horizons and high

Table 4
Morphological properties of soils.

Profile ^a	Horizon ^b	Depth (cm)	Munsell Colour	Colour description	Mottles	Mottle description	Structure ^c	Consistency ^d	Porosity ^e	Roots ^f	Pedo-features	Boundary ^g
EP-1	A	0–14	10YR 3/3	Dark Brown	–	–	2sbk	sst, npl	4f, i	5vf, 5 m, 3co	–	Cs
	BA	14–36	10YR 5/6	Yellowish Brown	–	–	2sbk	sst, npl	4f, i	5vf, 3 m, 3co	Few quartz stones and gravels	Cs
	Bt1	36–75	10YR 5/6	Olive Yellow	–	–	2sbk	sst, npl	4f, i	2vf, 2f	–	Cs
	Bt2	75–103	2.5Y 6/8	Olive Yellow	10YR 6/8	Brownish Yellow	2sbk	st, spl	5f, 3co, i	2vf, 3 m	–	Cs
	Btgs	103–134	2.5Y 6/8	Olive Yellow	10YR 6/8	Brownish Yellow	2sbk	st, spl	3f, i	–	Abundant Fe + MnO ₂ concretions.	–
EP-2	Ap	0–5	10YR 3/6	Yellowish Brown	–	–	2 g	nst, npl	2f, i	5vf, 5f, 4 m, 3co	–	Cs
	BAt	5–33	10YR 3/8	Yellowish Brown	–	–	2sbk	nst, npl	5f, i	3f, 3 m, 3co	Few ant & millipede cast	Cs
	Bt1	33–60	10YR 6/8	Brownish Yellow	–	–	3abk	sst, npl	3f, 3 m, i	3f, 3 m,	–	Cs
	Bt2	60–94	10YR 6/8	Brownish Yellow	–	–	3sbk	st, spl	3vf, 3 m, i	3 m	Very few stones and gravels	Cs
	Btg	94–103+	10YR 6/8	Brownish Yellow	2.5YR3/6	Dark Red	3sbk	nst, npl	3vf, 3 m, i	3 m	–	Cs
EP-3	Ap	0–14	10YR 3/3	Dark Brown	–	–	2sbk	sst, npl	4f, i	5vf, 5f, 3 m, 3co	–	Cs
	BA	14–48	10YR 5/6	Yellowish Brown	–	–	2sbk	sst, npl	5f, i	5vf, 5f, 3 m, 3co	Few quartz stones and gravels	Cs
	Bt1	48–89	2.5Y 6/8	Olive Yellow	–	–	2sbk	sst, npl	5f, i	2f	–	Cs
	Bt2	89–121	2.5Y 6/8	Olive Yellow	–	–	2sbk	st, spl	3co, i	2 m	–	Cs
	Btgs2	121–144	2.5Y 6/8	Olive Yellow	2.5YR3/6	Dark Red	2sbk	st, spl	3f, i	–	Abundant Fe + MnO ₂ concretion.	–
EP-4	Ap	0–7	10YR 3/2	Dark Greyish Brown	–	–	2 g	nst, npl	2f, i	5vf, 5f, 3 m	–	Cs
	AB	7–20	10YR 4/3	Brown	–	–	2 g	nst, npl	4f, i	2vf, 3f, 3 m	–	Cs
	Bt1	20–45	2.5YR 5/6	Light Olive Yellow	–	–	2sbk	st, spl	4f, i	2vf, 3f, 3 m	–	Cs
	Bt2	45–86/124	2.5Y 6/8	Olive Yellow	–	–	2sbk	st, spl	2f, i	2 m	–	Cs
	Btgs	124/137–141	2.5Y 6/8	Olive Yellow	2.5YR3/6	Dark Red	2sbk	sst, spl	–	–	–	–
EP-5	Ap	0–10	10YR 3/4	Dark Yellowish Brown	–	–	2 g	nst, npl	2f, i	5vf, 5f, 5 m	–	Cs
	AB	10–24	10YR 6/4	Light Yellowish Brown	7.5YR4/6	Strong Brown	2 g	nst, npl	3vf, i	3vf, f, 5 m	–	Cs
	Btg	24–50	2.5Y 6/6	Olive Yellow	10YR7/1	Light Grey	3sbk	sst, npl	2f, 2 m	–	–	Cs
	Btgs	50–65	2.5Y 6/8	Olive Yellow	10YR 7/1	Light Grey	2sbk	sst, spl	2f, i	–	Occasional stones and gravels	cs
	Btgcw	65–85	2.5Y 6/8	Olive Yellow	10YR 7/1	Light Grey	2abk	sst, spl	–	–	–	–

Adopted from: (Munsell Colour (Firm), 2012; Schoeneberger et al., 2012).

^a **Abbreviations:** EP-1 = Acrisol (*Kumasi series*); EP-2 = Acrisol (*Asuansi series*); EP-3 = Nitisol (*Akroso series*); EP-4 = Gleysol (*Nta series*); EP-5 = Gleysol (*Ofin series*).

^b **Abbreviations** used for subordinate distinctions within master horizons and layers: c = concretions and nodules; t = accumulation of silicate clay; g = strong gleying; p = tillage or other cultivation disturbance; s = illuvial accumulation of sesquioxides and organic matter; v = plinthite formation; w = development of colour and structure (Buol et al., 2011). The suffix p indicates the plough layer, 'g' indicates gravels, 's' indicates illuvial accumulation of sesquioxides, 't' indicates increase of clay, 'c' indicates concretions or nodules, and 'p' plinthic formation (IUSS Working Group WRB, 2022).

^c **Abbreviations** used for structure (grade, size, and type): Grade (degree of development): 1 = no structure; 2 = weak; 3 = moderate; 4 = strong; Size: vf = very fine; f = fine; m = medium; co = coarse. Type: gr = granular; abk = angular blocky; sbk = subangular blocky; bk = blocky; pr = prismatic; m = massive.

^d **Abbreviations** used for consistency (stickiness and plasticity): Stickiness: nst = non sticky; sst = slightly sticky; st = sticky; vst = very sticky. Plasticity: npl = not plastic; spl = slightly plastic; pl = plastic; vpl = very plastic.

^e **Abbreviations** used for the classification of porosity (quantity/abundance of pores, diameter of void, classification of voids): Quantity/Abundance of pores: 1n = none; 2v = very few; 3f = few; 4c = common; 5 m = many. Diameter of voids: vf = very fine; f = fine; m = medium; co = coarse; vco = very coarse. Classification of voids: i = interstitial; ve = vesicular; vu = vughs; c = channels; p = planes.

^f **Abbreviations** used for roots (abundance/quantity and size): Abundance/quantity: 1 = none; 2 = very few; 3 = few; 4 = common; 5 = many. Size: vf = very fine; f = fine; m = medium; co = coarse; vco = very coarse. ^gAbbreviations used for moisture: sm = slightly moist; m = moist; d = dry.

^g **Abbreviations** used for the classification of horizon boundary (distinctness and topography/configuration): Distinctness: a = abrupt; c = clear; g = gradual; d = diffuse. Topography/configuration: s = smooth; w = wavy; i = irregular; b = broken.

soil organic matter (SOM) content, with thick A-horizons. The B-horizons exhibited varied soil colours, ranging from yellowish-brown to olive-yellow. Mottles of varying colours were noted, including brownish-yellow (10YR 6/8) in pedon EP-1, dark red (2.5YR 3/6) in pedons EP-2, EP-3, and EP-4, and strong brown (7.5YR 4/6) in the AB horizon of pedon EP-5. Light grey (10YR 7/1) mottles were observed in the deeper horizons (Btg - Btgcw) of pedon EP-5 (Table 4). Pedons EP-1, EP-2, and EP-3 exhibited a consistent colour transition from dark brown (10 YR 3/3) in the upper horizon to yellowish brown (10YR 5/6) or brownish yellow (10 YR 3/8) in the middle horizon, and olive yellow (2.5Y 6/8) in the lower horizons. The Bt horizons across the pedons exhibited subangular blocky structures, with moist colours varying by topographic position: 10YR 5/6 at the summit (EP-1), 10YR 3/8 on the upper slope (EP-2), 2.5Y 5/6 on the middle slope (EP-3), 2.5YR 5/6 on the lower slope (EP-4), and 2.5Y 6/6 at the valley bottom (EP-5). The boundaries between horizons were generally smooth and gradual in the upper horizons. In contrast, clearer and more defined boundaries were observed in the lower Bt horizons. Most of the profiles exhibited

predominantly granular to angular blocky structures, with variations in grade and size from the Ap horizon to the subsurface horizons. In the B horizons, the structure transitioned to moderate to strong coarse angular blocky to subangular formations (Table 4). The peds (soil aggregates) were primarily held together by coatings (cutans) of translocated materials, with the size of these peds generally increasing with depth. The most prevalent pedological features observed were secondary Fe nodules, which were particularly abundant in Acrisols and the Nitisol. These nodules were predominantly intrusive, characterized by abrupt outlines and internal fabrics that contrasted sharply with the surrounding soil matrix.

3.2. Physical properties

3.2.1. Soil texture

The physical properties of the studied pedons (Table 5) suggests that soil texture is primarily influenced by the weathering of granite. Texture varied across the profiles, ranging from sandy loam in the surface

Table 5
Physical characteristics of the studied soils.

Profile	Horizon	Depth (cm)	Thickness (cm)	Sand (%)	Silt	Clay	Silt/Clay Ratio	CCI	Texture	BD (g cm ⁻³)
EP-1	A	0–14	14	90	6	4	1.5	0.08	Sand	1.41
	BA	14–36	22	88	2	10	0.2		Loamy Sand	1.47
	Bt1	36–75	39	49	27	24	1.13		Loam	1.44
	Bt2	75–103	28	50	2	48	0.04		Sandy Clay	1.47
	Btgcs	103–134	31	54	3	43	0.07		Sandy Clay	1.49
EP-2	Ap	0–5	5	81	7	12	0.58	0.29	Sandy Loam	1.48
	BAt	5–33	28	66	5	29	0.17		Sandy Clay Loam	1.53
	Bt1	33–60	27	47	15	38	0.39		Sandy Loam	1.46
	Bt2	60–94	34	76	9	15	0.6		Sandy Loam	1.50
	Btg	94–103+	9	57	2	41	0.05		Sandy Loam	1.51
EP-3	Ap	0–14	14	92	4	4	1.0	0.13	Sand	1.41
	BA	14–48	34	76	10	14	0.71		Sandy Loam	1.49
	Bt1	48–89	41	74	2	24	0.08		Sandy Clay Loam	1.54
	Bt2	89–121	32	72	2	26	0.08		Sandy Clay Loam	1.54
	Btgcs2	121–144	23	68	2	30	0.07		Sandy Clay Loam	1.54
EP-4	Ap	0–7	7	92	4	4	1.0	0.13	Sand	1.41
	AB	7–20	13	91	2	7	0.29		Sand	1.44
	Bt1	20–45	25	87	2	11	0.18		Loamy Sand	1.48
	Bt2	45–86/124	41	76	2	22	0.09		Sandy Clay Loam	1.53
	Btgcs	124/137–141	–	61	7	32	0.22		Sandy Clay Loam	1.52
EP-5	Ap	0–10	10	90	6	4	1.50	0.09	Sand	1.41
	AB	10–24	14	55	4	41	0.10		Sandy Clay	1.50
	Btg	24–50	26	52	4	43	0.11		Sandy Clay	1.48
	Btgcs	50–65	15	53	2	45	0.04		Sandy Clay	1.49
	Btgcw	65–85	20	66	2	32	0.06		Sandy Clay Loam	1.54

Abbreviations: EP-1 = Acrisol (*Kumasi series*); EP-2 = Acrisol (*Asuansi series*); EP-3 = Nitisol (*Akroso series*); EP-4 = Gleysol (*Nta series*); EP-5 = Gleysol (*Ofin series*), CCI = Clay Contrast Index.

