

Physico-Chemical Characteristics and Mineralogy of Soil in Catchment Areas around Penja-Manjo-Nkongsamba (Cameroon): Insights into Agriculture and Ecosystem Health

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How to cite this paper: Bih, L.P., Mboudou, G.M.M., Asongwe, G.A., Eyong, T.A., Mengu E.E.J., Okpara, D.D., Penn, E.N. and Bewah, E.B. (2025) Physico-Chemical Characteristics and Mineralogy of Soil in Catchment Areas around Penja-Manjo-Nkongsamba (Cameroon): Insights into Agriculture and Ecosystem Health. *Journal of Environmental Protection*, **16**, 948-964.

<https://doi.org/10.4236/jep.2025.169050>

Received: August 29, 2025

Accepted: September 27, 2025

Published: September 30, 2025

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Abstract

We examine the physico-chemical and mineralogical characteristics of soils of Penja-Manjo-Nkongsamba in Cameroon to evaluate their agricultural potential and ecosystem health. XRD, titration, photometry and statistics (multivariate and PCA) were used. The results show that the soils are generally loamy, slightly acidic [pH (H₂O) = 5.29 > pH (KCl) = 4.66; 45%] and composed of quartz (45% - 50%), kaolinite (10% - 40%), muscovite (10% - 35%), microcline (~5%), and minor haematite. These clay minerals are of low-activity type, can reduce heavy metal contamination, and promote soil fertility as well as crop productivity, but require careful management and control of agro materials in order to protect this ecosystem.

Keywords

Physico-Chemical Properties, Mineral Phase, Penja-Manjo-Nkongsamba, Ecosystem Health, Agriculture

1. Introduction

Soil is a vital natural resource, serving as the foundation for terrestrial ecosystems and playing a pivotal role in carbon sequestration, agricultural productivity, water filtration, and the flux of pollutants [1] [2]. Understanding the physico-chemical

characteristics of soil and its mineralogical composition is essential for agricultural productivity, land use, and conservation strategies [3] [4]. In this context, clay minerals emerge as key constituents influencing soil behavior, fertility, and their interaction with environmental factors. Clay minerals make up clay stone and soil that form as a result of chemical weathering of silicate-bearing rocks in warm sub-tropical to tropical regions [5]-[7]. According to Wilson [8] and Karathanasis [9], clay minerals can be classified as primary (deriving from igneous or metamorphic rocks under high pressure and temperature conditions) and secondary minerals resulting from the alteration of primary mineral structures into a more stable form [10]. Surface adsorption, no association with heavy metals, channel filtration, ion exchange, physical/nanometer effects, and biological interactions are the essential properties of clay minerals [7]. In soil environments, primary minerals include: silicates, Fe-oxides, Al, Zr, Ti and phosphates whereas the clay- and fine-silt-sized alumina-silicates (montmorillonite, kaolinite and illite), oxy-hydroxides, carbonate, sulphates and amorphous minerals represent the secondary minerals [9]. These minerals form the most reactive inorganic materials in soils thus impelling the availability of nutrients through various mechanisms [11]. Kaolinite (1:1 sheet) is mainly found in weathered soils of humid tropical regions where Fe- and Al rich minerals dominate over the smectite/vermiculite group (2:1 sheet). This group is characterized by high cation exchange capacity (CEC) and large surface areas [5]. Clay minerals are therefore important to assess soil/water quality (filtering of surface and ground water), nutrient (carbon storage) retention, soil structure stability, and heavy metals/pesticides contamination in order to enhance crop production [12]-[14]. Other studies in the field of soil mineralogy and fertility [15] [16], soil properties and land use [17] and the role of soil properties in catchment area protection [11] are known. The area of study is made up of igneous, metamorphic, and sedimentary rocks with varying topography (hills, flat land, catchment zones and valleys), where mining and agricultural activities take place [18]. It is therefore important to understand how the interplay between soil properties/mineralogy and the variable lithology can contribute to soil fertility. This article examines the physico-chemical and mineralogical characteristics of soil in catchments within the study area in order to assess its quality (soil damage), variability, as well as its impact on agriculture and ecosystem health.

2. Geologic Context

The North Equatorial Orogenic Belt (NEOB) according to Owona *et al.* [19] has experienced post-sinistral (dextral) shearing associated with significant plutonic activity and late tectonic faulting that led to the formation of the major shear zones in Cameroon [20] [21] (**Figure 1(a)**, **Figure 1(b)**). The NEOB is composed of: (1) the western Cameroon domain-830 Ma old meta-volcanic rocks of tholeiitic and alkaline affinities [18]; (2) the Adamawa-Yade domain is located between the Sanaga Shear Zone (SSZ) and the Tibati-Banyo Fault (TBF) to the north [22]; (3) the southern Cameroon domain which is made up of Proterozoic metavolcanic

formations [19].