Abbreviations used for subordinate distinctions within master horizons and layers: c = concretions and nodules; t = accumulation of silicate clay; g = strong gleying; p = tillage or other cultivation disturbance; s = illuvial accumulation of sesquioxides and organic matter; w = development of colour and structure. Source: (Buol et al., 2011).

horizons to sandy clay loam in the subsurface layers. Specifically, pedons EP-1 and EP-5 exhibited textures from sand to sandy clay, while pedons EP-2, EP-3, and EP-4 displayed textures ranging from sandy loam to sandy clay loam. Among these, sandy clay loam was the most prevalent textural class, with occasional occurrences of clay and loamy sand. The distribution of sand, silt, and clay across different depth ranges revealed notable variability. Sand content was consistently high, exceeding 50% in all pedons, with an average sand content of 70.52%. The highest percentages of sand were recorded in the 0–5 cm and 5–10 cm depth ranges, although there was a general decrease in sand content in deeper horizons, particularly within the 50–100 cm and 100–150 cm ranges. Silt content remained relatively stable across depths, averaging 5.36%, with a slight increase observed in the 30–50 cm and 50–100 cm ranges. In contrast, clay content averaged 4.12% and was less variable, yet it significantly contributed to the sandy clay loam texture found in several pedons. The predominance of sandy clay loam across the studied pedons highlights the significant impact of granite weathering and the characteristics of the parent material on soil texture. This variation in texture across different landscape positions accentuates the complex interactions between pedogenic processes and topography within these soils.

Overall, the percentage of sand decreased with depth across all pedons. The high sand content (> 60%) suggests that these pedons inherently have poor nutrient retention capabilities, primarily due to their low clay content. This is particularly pronounced in the sandy-textured pedons EP-1 and EP-2, located under Forest and Secondary Forest (cocoa), respectively. The content of sand and silt decreased while the clay fraction increased toward the middle and lower horizons of the profiles (Table 5). The minor differences in clay content between the highest and lowest amounts were observed at the foot slopes of pedons EP-4 and EP-5. In general, clay content increased with depth across all pedons except for EP-2, leading to the formation of an argic horizon. This phenomenon was visibly evident during the field morphological description, where argilluviation was observed as shiny peds on the profile walls and surfaces. Clay content in the soils ranged from as low as 4% in the surface horizon (Ap) of all pedons except for EP-2 to as high as 48% in the subsurface horizon (Bt2) of pedon EP-1, reflecting an advanced stage of weathering. Pedons EP-4 and EP-5 exhibited a high content of fine clays, with water-dispersible clays indicating active argilluviation. In the subsoils, textural differentiation was evident. The average contents of sand, silt, and clay in the surface soils were 80%, 6%, and 12%, respectively, indicating a predominance of sand over silt and clay. Similarly, clay content increased with depth across all soil profiles (Table 5), particularly within the 50–100 cm and 100–150 cm depth ranges.

Along the toposquence, the mean clay content was recorded as 25.80%, 27.00%, 19.60%, 15.20%, and 33.00% for EP-1, EP-2, EP-3, EP-4, and EP-5, respectively. In contrast, the mean silt content across these positions was 8.00%, 7.60%, 4.00%, 3.40%, and 3.78%. The soil textural characteristics followed the order: sand > clay > silt. High values of sand, silt, and clay were particularly observed in the BA and/or Bt horizons of all pedons, significantly influencing other soil properties such as water retention, drainage, aeration, and organic matter content. The subsurface horizons were generally finer in texture compared to the surface horizons, indicating the downward translocation of clay into the middle and lower horizons. This pattern deepens the ongoing pedogenic eluviation-illuviation processes, which are especially pronounced in the upper and middle slope soil profiles. The presence of faint to prominent clay coatings in the subsurface horizons of all pedons along the toposquence further supports the conclusion that clay illuviation and translocation are critical processes responsible for the formation of argillic horizons in these soils. Clay illuviation emerged as a significant pedological feature in these pedons, with clay coatings observed lining channel voids, ped surfaces, and dissolution voids in rock fragments during soil profile descriptions. Notably, circular laminated clay coatings associated with voids or ped surfaces indicated complete filling of

channels or welding with other peds, preserved as cemented relics. However, the intensity of clay illuviation was insufficient to classify diagnostic illuvial horizons in all cases. The presence of clay coatings lining circular-section channels in areas with higher clay concentrations suggests that these soils may have developed an incipient argic horizon, facilitating the dispersion and migration of clay from the A and AB horizons. Clay content in the uppermost B horizon increased progressively, eventually leading to the formation of a diagnostic argic horizon. The faint to prominent clay coatings observed in the subsurface horizons of pedon EP-5 further confirm that clay illuviation was the primary factor contributing to the formation of an argillic horizon.

The CCI offers valuable insights into the relative accumulation of clay between various horizons within the soil profile, enabling a deeper understanding of pedogenic processes such as clay translocation and horizon differentiation (Table 5). This index is particularly useful for assessing soil development and the degree of horizonation, which can indicate soil fertility and its suitability for various land uses. A high CCI indicates low textural differentiation within the soil profile. This suggests that the processes of clay translocation and enrichment in pedon EP-2 fulfill the criteria for forming an argillic and/or argic subsurface horizon. Conversely, the lower CCI values observed in pedons EP-1 and EP-5 indicate greater textural differentiation. The pattern of clay enrichment followed a decreasing order: 0.29 for pedon EP-2, 0.13 for both pedon EP-3 and EP-4, 0.09 for pedon EP-5, and 0.08 for pedon EP-1. The variation in clay enrichment ratios was closely linked to slope position and prevailing land use.

3.2.2. Hydro sequence and water retention characteristics

Soil porosity varied across the profiles (Table 6), with the Acrisols (EP-1 and EP-2) exhibiting packed voids and channels, while Nitisol (EP-3) displayed planar voids, vughs, and rock fragments. The coarse materials found in both Acrisols and Nitisol were predominantly composed of iron (Fe) nodules, with sub-rounded quartz grains that were generally smaller than the Fe nodules. Despite these conditions, many of the nodules appeared stable in the well-drained soil environment, often showing signs of advanced dissolution. The hydro-sequence of the pedons (Table 6) exhibited variability across the landscape. The upper slope position was classified as well-drained, while the middle slope position displayed a range from moderate to well-drained. In contrast, the lower slope position was predominantly moderately drained. This drainage sequence was primarily influenced by the landscape relief, as the drainage capacity gradually diminished toward the depositional areas found in the lower slope and valley bottom.

Along the catena, WP and FC followed the sequence: VB > US > SU > MS > LS. In contrast, AWC and HC followed the sequences: VB > SU > US > MS > LS and LS > SU > MS > VB, respectively. HC generally decreased with depth but exhibited irregularities in the lower subsoil of pedon EP-2. In pedon EP-2, WP and FC increased with depth; however, a sudden decrease was noted in the fourth horizon, linked to a significant textural shift where sand content increased (76%) with a corresponding decrease in clay content (15%) (Table 6). Soils with an AWC of less than 10 are classified as low, those between 10 and 20 as moderate, and those greater than 20 as high. In this study, the AWC of pedons EP-1, EP-2, and EP-3 was rated as moderate, while the lower slope and valley bottom soils displayed low to moderate AWC values. The AWC values below the acceptable range in some pedons may be attributed to high bulk density, which often results from intensive cultivation practices and/or low SOM content due to the removal of crop residues.

3.3. Nutrient dynamics

3.3.1. Soil pH and exchangeable cations

Soil pH in the studied pedons ranged from very acidic (pH 4.9) in EP-2 to moderately acidic (pH 5.9) in EP-1 in the surface horizons (Table 7). In subsurface horizons, pH ranged from 4.0 to 5.7 in the AB and/or BA horizons. Profiles EP-1, EP-2, and EP-3 demonstrated acidic conditions,

Table 6
Hydrological parameters properties.

Profile	Horizon	Depth (cm)	Porosity (P)	WP (%)	FC	Sat.	AWC (in ft ⁻¹)	SHC (in hr ⁻¹)
EP-1	A	0–14	0.43	4.4	9.3	46.6	0.59	4.78
	BA	14–36	0.73	8.0	13.0	44.4	0.60	2.73
	Bt1	36–75	0.74	8.2	21.6	45.7	1.62	1.52
	Bt2	75–103	0.76	29.3	40.5	44.5	1.34	0.01
	Btgcs2	103–134	0.79	26.6	37.5	43.6	1.30	0.02
EP-2	Ap	0–5	0.55	9.2	15.5	44.0	0.77	2.08
	BAt	5–33	0.60	18.9	28.0	42.3	1.10	0.27
	Bt1	33–60	0.69	23.7	35.3	44.9	1.40	0.09
	Bt2	60–94	0.72	10.9	18.2	43.5	0.88	1.47
	Btg	94–103+	0.75	25.6	36.1	43.1	1.27	0.03
EP-3	Ap	0–14	0.51	4.4	8.9	46.7	0.54	4.91
	BA	14–48	0.62	10.3	17.7	43.7	0.88	1.62
	Bt1	48–89	0.65	16.1	23.8	41.9	0.93	0.54
	Bt2	89–121	0.68	17.2	25.3	41.8	0.97	0.41
	Btgcs2	121–144	0.69	19.5	28.3	41.9	1.06	0.23
EP-4	Ap	0–7	0.56	4.4	8.9	46.7	0.54	4.91
	AB	7–20	0.68	6.2	10.7	45.5	0.55	3.72
	Bt1	20–45	0.69	8.5	13.8	44.1	0.63	2.46
	Bt2	45–86/124	0.71	14.9	22.3	42.0	0.88	0.70
	Btgcs	124/137–141	0.74	20.5	30.5	42.7	1.19	0.18
EP-5	Ap	0–10	0.50	4.4	9.3	46.6	0.59	4.78
	AB	10–24	0.53	25.5	36.3	43.5	1.29	0.04
	Btg	24–50	0.59	26.6	37.6	44.0	1.32	0.03
	Btgcs	50–65	0.62	27.7	38.7	43.9	1.32	0.01
	Btgcs	65–85	0.67	20.6	29.8	42.0	1.11	0.17

Abbreviations: EP-1 = Acrisol (*Kumasi series*); EP-2 = Acrisol (*Asuansi series*); EP-3 = Nitisol (*Akroso series*); EP-4 = Gleysol (*Nta series*); EP-5 = Gleysol (*Ofin series*).

with pH values generally increasing down the soil profile. Higher pH values and lower base saturation were observed in the lowland and valley bottom soils, whereas upland soils exhibited lower pH and base saturation levels. An increase in soil pH with depth was observed in the upland soils. In contrast, soils at the lower slope (lower elevation) exhibited consistently higher pH values throughout the entire soil profile. In the B-horizon, soil pH was found to be highly acidic, ranging from 4.00 to 4.51, and demonstrated an irregular trend with increasing depth. In general, the surface horizon (Ap horizon) showed higher nutrient concentrations, particularly in pedons EP-1 and EP-5, compared to the subsurface layers (Table 7).

Exchangeable cations within the pedons varied with depth and across the toposequence, exhibiting irregular trends associated with zones of eluviation and illuviation. Also, CEC decreased with depth across all pedons. In pedons EP-2 and EP-3, exchangeable Ca^{2+} exhibited an eluvial-illuvial pattern (Table 7). The mean CEC of the surface horizons ranged from 3.62 $\text{cmol}_c \text{kg}^{-1}$ in EP-5 to 5.11 $\text{cmol}_c \text{kg}^{-1}$ in EP-1. Furthermore, CEC values were higher in the surface (A) horizons compared to the subsurface horizons, with a significant correlation observed between CEC and SOM ($r = 0.453$; $p < 0.05$; Fig. 4) in both upland and lowland soils. The dominance of acidic cations, such as Al^{3+} and H^+ , in the exchange complex resulted in lower base saturation values in these subsurface horizons. In contrast, the exchangeable complexes in pedons EP-1, EP-2, and EP-3 were predominantly composed of basic cations, contributing to higher base saturation levels. Soils with low CEC are more susceptible to deficiencies in potassium (K^+), magnesium (Mg^{2+}), and other essential cations compared to soils with higher CEC, which are less vulnerable to the leaching of base cations.

In the surface horizons, CEC values exceeded 6.0 $\text{cmol}_c \text{kg}^{-1}$, showing a gradual decrease with depth (Table 7). In contrast, the subsurface horizons exhibited CEC values ranging from 0.9 to 5.2 $\text{cmol}_c \text{kg}^{-1}$. The mean CEC across the soils was 2.6 $\text{cmol}_c \text{kg}^{-1}$, while the ECEC

was 3.7 $\text{cmol}_c \text{kg}^{-1}$. Generally, ECEC was lower in the subsurface horizons across all pedons. Cation exchange capacity exhibited variability across textural classes and with depth. Sandy clay and sandy clay loam had higher CEC values. The concentrations of exchangeable cations varied across the landscape. The highest concentrations of exchangeable cations were observed in the surface horizons of the pedons along the toposequence, with a general decrease in concentration with depth. This decrease was more consistent in pedons EP-3 and EP-5, while it was more variable in pedons EP-1, EP-2, and EP-4. The analyzed pedons indicated that Ca^{2+} was the predominant exchangeable cation, followed by magnesium (Mg^{2+}) along the toposequence (Table 7). In contrast, K^+ content ranged from 0.1 $\text{cmol}_c \text{kg}^{-1}$ in EP-1 and EP-4 to 0.3 $\text{cmol}_c \text{kg}^{-1}$ in EP-2. Across profiles EP-1, EP-2, EP-3, EP-4, and EP-5, the exchange complex was predominantly composed of Ca^{2+} , followed by Mg^{2+} , K^+ , and Na^+ . The BS ranged from 40.36% to 93.82%, generally decreasing unevenly with depth across all pedons. In the surface horizons, BS values exceeded 85%.

3.3.2. Soil biogenic elements

The SOC consistently decreased with depth across all pedons, with the highest SOC values observed in pedons EP-4 and EP-5, located under riverine thicket and swampy conditions. In the surface horizons of all pedons, SOC ranged from 0.3% to 1.8% (Table 8). As expected, lower SOC values were recorded in pedons EP-1, EP-2, and EP-3. SOC values in the subsurface horizons varied between 0.20% in EP-5 and 1.28% in EP-3. Notably, relatively high SOC levels of 0.8% and 1.3% were recorded in the Bt2 and Bt1 horizons of pedons EP-2 and EP-3, respectively. Also, TN content ranged from 0.03% to 0.15% in the surface horizons and from 0.02% to 0.11% in the subsurface horizons. Total N displayed an inconsistent pattern with depth across all pedons (Table 8). Generally, soils with TN content below 0.07% have limited nitrogen mineralization potential, while soils with TN levels above 0.15% are expected to mineralize significant amounts of nitrogen during the subsequent crop

Table 7
Soil pH and Exchangeable bases.

Profile	Horizon	Depth (cm)	pH (1:2.5)	Ca (cmol _c kg ⁻¹)	Mg (cmol _c kg ⁻¹)	K	Na	CEC	ECEC	Ex. Acidity	SEC (%)	BS
EP-1	A	0–14	5.87	4.05	1.92	0.10	0.01	6.08	6.48	0.40	106.58	93.82
	BA	14–36	4.00	1.49	0.43	0.05	0.01	1.97	3.67	1.70	186.29	53.69
	Bt1	36–75	4.00	0.85	0.21	0.04	0.01	1.11	2.86	1.75	257.66	38.84
	Bt2	75–103	5.00	1.07	0.75	0.02	0.01	1.85	2.55	0.70	137.84	72.53
	Btgcs2	103–134	4.92	0.85	0.64	0.69	0.02	2.19	3.29	1.10	150.23	66.58
EP-2	Ap	0–5	4.90	4.05	2.34	0.25	0.01	6.66	7.76	1.10	116.52	85.82
	BAt	5–33	4.26	0.85	0.21	0.40	0.01	1.47	2.97	1.50	202.04	49.51
	Bt1	33–60	4.60	0.64	0.64	0.04	0.01	1.33	2.73	1.40	205.26	48.78
	Bt2	60–94	4.49	3.20	1.92	0.10	0.01	5.23	6.73	1.50	128.68	77.70
	Btg	94–103+	4.92	0.64	0.43	0.05	0.01	1.12	2.32	1.20	207.14	48.30
EP-3	Ap	0–14	5.41	5.11	1.28	0.12	0.01	6.52	7.17	0.65	109.97	90.93
	BA	14–48	5.73	1.92	0.53	0.02	0.01	2.49	3.19	0.70	128.11	78.02
	Bt1	48–89	5.31	1.07	0.96	0.01	0.01	2.05	2.85	0.80	139.02	71.95
	Bt2	89–121	5.00	1.07	0.53	0.06	0.01	1.68	2.38	0.70	141.67	70.55
	Btgcs2	121–144	4.92	0.85	0.64	0.04	0.01	1.54	2.74	1.20	177.92	56.24
EP-4	Ap	0–7	5.32	4.47	1.70	0.10	0.01	6.29	6.94	0.65	110.33	90.63
	AB	7–20	4.51	0.75	0.32	0.05	0.01	1.13	2.63	1.50	232.74	42.95
	Bt1	20–45	4.72	0.85	0.43	0.02	0.01	1.30	2.55	1.25	196.15	51.00
	Bt2	45–86/124	4.76	1.07	0.21	0.02	0.01	1.32	2.62	1.30	198.48	50.34
	Btgcs	124/137–141	4.20	0.64	0.53	0.03	0.01	1.21	2.71	1.50	223.97	44.63
EP-5	Ap	0–10	5.44	3.62	2.56	0.18	0.01	6.36	7.01	0.65	110.22	90.73
	AB	10–24	4.00	0.96	0.19	0.06	0.01	1.22	3.02	1.80	247.54	40.36
	Btg	24–50	4.32	0.73	0.20	0.05	0.01	0.99	2.34	1.35	236.36	42.31
	Btgcs	50–65	4.61	0.64	0.21	0.04	0.01	0.90	2.00	1.10	222.22	44.98
	Btgcs2	65–85	4.64	0.53	0.32	0.07	0.01	0.93	2.03	1.10	218.28	45.91

Abbreviations: EP-1 = Acrisol (*Kumasi series*); EP-2 = Acrisol (*Asuansi series*); EP-3 = Nitisol (*Akroso series*); EP-4 = Gleysol (*Nta series*); EP-5 = Gleysol (*Ofin series*), SEC = Saturation of the Exchange Complex.

cycle.

Most of the studied pedons exhibited low available phosphorus (AP) content in decreasing trends with depth across all pedons. The combined effects of slope position and land use have led to variations in base saturation, exchangeable cations, SOC, TN, and AP across the landscape. Along the catena, the mean concentrations of SOC, TN, and AP followed the order: EP-4 > EP-5 > EP-3 = EP-2 > EP-1, EP-4 > EP-5 = EP-3 > EP-1 > EP-2, and EP-2 > EP-4 > EP-5 = EP-3 > EP-1, respectively. The stoichiometric ratios of C:N, C:P, and N:P in surface soils along the toposequence ranged from 9.33 to 14.67, 0.05 to 0.79, and 0.01 to 0.06, respectively (Table 8). In the subsurface horizons, these ratios varied from 9.33 (EP-3) to 18.00 (EP-5) for C:N, 0.03 (EP-5) to 0.90 (EP-1 and EP-3) for C:P, while N:P consistently recorded 0.01 in EP-1, EP-2, and EP-4. Generally, C:N, C:P, and N:P ratios decreased with depth, although this pattern was uneven in the lower subsoils of all pedons along the toposequence. Also, elevated C:N ratios were observed in the subsurface horizons of Bt2 (EP-1), Btg (EP-2), Btgcs2 (EP-3), Btgcs (EP-4), and Btgcs2 (EP-5). Across the catena, the mean ratios were observed in the following order: C:N: EP-4 > EP-2 > EP-5 > EP-1 > EP-3; C:P: EP-3 > EP-1 > EP-5 > EP-4 > EP-2; and N:P: EP-1 = EP-3 > EP-4 = EP-5 > EP-2.

3.3.3. Micronutrients

The distribution and interaction of extractable micronutrients (Cu, Fe, Mn, and Zn) along the biotite-granite toposequence revealed significant spatial and vertical variability (Table 9). Concentrations of Fe, Mn, and Zn generally decreased with soil depth, while Cu remained relatively stable across horizons. The average Cu and Fe concentrations were 2.3 mg kg⁻¹ and 6.8 mg kg⁻¹, respectively. Manganese had higher concentrations in the surface and subsurface horizons, while Fe showed a slight enrichment in the subsurface horizons. Zinc levels were notably low, ranging from 0.02 mg kg⁻¹ in the riverine thickets (EP-5) to 0.4 mg kg⁻¹ in the vegetable fields (EP-4), indicating substantial Zn depletion

across most landscape positions. Overall, extractable micronutrients were in the order Mn > Fe > Cu > Zn, with forested pedons (EP-1 and EP-2) recording higher values than cultivated lands.

3.3.4. Carbon, nitrogen, and phosphorus stocks

The highest stocks of C, N, and P were recorded in pedons EP-3 (13.6 kg m⁻²), EP-4 (1.2 kg m⁻²), and EP-2 (57.3 kg m⁻²), corresponding to the middle, lower, and upper slopes, respectively (Table 10). As observed, carbon stocks generally increased with a decrease in elevation, apart from the valley bottom pedon (EP-5). In this study, the mean carbon stocks for the A-horizon were 8.5 kg m⁻² (EP-1) and 6.3 kg m⁻² (EP-5) at depths ranging from 0 to 100 cm. In the mineral layer (B horizon), mean carbon stocks ranged from 0.8 kg m⁻² (EP-1) to 8.1 kg m⁻² (EP-3), indicating that the A and B horizons accounted for 20–30% and 40–60% of the total carbon stocks, respectively. Phosphorus stocks generally decreased with depth, although uneven distribution was noted in pedons EP-2 and EP-5. The highest accumulation of carbon and nitrogen stocks was observed in the Bt1 and Bt2 horizons across all pedons. The highest P stocks were recorded in the BAt horizon of pedon EP-2. Across the pedons, the total and mean C and N stocks followed the order: EP-3 > EP-4 > EP-2 > EP-1 > EP-5.

3.4. Relationships among the soil physico-chemical properties and soil-forming processes

3.4.1. Principal component analysis

Principal Component Analysis (PCA) effectively identified the dominant soil properties controlling spatial variability along the toposequence (EP-1 to EP-5). The resulting Composite Soil Quality Index (CSQI) equations integrate key physical and chemical indicators, providing a quantitative framework for assessing soil quality variations across contrasting slope positions. For the summit (forest) and upper

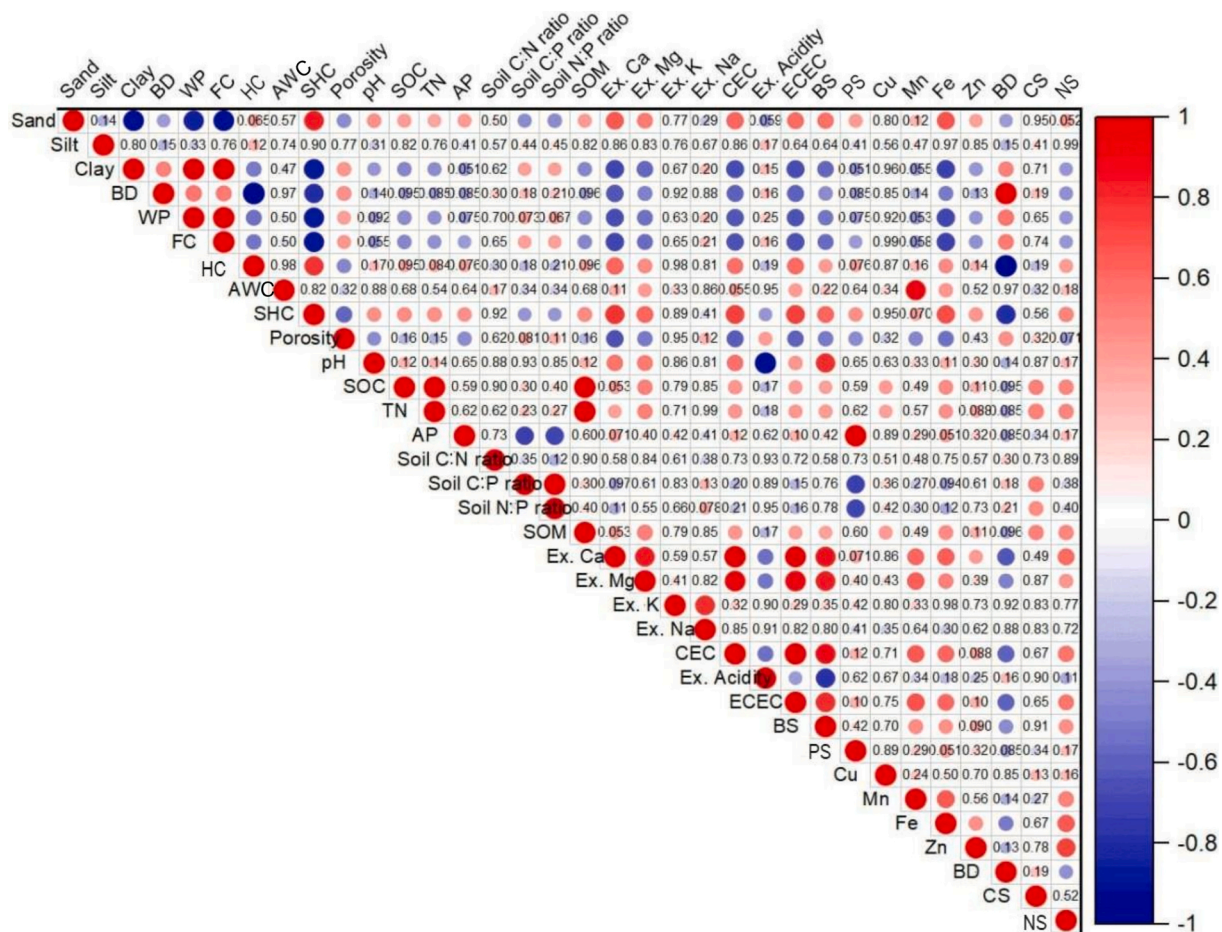


Fig. 4. Correlation matrix (significant level: $p \leq 0.05$) indicating the relationships between soil physico-chemical properties in the studied pedons.

slope (cocoa farm) soils (EP-1–EP-2; see Eq. 4), CSQI was primarily controlled by silt (0.997) and phosphorus stocks (0.972), with substantial contributions from base saturation (0.932) and sand (0.841). The strong influence of silt highlights its role in moisture retention and aggregate stability, while phosphorus availability and base saturation reflect improved nutrient supply and chemical fertility under perennial vegetation. These results indicate that both textural and fertility-related properties jointly regulate soil quality at upper slope positions. At the middle slope (Eq. 5) under maize cultivation (EP-3), phosphorus stocks emerged as the most influential factor (0.999), followed by base saturation (0.983) and manganese (0.954). This pattern underscores the importance of phosphorus supply capacity and nutrient base status in sustaining annual cropping systems. The continued influence of sand (0.892) suggests that favourable drainage and aeration remain critical for crop productivity at this slope position. Lower slope and valley bottom soils (EP-4–EP-5) were dominated by iron (0.996) and manganese (0.992), reflecting redox-driven processes associated with periodic saturation and depositional environments (Eq. 6). The significant contribution of clay (0.841) indicates increased fine-particle accumulation, enhancing nutrient retention but potentially constraining drainage. Across the entire toposequence (EP-1–EP-5), soil quality was primarily governed by silt (0.960), base saturation (0.847), manganese (0.826), and phosphorus stocks (0.768), demonstrating the combined influence of texture, nutrient availability, and redox-sensitive elements in regulating soil quality along the landscape gradient (Eq. 7).

3.4.2. Structural equation model (SEM)

The SEM analysis of the surface soil horizons distinguished three major, functionally linked soil domains: physical soil properties (PSP),

chemical soil properties (CSP), and soil nutrient dynamics (SND) (Fig. 5a). The PSP cluster comprised bulk density, porosity, field capacity, wilting point, available water capacity, and hydraulic conductivity, reflecting strong internal associations among pore structure and water-retention attributes. Bulk density exhibited an inverse relationship with porosity and moisture-related variables, emphasizing its regulatory role in surface soil physical condition. Chemical soil properties formed a separate CSP cluster dominated by exchangeable base cations (Ca, Mg, K, and Na), soil pH, and available phosphorus. High loadings of exchangeable Ca and available P indicate their importance in controlling nutrient availability and buffering capacity in surface horizons. A strong positive linkage between PSP and CSP suggests that favourable physical structure enhances nutrient retention and exchange processes. Soil nutrient dynamics clustered independently and were represented by C:N, C:P, and N:P ratios. The stronger association of the C:P ratio highlights phosphorus limitation as a key control on nutrient stoichiometry. Overall, the hierarchical structure demonstrates integrated controls of soil physical condition and chemical fertility on surface soil nutrient balance.

The SEM analysis (Fig. 5b) of the subsurface soil horizons revealed that the PSP cluster was dominated by field capacity, wilting point, and available water capacity, indicating that moisture retention characteristics strongly control subsurface soil physical behavior. Bulk density showed a negative association with PSP, while porosity contributed weakly, reflecting compaction effects at depth. Chemical soil properties formed a distinct CSP cluster, with soil organic carbon and total nitrogen exhibiting the strongest loadings, followed by cation exchange capacity and available phosphorus. These results highlight the importance of organic matter and nitrogen storage in regulating subsurface soil

Table 8
Biogenic elemental contents.

Profile	Horizon	Depth (cm)	SOC (%)	TN	Available P (mg kg ⁻¹)	C:N Ratios	C:P	N:P
EP-1	A	0–14	0.60	0.05	4.87	12.0	0.12	0.01
	BA	14–36	0.24	0.02	1.93	12.0	0.12	0.01
	Bt1	36–75	0.56	0.05	0.62	11.2	0.90	0.08
	Bt2	75–103	0.24	0.02	0.23	12.0	1.04	0.09
	Btgcs2	103–134	0.52	0.05	0.46	10.4	1.13	0.11
EP-2	Ap	0–5	0.44	0.03	3.79	14.67	0.12	0.01
	Bat	5–33	0.60	0.05	8.12	12.0	0.07	0.01
	Bt1	33–60	0.44	0.04	0.62	11.0	0.71	0.06
	Bt2	60–94	0.76	0.07	3.02	10.86	0.25	0.02
	Btg	94–103+	0.40	0.03	1.39	13.33	0.29	0.02
EP-3	Ap	0–14	0.28	0.03	6.03	9.33	0.05	0.01
	BA	14–48	0.52	0.04	1.16	13.0	0.45	0.03
	Bt1	48–89	1.28	0.11	0.93	11.64	1.38	0.12
	Bt2	89–121	0.28	0.03	0.31	9.33	0.90	0.10
	Btgcs2	121–144	0.28	0.02	0.46	14.0	0.61	0.04
EP-4	Ap	0–7	1.80	0.15	4.79	12.0	0.38	0.03
	AB	7–20	0.56	0.04	6.19	14.0	0.09	0.01
	Bt1	20–45	0.96	0.08	4.33	12.0	0.22	0.02
	Bt2	45–86/124	0.36	0.03	0.62	12.0	0.58	0.05
	Btgcs	124/137–141	0.80	0.06	0.70	13.33	1.14	0.09
EP-5	Ap	0–10	1.72	0.14	2.17	12.29	0.79	0.06
	AB	10–24	0.48	0.05	0.54	9.60	0.89	0.09
	Btg	24–50	0.34	0.03	0.81	11.33	0.42	0.04
	Btgcs	50–65	0.20	0.02	7.65	10.0	0.03	0.01
	Btgcw	65–85	0.36	0.02	1.16	18.0	0.31	0.02

Abbreviations: EP-1 = Acrisol (*Kumasi series*); EP-2 = Acrisol (*Asuansi series*); EP-3 = Nitisol (*Akroso series*); EP-4 = Gleysol (*Nta series*); EP-5 = Gleysol (*Ofin series*).

fertility and nutrient buffering capacity. Soil pH showed a relatively low contribution, suggesting limited vertical variability in acidity. Soil nutrient dynamics clustered separately and were represented by C:N, C:P, and N:P ratios. Stronger associations of C:P and N:P ratios indicate phosphorus-related constraints on nutrient balance in subsurface horizons. Structural linkages suggest that CSP strongly governs nutrient stoichiometry, whereas physical properties exert an indirect influence through their effect on chemical fertility.

3.4.3. Hierarchical cluster analysis of surface soil horizons

Hierarchical cluster analysis based on Euclidean rescaled distances revealed a clear separation of soil horizons into two major groups corresponding to organic-dominated and organo-mineral/mineral horizons (Fig. 6). The primary bifurcation occurred at a relatively large rescaled distance (0.35–0.40), indicating strong dissimilarity between surface organic horizons (Ap, AB) and subsurface horizons characterized by greater mineral influence (BA, Bt and their variants). The first major cluster comprised predominantly organic horizons, including Ap and AB horizons from multiple profiles (EP-3, EP-4, and EP-5). These samples clustered tightly at low rescaled distances (<0.10), reflecting high similarity in their measured properties. Within this group, Ap horizons from different profiles (e.g., EP-3/Ap, EP-4/Ap, EP-5/Ap) formed a cohesive subcluster, suggesting consistent organic matter-related characteristics across sites. AB and BA horizons associated with surface or near-surface layers also grouped closely with Ap horizons, indicating transitional behavior between purely organic and more mineral-dominated layers. The second major cluster consisted of organo-mineral and mineral horizons, including BA, Bt, and Btg horizons with various suffixes (e.g., Btgcs, Btgcw). This group displayed greater internal heterogeneity, with subclusters forming at rescaled distances of approximately 0.10–0.20. Bt and Btg horizons from different profiles often clustered together, suggesting that pedogenic processes such as clay illuviation and redoximorphic features exert a stronger influence on

similarity than site-specific factors. Notably, horizons with gleying or carbonate-related suffixes (e.g., Btg, Btgcs) tended to cluster in close proximity, reflecting shared hydromorphic or geochemical conditions. Overall, the dendrogram demonstrates that horizon designation is a primary driver of clustering, overriding profile-level differences. The pronounced separation between organic and mineral horizons underscores fundamental contrasts in soil properties, while the finer sub-clusters highlight the gradual changes associated with pedogenic development within the soil profiles.

4. Discussion

4.1. Morphology

The soils developed along the biotite-granite toposequence in the humid tropical rainforest zone of Ghana exhibit strong vertical and lateral differentiation driven by topography, hydrology, land use, and long-term pedogenic processes. The integration of morphological observations, soil physical and chemical properties, nutrient dynamics, and multivariate analyses provides a coherent understanding of how soil-forming processes operate from summit to valley bottom in highly weathered tropical landscapes. The studied pedons (EP-1 to EP-5) exhibited well-developed horizonation, reflecting advanced soil development under humid tropical conditions (Table 2). Morphological variability along the toposequence was strongly controlled by landscape position, drainage regime, erosion-deposition dynamics, and vegetation cover. These interacting factors governed horizon thickness, colour patterns, structural development, and boundary characteristics, highlighting the close linkage between pedogenesis and geomorphic setting in tropical environments. Soil colour showed clear vertical differentiation across all pedons, with surface horizons dominated by dark brown to yellowish-brown hues (10YR 3/3–3/6) and subsurface horizons (Btg and Btgcs) transitioning to yellowish-brown, brownish-yellow, and

Table 9

Micronutrients.

Profile	Horizon	Depth (cm)	Cu (mg kg ⁻¹)	Mn	Fe	Zn
EP-1	A	0–14	1.81	19.39	10.56	0.13
	BA	14–36	2.30	0.62	4.41	0.08
	Bt1	36–75	1.60	15.26	6.69	0.10
	Bt2	75–103	2.10	0.61	3.04	0.11
	Btgcs2	103–134	1.48	0.49	2.81	0.06
EP-2	Ap	0–5	3.17	97.30	15.50	0.05
	BAt	5–33	2.99	5.45	5.62	0.10
	Bt1	33–60	3.47	2.95	3.63	0.07
	Bt2	60–94	1.13	4.04	4.88	0.15
	Btg	94–103+	3.02	1.42	3.47	0.02
EP-3	Ap	0–14	1.94	22.65	8.39	0.16
	BA	14–48	1.40	0.92	6.68	0.10
	Bt1	48–89	5.22	3.98	4.83	0.08
	Bt2	89–121	1.64	9.37	6.26	0.18
	Btgcs2	121–144	1.94	0.58	2.41	0.06
EP-4	Ap	0–7	3.47	29.12	15.64	0.44
	AB	7–20	2.41	2.92	9.66	0.21
	Bt1	20–45	1.75	0.61	12.36	0.01
	Bt2	45–86/124	1.71	0.54	10.46	0.19
	Btgcs	124/137–141	1.79	0.52	3.52	0.05
EP-5	Ap	0–10	2.69	18.93	10.58	0.02
	AB	10–24	2.74	10.27	7.00	0.09
	Btg	24–50	2.10	0.90	4.25	0.05
	Btgcs	50–65	1.70	0.55	3.76	0.02
	Btgcw	65–85	2.35	0.85	3.91	0.07

Abbreviations: EP-1 = Acrisol (*Kumasi series*); EP-2 = Acrisol (*Asuansi series*); EP-3 = Nitisol (*Akroso series*); EP-4 = Gleysol (*Nta series*); EP-5 = Gleysol (*Ofin series*).

olive-yellow colours (2.5YR-10YR). Darker surface colours primarily reflect the accumulation of soil organic matter (SOM), which is enhanced under forest (EP-1) and agroforestry (EP-2) systems typical of humid tropical landscapes. Recent studies have consistently shown that organic matter inputs from litterfall and root turnover exert strong control on topsoil colour and structure in tropical soils (Lehmann and Kleber, 2015; Schmidt et al., 2011; Yitbarek et al., 2016). However, higher chroma values (≥ 4) in subsurface horizons indicate the dominance of iron oxides and generally well-drained conditions in most profiles. Pedons EP-1, EP-2, and EP-3 displayed evidence of oxidized iron, suggesting favourable aeration and drainage conditions that promote the formation and persistence of stable iron oxides such as hematite and goethite (Phogat and Dahiya, 2015). These oxides contribute to the brownish colouration typical of tropical soils developed on granitic parent materials and play an important role in aggregate stabilization and nutrient retention (Almeida & Santos, de, 2021; Anderson, 2005; Torrent and Barrón, 1993). The systematic increase in chroma with depth reflects progressive pedogenic differentiation driven by iron redistribution, weathering intensity, and decreasing organic matter influence.

While pedons EP-4 and EP-5 exhibited pronounced gleyic colour patterns, characterized by grey to olive-yellow hues in subsurface horizons. These features indicate periodic or prolonged water saturation associated with fluctuating water tables and lateral water movement in foot slope and valley-bottom positions. Such hydromorphic conditions promote alternating oxidation-reduction reactions, leading to iron mobilization and redistribution within the profile (Almeida & Santos, de, 2021; S Anderson, 2005; Brady & Weil, 2017). The classification of these pedons as Gleysols is consistent with their poor drainage, grey-coloured B horizons, relatively high SOM content, and thick A horizons (IUSS Working Group WRB, 2022). Fine-textured colluvial and

Table 10

Depth distribution of carbon, nitrogen and phosphorus stocks.

Profile	Horizon	Depth (cm)	Carbon (kg m ⁻²)	Nitrogen	Phosphorus
EP-1	A	0–14	1.18	0.10	9.61
	BA	14–36	0.78	0.06	6.24
	Bt1	36–75	3.14	0.28	3.48
	Bt2	75–103	0.99	0.08	0.95
	Btgcs	103–134	2.40	0.23	2.12
		Total	8.50	0.76	22.41
EP-2	Ap	0–5	0.33	0.02	2.80
	BAt	5–33	2.57	0.21	34.79
	Bt1	33–60	1.73	0.16	2.44
	Bt2	60–94	3.88	0.36	15.40
	Btg	94–103+	0.54	0.04	1.89
		Total	9.05	0.79	57.33
EP-3	Ap	0–14	0.55	0.06	11.90
	BA	14–48	2.63	0.20	5.88
	Bt1	48–89	8.08	0.69	5.87
	Bt2	89–121	1.38	0.15	1.53
	Btgcs2	121–144	0.99	0.07	1.63
		Total	13.64	1.18	26.81
EP4	Ap	0–7	1.78	0.15	4.73
	AB	7–20	1.05	0.07	11.59
	Bt1	20–45	3.55	0.30	16.02
	Bt2	45–86	2.26	0.19	3.89
	Btgcs	124/137–141	4.62	0.35	4.04
		Total	13.26	1.05	40.27
EP-5	Ap	0–10	2.43	0.20	3.06
	AB	10–24	1.01	0.11	1.13
	Btg	24–50	1.31	0.12	3.12
	Btgcs	50–65	0.45	0.04	17.10
	Btgcw	65–85	1.11	0.06	3.57
		Total	6.30	0.52	27.8

Abbreviations: EP-1 = Acrisol (*Kumasi series*); EP-2 = Acrisol (*Asuansi series*); EP-3 = Nitisol (*Akroso series*); EP-4 = Gleysol (*Nta series*); EP-5 = Gleysol (*Ofin series*).

alluvial deposits in these landscape positions further enhance moisture retention and slow organic matter decomposition, reinforcing hydromorphic soil development. Across the toposequence, a consistent vertical colour transition from dark surface horizons to lighter, iron-dominated subsurface horizons was observed. This pattern underscores the combined influence of organic matter accumulation at the surface and iron oxide dynamics at depth. Colour heterogeneity within Bt horizons, particularly in EP-4 and EP-5, likely reflects both chemical weathering of the parent material and redox-driven redistribution of iron under fluctuating moisture conditions. In some cases, buried horizons associated with occasional sediment deposition may also contribute to colour variability, especially in downslope positions.

Soil structure exhibited systematic changes with depth and landscape position. Surface horizons generally displayed granular to fine subangular blocky structures, reflecting intense biological activity, organic binding agents, and frequent wetting-drying cycles. Subsurface Bt horizons transitioned to moderate to strong angular or subangular blocky structures, associated with increased clay content and the accumulation of iron oxides within the clay fraction. The presence of clay coatings (cutans) on ped surfaces provides clear evidence of clay translocation from upper to lower horizons, indicating active eluviation-illuviation processes and contributing to horizon differentiation. Increasing ped size with depth reflects stronger aggregation and reduced biological disturbance in subsurface layers. Horizon boundary characteristics further support active pedogenic processes along the toposequence. Smooth and gradual boundaries in upper horizons are indicative of bioturbation and organic matter turnover, while clearer

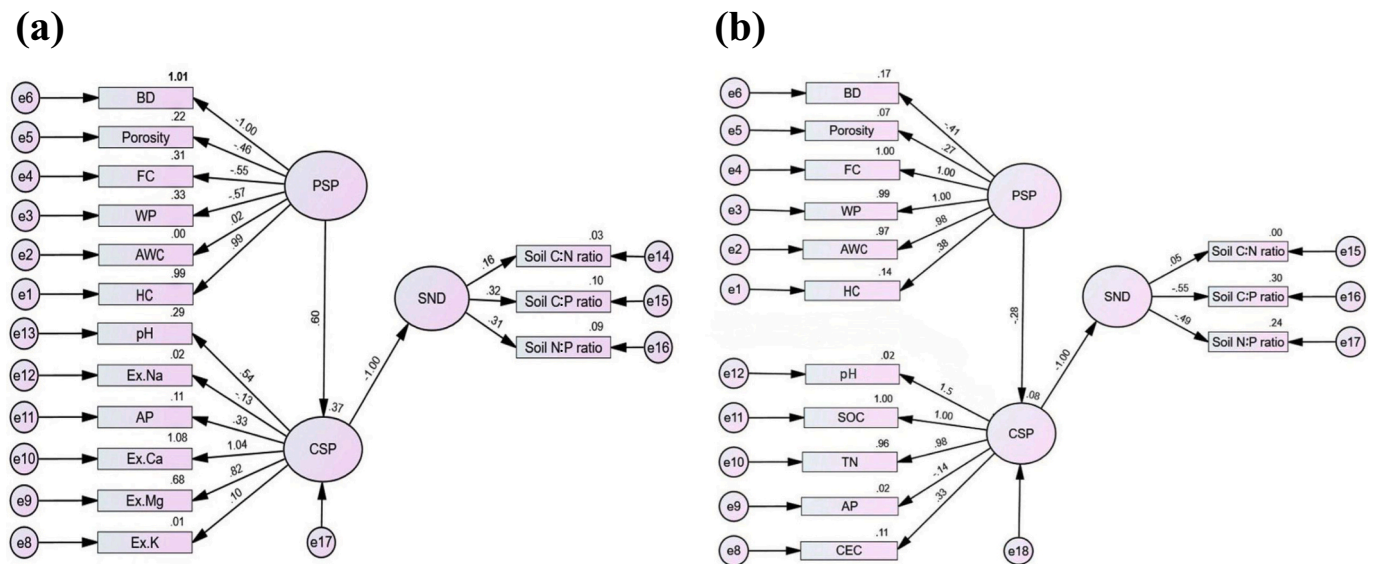


Fig. 5. (a) Structural Equation Model of soil physico-chemical properties for topsoil of depth 0–20 cm (organic horizon i.e., Ap, AB, etc.) as influenced by soil moisture (water holding capacity). (b) Structural Equation Model of soil physico-chemical properties for subsoil of depth 40–100 cm (organo-mineral and mineral horizon i.e., Bt, Btg, etc.) as influenced by soil moisture (water holding capacity). Rectangular frames denote the measurable variables and the ellipse frames denote the latent variables. The arrows denote causal paths or positive and negative correlation.

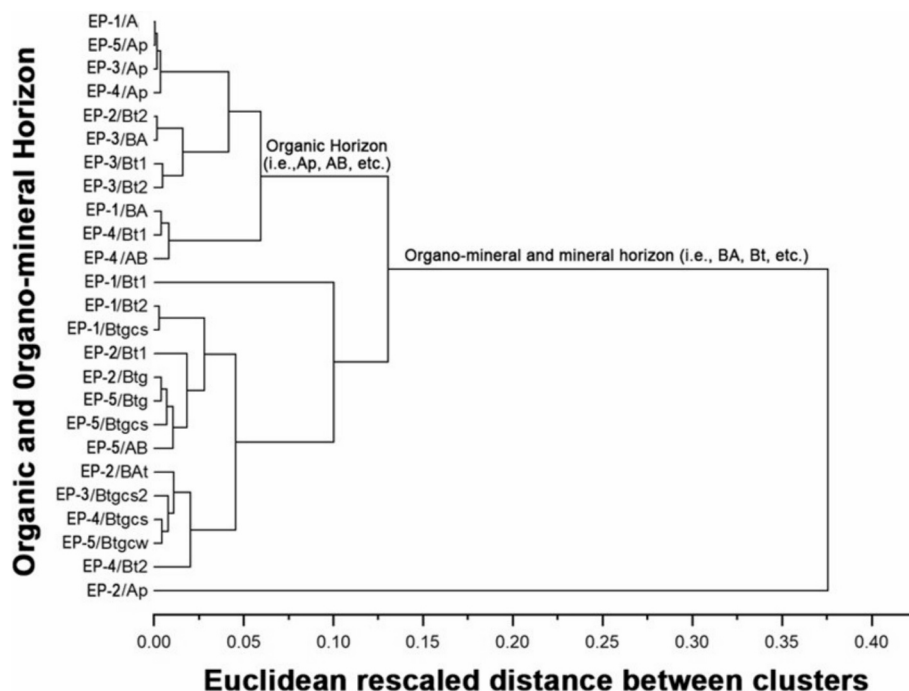


Fig. 6. Dendrogram results of hierarchical cluster analysis indicating the relationship of soil horizons in different profiles using the average linkages between the different horizons of 5 pedons along the Cape Coast biotite-granite toposquence in the High Rainforest Zone of Ghana.

and more abrupt boundaries in lower Bt horizons reflect the downward movement of solutes and fine particles. Horizon thickness varied systematically with slope position. The thick A horizon in EP-1 reflects minimal disturbance under native forest, whereas the shallow surface horizon in EP-2 indicates erosion on steep upper slopes. Increased horizon thickness in middle and lower slope pedons reflects depositional processes, consistent with observations from similar tropical landscapes (Dessalegn et al., 2014). Overall, the morphological characteristics of the pedons demonstrate that soil development along the toposquence is governed by strong interactions among topography, drainage, parent material, and land use. Organic matter accumulation, iron oxide dynamics, clay translocation, and erosion-deposition processes collectively

shape horizon development and soil differentiation. These findings emphasize the importance of landscape position in controlling soil morphology and highlight the need for site-specific soil management strategies to sustain soil quality in humid tropical environments.

4.2. Physical properties

4.2.1. Soil texture

The textural characteristics of the studied pedons demonstrate strong control by granitic parent material, topographic position, and pedogenic processes operating along the toposquence under humid tropical conditions. Soil textures ranged from sandy loam in surface horizons to

sandy clay loam in subsurface horizons, indicating clear vertical textural differentiation with depth. This pattern reflects the dominance of eluviation-illuviation processes, which are intensified by high rainfall, slope-driven water movement, and drainage variability typical of tropical landscapes (Buol et al., 2011; Schaetzl and Thompson, 2015). Subsurface horizons were consistently finer textured than surface layers, confirming the downward translocation of clay from A and AB horizons into BA and Bt horizons. Morphological evidence of this process was provided by the presence of faint to prominent clay coatings (cutans) on ped faces and pore walls across all pedons. In some profiles, laminated and circular clay coatings associated with voids and ped surfaces indicate advanced infilling of pores and partial welding of soil aggregates, preserved as cemented relics. Although clay accumulation was not sufficient in all cases to define fully developed diagnostic illuvial horizons, these features clearly indicate the formation of incipient argic horizons, a common feature in tropical soils undergoing progressive development (IUSS Working Group WRB, 2022; Schaetzl and Thompson, 2015; Torrent and Barrón, 1993). In pedons EP-2 and EP-5, clay content in the upper B horizons met the criteria for argic or argillic horizons, confirming that clay illuviation is a dominant pedogenic process along the landscape.

Clay content increased systematically with depth across all pedons (Table 5), particularly within the 50–100 cm and 100–150 cm intervals, reflecting sustained clay translocation over time (Maniyunda et al., 2015). Similar depth-related trends have been widely reported in tropical soils, where clay accumulation is most pronounced in mid- and lower-profile positions due to prolonged percolation and eluviation-illuviation dynamics (Brady and Weil, 2017; Buol et al., 2011). The accumulation of clay in BA and Bt horizons has important functional implications, including enhanced water retention, reduced permeability, altered aeration, and improved stabilization of soil organic matter. However, these finer textures may also restrict drainage, especially in lower slope positions where water convergence occurs. The silt-to-clay ratio provided valuable insight into the degree of weathering and soil development along the toposequence. Mean ratios generally decreased with depth in all pedons, reflecting progressive weathering, selective loss of silt-sized particles, and the illuviation of clay into subsurface horizons. Such depth-related declines in silt-to-clay ratios are widely used as indicators of advanced pedogenic development in tropical soils. Ratios below 0.15 in Bt horizons suggest soils derived from older, more intensely weathered materials, whereas higher ratios in surface horizons indicate relatively younger or periodically rejuvenated materials (Egbuchua and Ojor, 2011; Levy et al., 1993). Elevated surface ratios in pedons EP-1 and EP-5 reflect seasonal alluvial enrichment, where sediment deposition introduces less-weathered material and temporarily masks underlying weathering intensity (Elias, 2017; Seifu et al., 2023). These findings support the continued use of silt-to-clay ratio as an effective index of pedogenic weathering and soil degradation in humid tropical environments.

Clay concentration indices (CCI) further highlighted differences in textural differentiation driven by slope position and land use. Higher CCI values in pedon EP-2 (Table 5) indicate relatively uniform clay distribution and limited surface erosion, likely associated with protective forest cover that minimizes soil loss and promotes internal pedogenic processes. In contrast, lower CCI values in pedons EP-1 and EP-5 reflect stronger textural differentiation, attributed to either surface soil removal through erosion or depositional processes that dilute surface clay content. These patterns underscore the strong interaction between topography, vegetation cover, and land use in regulating clay redistribution and horizon development (Dessalegn et al., 2014). Bulk density (BD) increased consistently with depth across all pedons, reflecting declining soil organic matter (SOM) content and reduced aggregation in subsurface horizons (Table 5). Surface horizons with higher SOM exhibited lower BD due to enhanced aggregation and pore development, whereas clay-rich subsurface horizons showed higher BD values. Cultivated pedons, particularly EP-3 on the middle slope, recorded relatively

high BD due to repeated tillage, and aggregate disruption, processes known to accelerate SOM decomposition and soil compaction (Mojiri et al., 2012). In contrast, pedons under forest or minimally disturbed conditions exhibited lower BD values. Porosity showed an inverse relationship with BD and generally increased with depth, reflecting increased clay content and aggregate development. However, higher total porosity in clay-rich horizons (Bt) does not necessarily translate to improved hydraulic conductivity, as these horizons are dominated by micropores that retain water but restrict rapid drainage. This highlights the importance of pore-size distribution, rather than total porosity alone, in controlling soil hydraulic behavior in tropical landscapes (Hillel, 2003).

4.2.2. Hydro sequence and water retention characteristics

Soil hydrological properties exhibited marked vertical and lateral variability along the toposequence, reflecting strong interactions among soil texture, structure, horizon development, and landscape position under humid tropical conditions. Variations in porosity, water retention at field capacity (FC) and wilting point (WP), available water capacity (AWC), and saturated hydraulic conductivity (SHC) highlight the central role of pedogenic processes in regulating soil-water relationships across the landscape. Water retention at both FC and WP increased consistently with depth in most pedons, primarily due to progressive clay enrichment and micropore development in subsurface horizons. Clay-rich layers retain water at higher matric potentials, resulting in elevated FC and WP values relative to surface horizons (Hillel, 2003). Pedons EP-1 and EP-2 exhibited particularly high AWC in Bt horizons, indicating favourable subsurface moisture storage that supports deep-rooted perennial vegetation such as forest and cocoa systems. Similar enhancements in plant-available water associated with argic or argillic horizons have been widely reported in tropical soils (van Tol, 2020). However, surface horizons generally showed lower AWC due to coarser textures, reduced clay content, and structural degradation linked to cultivation and organic matter depletion. Aggregate disruption in cultivated Ap horizons reduces microporosity and limits water retention despite relatively high infiltration rates (Lal, 2020). These findings emphasize the sensitivity of surface soil hydraulic properties to land-use practices in tropical agroecosystems.

Saturated water content varied within a narrow range across horizons (Table 6), indicating that saturation is largely controlled by total pore volume rather than horizon designation alone. Slightly higher saturation in surface horizons reflects better aggregation and the presence of biogenic macropores formed by roots and soil fauna. However, such macropores are vulnerable to mechanical disturbance, and their collapse under continuous cultivation contributes to reduced hydraulic conductivity even where total porosity remains high (Brady and Weil, 2017; Lal, 2020). Saturated hydraulic conductivity showed the greatest variability among hydrological properties and declined sharply with depth across all pedons. High SHC values in surface horizons reflect rapid water transmission through interconnected macropores, whereas extremely low values in Bt, Btg, and Btgc horizons indicate restricted permeability due to clay illuviation, compaction, and hydromorphic features (de Lima and da Silva, 2022). These restrictive layers impede vertical water movement and increase susceptibility to waterlogging, particularly in lower slope (EP-4) and valley-bottom (EP-5) positions (Rabbi et al., 2014). The valley-bottom pedon (EP-5) illustrates strong topographic control on soil-water dynamics. High WP, FC, and AWC combined with very low SHC indicate prolonged water retention and slow drainage, conditions that favour hydromorphic processes but limit aeration and root respiration (Buol et al., 2011). Overall, soil hydrological behavior along the toposequence reflects a balance between clay translocation, land use, and hydromorphism, underscoring the need for landscape-specific soil management strategies to enhance water use efficiency and minimize degradation in humid tropical environments.

4.3. Nutrient dynamics

4.3.1. Soil pH and exchangeable cations

Soil reaction across the studied pedons ranged from very strongly acidic to moderately acidic, with surface horizon pH values between 4.9 and 5.9 (Table 7). This acidity range is characteristic of highly weathered tropical soils formed under humid climatic conditions and reflects prolonged leaching, dominance of low-activity clays, and organic acid inputs from vegetation (Sanchez, 2019). Although acidic, such soils can sustain diverse food and cash crops when appropriate fertility management practices—particularly liming and organic amendments—are applied. In tropical environments, soils within this pH range commonly contain hydroxyl aluminum polymers, indicative of advanced weathering and strong acidity buffering (Sanchez, 2019; Vorob'eva & Avdon'kin, 2006). Soil pH generally increased with depth across all pedons, a trend attributed to declining organic matter inputs, reduced biological activity, and the redistribution of base cations through leaching and illuviation. Surface horizons receive continuous organic inputs that generate organic acids during decomposition, whereas subsurface horizons are less influenced by biological processes and may retain leached base cations. Along the catena, upland pedons exhibited lower pH and base saturation (BS), reflecting enhanced leaching under well-drained conditions. In contrast, lower slope and valley-bottom soils showed relatively higher pH values but lower BS in subsurface horizons, reflecting hydromorphic conditions and prolonged saturation that alter redox processes and cation exchange dynamics (van Tol, 2020).

High BS values (>85%) in surface horizons indicate relatively favourable nutrient status, while declining BS with depth highlights the cumulative effects of leaching, clay translocation, and land-use change. Conversion from natural forest to cocoa and maize cultivation has significantly modified exchangeable base distribution, particularly in upland pedons. Continuous cropping, residue removal, and limited nutrient replenishment accelerate base cation depletion, reinforcing the combined influence of slope position and land use on soil fertility gradients along the catena (Lal, 2020). These interactions strongly regulate the spatial distribution of soil organic carbon (SOC), total nitrogen (TN), and available phosphorus (AP). Exchangeable cations exhibited pronounced vertical and lateral variability, reflecting zones of eluviation and illuviation within the profiles. Leaching of basic cations from surface horizons was particularly evident in upper-slope pedons, consistent with intense rainfall and acidic conditions typical of humid tropical regions. Cation exchange capacity (CEC) decreased with depth across all pedons, closely following declines in SOC and the dominance of kaolinitic clays. Higher CEC values in surface horizons were strongly associated with organic matter content, underscoring the critical role of SOM in enhancing nutrient retention in soils dominated by low-activity clays.

In subsurface horizons of lower-slope pedons, low CEC and BS values reflect the dominance of acidic cations (Al^{3+} and H^{+}) on exchange sites, increasing the risk of nutrient deficiencies and aluminum toxicity. However, the exchange complexes of upland and mid-slope pedons were dominated by basic cations, resulting in higher BS and more favourable chemical conditions for crop production (Krasilnikov et al., 2009). Across all pedons, the relative abundance of exchangeable cations followed the order $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^{+} > \text{Na}^{+}$, a sequence typical of productive tropical soils and indicative of balanced base cation chemistry (Sanchez, 2019). Deviations from this order may induce nutrient imbalances and constrain plant growth. Textural class exerted a strong influence on CEC, with sandy clay and sandy clay loam horizons exhibiting higher values than sandier horizons due to greater clay content and surface area. However, the predominance of kaolinitic mineralogy resulted in generally low CEC values ($<8 \text{ cmol}_c \text{ kg}^{-1}$), increasing vulnerability to nutrient leaching and emphasizing the importance of organic matter inputs for sustaining soil fertility (Buol et al., 2011; IUSS Working Group WRB, 2022; Lal, 2020; Sanchez, 2019). Calcium was the dominant exchangeable cation across all pedons, followed by

magnesium, potassium, and sodium. Exchangeable cation concentrations were highest in surface horizons and generally declined with depth, reflecting biocycling, litter inputs, and surface-applied nutrients. Forested pedons retained higher K^{+} levels due to efficient nutrient recycling, whereas cultivated pedons exhibited signs of potassium depletion. Despite spatial variability, the dominance of Ca^{2+} and Mg^{2+} suggests that, from a base cation perspective, the soils remain broadly suitable for crop production, provided nutrient losses are replenished. Overall, the toposquence analysis highlights the fundamental role of erosion, transport, and deposition in redistributing nutrients across the landscape. Summit and upper-slope positions are dominated by erosional processes, resulting in thinner soils with lower SOC, clay, and exchangeable base contents. In contrast, foot slope and valley-bottom positions function as depositional environments, accumulating fine particles and nutrients transported from upslope. These processes collectively underpin the strong spatial heterogeneity of soil chemical properties observed along the catena and emphasize the need for landscape- and land-use-specific soil fertility management strategies in humid tropical environments.

4.3.2. Soil biogenic elements

The vertical and lateral distribution of soil biogenic elements across the studied pedons reflects the combined influence of pedogenic processes, land use, and topographic position on soil fertility under humid tropical conditions. Soil organic carbon (SOC) exhibited a pronounced decline with depth across most pedons, particularly in EP-2 and EP-3 (Table 8), consistent with typical carbon stratification patterns reported for tropical soils (Schmidt et al., 2011; Wakene and Heluf, 2004). Organic matter inputs are concentrated in surface horizons (A and Ap) through litterfall, root turnover, and microbial activity, whereas deeper horizons (e.g., Bt-Btgc) receive limited inputs and experience slower carbon cycling. Higher SOC contents in the lower slope and valley-bottom pedons (EP-4 and EP-5) are attributed to sediment and organic matter accumulation driven by erosion–deposition processes. Periodic waterlogging in these landscape positions further suppresses microbial decomposition, enhancing carbon preservation (Brady and Weil, 2017; Buol et al., 2011). While, reduced SOC levels in summit and mid-slope pedons (EP-1 to EP-3) reflect coarser textures, better drainage, and intensive cultivation, all of which accelerate organic matter oxidation and erosion losses (Lal, 2020). Localized SOC enrichment in Bt horizons of EP-2 and EP-3 suggests subsurface carbon stabilization through organo-mineral associations promoted by clay illuviation, which protects carbon from microbial degradation by increasing sorption to mineral surfaces (Buol et al., 2011).

Total nitrogen (TN) closely mirrored SOC distribution, reflecting their strong biogeochemical coupling. However, TN showed greater variability with depth due to differences in mineralization rates, leaching, and crop uptake. Several pedons exhibited TN levels indicative of moderate nitrogen supply potential, suggesting that these soils can support productive systems under appropriate management (Masunga et al., 2016; Motavalli et al., 1995). Nonetheless, sustained SOC depletion may reduce long-term nitrogen availability, emphasizing the importance of organic matter management. Available phosphorus (AP) was generally low across all pedons, a characteristic constraint by tropical soils dominated by Fe and Al oxides. Phosphorus availability declined with depth due to reduced organic inputs and increased fixation in clay-rich subsoil horizons (Brady and Weil, 2017). Localized subsurface AP enrichment in EP-2, EP-4, and EP-5 reflects depositional processes and SOM redistribution. However, higher surface AP in summit and mid-slope pedons is linked to fertilizer inputs and biological activity. Strong P fixation under acidic conditions remain a major limitation to productivity, although organic amendments can enhance P availability by chelating Fe and Al, competing for adsorption sites, and moderating soil acidity (Gerke, 2015; Neufeldt et al., 2000). Stoichiometric ratios further elucidated nutrient dynamics. Surface C:N ratios indicated moderate organic matter quality and balanced decomposition,

whereas higher ratios at depth reflect slower decomposition under reduced aeration. Declining C:P and N:P ratios with depth indicate increasing phosphorus limitation in subsoils, underscoring the need for profile-wide nutrient management strategies to sustain soil fertility in tropical landscapes (Vitousek et al., 2010).

4.3.3. Micronutrients and low soil zinc: Implications for hidden hunger

Extractable micronutrients displayed pronounced vertical and lateral variability along the toposequence, reflecting the combined influence of organic matter inputs, redox conditions, land use, and pedogenic processes (Table 9). Concentrations of iron (Fe), manganese (Mn), and zinc (Zn) generally declined with depth, indicating surface enrichment driven by biological cycling and organic matter accumulation, while copper (Cu) showed relatively uniform distribution, consistent with its stronger association with mineral fractions and lower mobility under tropical conditions (Yitbarek et al., 2016). Among the micronutrients, Mn was most abundant, followed by Fe, Cu, and Zn. Elevated Mn levels in surface horizons likely reflect redox-sensitive processes, particularly under periodically waterlogged or compacted conditions where Mn oxides are reduced and mobilized (Galić et al., 2025). Iron enrichment in subsurface horizons is indicative of clay illuviation and the accumulation of Fe oxides, a characteristic feature of highly weathered tropical soils (Buol et al., 2011). Although, zinc emerged as the most limiting micronutrient across all pedons. Extractable Zn concentrations were consistently below established critical thresholds, indicating widespread Zn deficiency regardless of slope position or land use. This pattern reflects intense weathering, leaching losses, low soil organic matter, and strong Zn sorption by Fe and Al oxides, which severely limit its bioavailability (Alloway, 2008; Brady and Weil, 2017). Forested pedons retained marginally higher Zn levels due to organic matter inputs and chelation effects, whereas cultivated soils exhibited greater depletion due to continuous cropping and insufficient nutrient replenishment. Soil pH strongly influenced micronutrient availability. While acidic conditions enhance micronutrient solubility, excessive acidity can restrict root growth and nutrient uptake, resulting in physiological limitations despite chemical availability (Tamir et al., 2023). Additionally, antagonistic interactions between phosphorus and zinc further exacerbate Zn deficiency, as elevated P levels suppress Zn uptake through competitive and precipitation mechanisms (Buri et al., 2000). Further, approximately one-third of the global population, particularly in tropical regions, suffers from insufficient Zn intake due to poor soil Zn status (Cakmak and Kutman, 2018; De Groote et al., 2021). The agronomic and nutritional implications of widespread Zn deficiency are substantial. Zinc-deficient soils produce crops with low Zn concentrations, contributing to “hidden hunger,” a major public health concern in sub-Saharan Africa (Atukunda et al., 2021). Addressing this challenge requires integrated soil and crop management strategies, including Zn fertilization, organic amendments, conservation agriculture, and the adoption of Zn-biofortified crop varieties, thereby linking soil fertility management with nutrition-sensitive agriculture along the soil-plant-human continuum.

4.3.4. Carbon, nitrogen, and phosphorus stocks in the soil profile along the Toposequence

Depth-wise analysis of soil carbon (C), nitrogen (N), and phosphorus (P) stocks revealed pronounced vertical stratification across the pedons, highlighting the importance of subsoil horizons in regulating long-term nutrient storage (Table 10). Surface horizons contained higher C and N concentrations due to continuous organic matter inputs, root activity, and intense microbial processes. However, subsurface horizons contributed substantially to total profile stocks, confirming that deeper soil layers play a critical role in long-term C and N sequestration through stabilization mechanisms such as organo-mineral associations and physical protection within clay-rich matrices (Rumpel and Kögel-Knabner, 2011). Pedons EP-3 and EP-4 exhibited the highest total C and N stocks, reflecting the accumulation of stabilized organic matter in Bt

and gleyed horizons under conditions of reduced decomposition and periodic saturation. Such environments favour organic matter preservation by limiting oxygen availability and enhancing mineral binding (Matus, 2021; Schmidt et al., 2011). Also, phosphorus stocks displayed greater spatial variability among profiles, reflecting the combined influence of parent material, weathering intensity, and redox dynamics. Elevated P stocks in EP-2 and EP-4 were largely associated with sub-surface horizons, suggesting the accumulation of secondary P forms through fixation by iron and aluminum oxides under acidic tropical conditions (Luna et al., 2022; Maranguit et al., 2017). Lower P stocks in EP-1 and EP-5 indicate contrasting lithological controls and degrees of pedogenic development. Overall, these results emphasize the necessity of considering entire soil profiles when assessing nutrient stocks and ecosystem services. Subsoil horizons act as critical reservoirs for C and nutrients, and management practices that modify subsoil structure, drainage, or redox conditions may have long-lasting impacts on soil fertility and sustainability. Nutrient dynamics along the toposequence are governed by complex interactions among pedogenesis, topography, land use, and mineralogy, while soil acidity, low cation exchange capacity, nutrient fixation, and micronutrient limitations further constrain productivity. Sustainable soil management therefore requires integrated strategies that enhance organic matter inputs, reduce erosion, balance nutrient supply, and address micronutrient deficiencies to improve resilience in tropical agroecosystems.

4.4. Relationships among the soil physico-chemical properties and soil-forming processes

Multivariate statistical approaches provide powerful tools for resolving the complex and interdependent relationships among soil physical, chemical, and biological properties that regulate soil formation and functioning along toposequences. In this study, the combined application of principal component analysis (PCA), structural equation modeling (SEM), and hierarchical cluster analysis (HCA) revealed pronounced vertical and lateral differentiation of soils from summit to valley bottom. These patterns reflect the integrated influence of geomorphology, hydrology, land use, and dominant pedogenic processes, consistent with contemporary soil-landscape and soil-ecosystem frameworks developed for humid tropical environments.

4.4.1. Principal component analysis

Principal component analysis effectively captured the dominant soil attributes controlling spatial variability in soil quality along the hill-slope. The PCA-derived Composite Soil Quality Index (CSQI) equations demonstrated that soil quality is governed by distinct but interconnected physical and chemical drivers that vary systematically with slope position (Eqs. 4–7). This spatial organization reflects the combined effects of erosion and deposition, drainage conditions, parent material transformation, and land-use history, in agreement with conceptual soil catena models for tropical landscapes (Doetterl et al., 2016). At the summit and upper slope positions (EP-1 and EP-2), silt content and phosphorus stocks emerged as the most influential contributors to soil quality, together with base saturation and sand content. The strong contribution of silt highlights its importance for aggregate stability, water retention, and resistance to surface erosion, properties that are critical for sustaining forest and perennial cocoa agroforestry systems under high rainfall conditions (Dawoe et al., 2014). High base saturation and phosphorus availability indicate relatively favourable chemical fertility, likely maintained by continuous organic matter inputs, efficient nutrient recycling, and well-drained conditions that limit nutrient losses. The contribution of sand further reflects adequate aeration and drainage, which reduce anaerobic stress and support active root growth and microbial processes.

In the middle slope maize system (EP-3), phosphorus availability was identified as the dominant control on soil quality, followed by base saturation and manganese. This pattern emphasizes the central role of

phosphorus supply in intensively cultivated annual cropping systems, where high nutrient demand and frequent biomass removal can rapidly deplete soil P pools if not replenished (Bationo et al., 2007; Nziguheba et al., 2015; Sanchez, 2019). The influence of manganese reflects its redox sensitivity and its importance in enzymatic activity and plant physiological processes, particularly under fluctuating moisture regimes. The continued relevance of sand content underscores the importance of balanced drainage and aeration for sustaining maize productivity in tropical environments. Lower slope and valley bottom soils (EP-4 and EP-5) were characterized by the dominance of iron, manganese, and clay content in controlling soil quality. These variables are indicative of depositional environments and hydromorphic conditions, where fine particles accumulate and fluctuating water tables promote intense redox cycling (Szalai et al., 2021). Elevated clay content enhances nutrient retention and buffering capacity but simultaneously restricts drainage and oxygen diffusion, creating chemically reactive yet physically constrained soil environments. Across the entire toposequence, silt, base saturation, manganese, phosphorus stocks, and clay collectively controlled soil quality gradients. The persistent influence of base saturation highlights its central role in regulating soil pH, nutrient availability, and cation exchange processes in tropical soils (Albuquerque et al., 2024). Overall, the PCA results emphasize pronounced spatial heterogeneity in soil quality controls and underscore the necessity of slope-specific soil management strategies that reflect local pedogenic and hydrological conditions.

4.4.2. Structural equation modeling

Structural equation modeling (SEM) provided deeper insight into the contrasting mechanisms regulating soil functioning between upper and lower horizons along the toposequence (Fig. 5). The SEM results clearly demonstrate vertical stratification in soil process controls, reflecting a transition from biologically mediated regulation in surface soils to hydrologically and geochemically constrained processes in subsoils, a pattern widely reported for deeply weathered tropical soils (Manzoni et al., 2010; Schmidt et al., 2011). In the upper horizons, soil function was strongly governed by interactions among physical structure, chemical fertility, and nutrient stoichiometry. Physical soil properties, particularly bulk density and hydraulic conductivity, exerted strong control over aeration and water movement. Lower bulk density enhances pore connectivity, facilitating root penetration, microbial activity, and nutrient diffusion. Chemical soil properties in these horizons were dominated by exchangeable calcium and magnesium, highlighting the importance of base cation balance and base saturation in buffering soil acidity and supporting nutrient availability. The positive linkage between physical and chemical properties suggests that favourable soil structure enhances chemical fertility by improving moisture regimes and cation exchange processes (Brady and Weil, 2017; Buol et al., 2011). Soil nutrient dynamics in surface horizons were strongly controlled by chemical fertility, as indicated by the dominant influence of C:P and N:P ratios. These stoichiometric relationships emphasize phosphorus as a key limiting and regulatory nutrient in surface soils, consistent with its central role in tropical nutrient cycling and ecosystem productivity (Tiessen, 2005; Vitousek et al., 2010).

Furthermore, SEM for lower horizons revealed a marked shift in dominant controls (Fig. 5). Physical properties such as wilting point, field capacity, and available water capacity showed strong loadings, reflecting enhanced water retention associated with finer textures, compaction, and reduced drainage. Chemical properties were strongly influenced by soil organic carbon, total nitrogen, and pH, underscoring the role of organic matter accumulation and acidity in regulating chemical reactivity at depth. However, very low loadings for available phosphorus and cation exchange capacity indicate strong phosphorus fixation and limited exchange potential, likely driven by interactions with iron and aluminum oxides common in highly weathered tropical subsoils (Sanchez, 2019). Negative relationships among physical properties, chemical properties, and nutrient dynamics suggest that

prolonged moisture saturation restricts aeration, suppressing microbial activity, organic matter decomposition, and nutrient mineralization. Weak C:N coupling and negative C:P and N:P relationships further indicate phosphorus limitation and partial decoupling of carbon and nitrogen cycling in the subsoils (Capek et al., 2016; Gong et al., 2025). Collectively, these results demonstrate a transition from biologically regulated nutrient cycling in surface soils to hydrologically and geochemically constrained processes in deeper horizons, emphasizing the importance of depth-specific soil management interventions.

4.4.3. Hierarchical cluster analysis

Hierarchical cluster analysis provided an integrative synthesis of soil differentiation along the toposequence by grouping horizons according to shared physicochemical and morphological attributes (Fig. 6). The dendrogram clearly separated organic-rich surface horizons (Ap, AB, BA) from organo-mineral and mineral subsurface horizons (Bt, Btg, Btgc), reflecting fundamental pedogenic distinctions between biologically dominated topsoils and physically and chemically controlled subsoils (IUSS Working Group WRB, 2022). Surface horizons clustered at low dissimilarity distances, indicating strong similarity in soil organic carbon, total nitrogen, structure, and colour across different land-use systems. This suggests that biological processes, including litter input, root turnover, and bioturbation, exert a regulating influence on surface soils despite differences in vegetation and management. Such convergence highlights the resilience of topsoil biological function under sustained organic inputs (Lal, 2020; Six et al., 2002). However, subsurface horizons formed clusters at higher dissimilarity distances, reflecting greater heterogeneity in clay content, mineralogy, and redox features. Bt horizons were characterized by clay enrichment and evidence of eluviation-illuviation, while Btg and Btgc horizons exhibited features associated with prolonged water saturation and hydromorphism. These distinctions were particularly pronounced in valley-bottom positions (EP-4 and EP-5), where restricted drainage alters iron and manganese dynamics and promotes gleying. Clustering patterns also reflected the combined influence of land use and topographic position on soil development. Horizons belonging to similar soil series and drainage conditions clustered closely, indicating shared pedogenic pathways, while unique clustering of certain horizons, such as the Ap horizon under cocoa agroforestry, demonstrated how land-use systems can modify soil properties through enhanced organic inputs, altered microclimate, and modified nutrient cycling (Adiyah et al., 2022; Suárez et al., 2025).

4.5. Integrated implications for soil development and management

Taken together, the PCA, SEM, and HCA analyses provide complementary and convergent evidence that soil physico-chemical properties and nutrient dynamics along the biotite-granite toposequence are governed by strong depth- and position-dependent controls. Surface horizons are primarily shaped by biological activity, base cation dynamics, and phosphorus availability, whereas subsurface horizons are increasingly constrained by hydrology, redox processes, and mineral interactions. Fig. 7 synthesizes these interactions, illustrating how soil texture, physical properties, chemical characteristics, and fertility parameters interact with topography, soil depth, and land-use systems to produce diverse soil horizons from summit to valley bottom. These findings underscore the necessity of integrated, depth- and slope-specific soil management strategies that acknowledge the inherent heterogeneity of tropical landscapes. Such approaches are critical for sustaining soil quality, optimizing nutrient use efficiency, and enhancing the long-term resilience of agroecosystems in humid tropical environments.

5. Conclusion

This study demonstrates that soil formation and functional variability along the gently undulating landscape of the High Rainforest

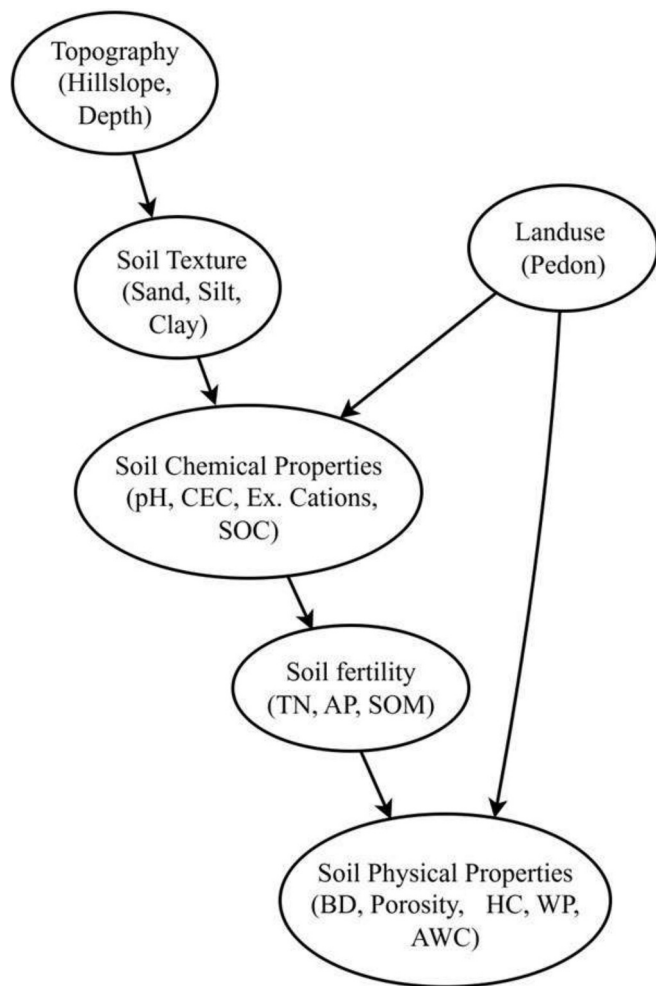


Fig. 7. Summarizes the complex relationship observed between soil texture (sand, silt and clay), soil physical properties (BD, porosity, HC, WP, FC, and AWC), soil chemical properties (pH, CEC, Ex. Cations, SOC), and soil fertility (TN, AP, and SOM) as influenced by topography (i.e., hillslope, and soil depth) and land use systems.

Zone of Ghana are strongly controlled by topography, parent material, and land use, resulting in a well-defined catena comprising Acrisols (*Kumasi and Asuansi series*), Nitisols (*Akroso series*), and Gleysols (*Nta and Ofin series*). Upland and mid-slope positions developed predominantly from granite parent material were characterized by intense weathering and leaching, leading to acidic, highly oxidized pedons with iron concretions and coatings. Also, footslope and valley-bottom soils formed from alluvial and colluvial deposits, exhibiting hydromorphic features typical of Gleysols. These findings confirm that landscape position exerts a first-order control on pedogenesis, nutrient dynamics, and soil physical behavior along the catena. Across all pedons, soils exhibited inherently low natural fertility, reflected by strong acidity, low cation exchange capacity ($< 10 \text{ cmol}_c \text{ kg}^{-1}$), and nutrient imbalances. Vertical nutrient distribution revealed a pronounced decline in available phosphorus and soil organic carbon with depth, exceeding reductions observed for total nitrogen, indicating strong surface accumulation of organic matter and limited nutrient translocation. The combined effects of advanced weathering, leaching, low organic matter inputs, and prolonged use of P-rich NPK fertilizer blends further constrained micronutrient availability, particularly zinc. These limitations underscore the need to move beyond macronutrient-focused fertility management in these systems.

Despite their constraints, the studied soils possess moderate to good agricultural potential when managed appropriately. Water dynamics in

pedons EP-4 and EP-5 can be improved in poorly drained pedons through ridging, furrowing to protect crops from waterlogging, as well as bunding to enhance infiltration. Conservation of forest cover, buffer strips, and reduced disturbance on lower slope positions is critical for protecting high soil organic carbon stocks and sustaining ecosystem services. To enhance and sustain food and cash crop production, integrated soil fertility management tailored to soil type and landscape position is essential. Liming to reduce acidity and aluminum toxicity, use of balanced fertilizer formulations including zinc and other micronutrients, and incorporation of organic amendments such as compost, manure, biochar, and green manures can substantially improve nutrient availability and soil resilience. Adoption of Zn-efficient or biofortified crop varieties further offers a viable pathway to address micronutrient deficiencies. Finally, the study highlights the urgent need for high-resolution digital soil nutrient maps to support site-specific management and informed decision-making by farmers, extension services, and policymakers. Implementing soil and catena-specific land use strategies is crucial for achieving sustainable agricultural intensification and long-term soil health in the High Rainforest Zone of Ghana.

CRediT authorship contribution statement

Johnny Kofi Awoonor: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dora Neina:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Formal analysis. **Alexander Owusu Ansah:** Writing – review & editing, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation. **Jackson Kwame Gyamfi:** Writing – review & editing, Visualization, Validation, Software, Methodology. **Prince Addai:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Collins Korbla Tay:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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