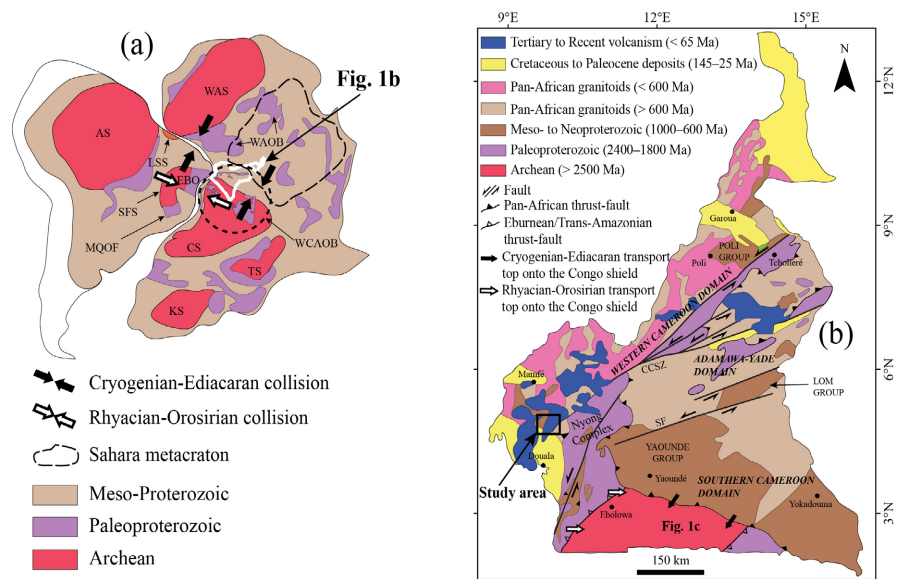


Figure 1. (a) African/Brasiliano shear and thrust belt between the Sao Francisco, Congo, and West African cratons (modified after Girma *et al.* [3]); (b) Geologic map of Cameroon showing the study area and the orogenic belt, faults, and shear zones: Central Cameroon shear zone (CCSZ), Betare Oya shear zone (BOSZ), Tibati-Banyo fault (TBF), Campo-Kribi fault (KCF), and Sanaga fault (SF) after Yaseen *et al.* [4].

The study area is located in the southwestern part of the central domain of the NEOB. Three sites (Penja, Manjo and Nkongsamba) make up the research area and are found within a plutonic/volcanic horst which is intercalated between two stratovolcanoes (Mounts Cameroon and Manengouba) sitting on a Precambrian metamorphic basement [23]. The main controlling structural feature of the area is the tertiary plutonic/volcanic mass in line with the NE–SW and NW–SE alignment of the existing volcanic cones [24]. These features have impacted groundwater availability and irrigation since most aquifers are found in fractured rocks and zones.

Lithology and soil

Numerous igneous (granite and pegmatite) and volcanic products such as ankaramite, basaltic lava and volcanic plugs, hawaiite, and basanite as well as the basement rocks (gneiss and migmatite), are the main lithologies of the study area [24]. Continental and fluvio-deltaic clay, coarse-grained sandstone, and conglomerate of the Aptian-Cenomanian Mundeck formation [25]–[27] are equally observed (Njombe-Penja area). Due to extensive weathering (tropical climate) and landscape features (hills and valleys) soil characteristics have been significantly affected and have impacted soil fertility. Moreover, lateritic soil (rich in Fe and Al with low nutrient content and good drainage properties) has developed unlike the accumulation of river- and lake sediments (water supply, contaminant- and nutrient retention) that can play an important role in local agriculture [28] [29].

3. Materials and Methods

3.1. Soil Sampling and Determination of Soil Physicochemical Properties

Before sample collection, the catchment area was subdivided into five (05) zones (settlement, bare soils, crops and market gardens, dense- and secondary forests) as shown in **Figure 2**. Twenty (20) composite (5 samples in one) soil samples were collected in each zone around Njombe Penja (07), Manjo (06), and Nkongsamba (07). At each sampling site surface soil samples (0 - 25 cm depth) were collected using a well cleaned soil auger in order to prevent cross-contamination. Composite (five bulk samples together) samples were used for the determination of the bulk density and moisture content of the soil. Flow directions and drainage features were noted. The collected soil samples were air-dried, screened through a

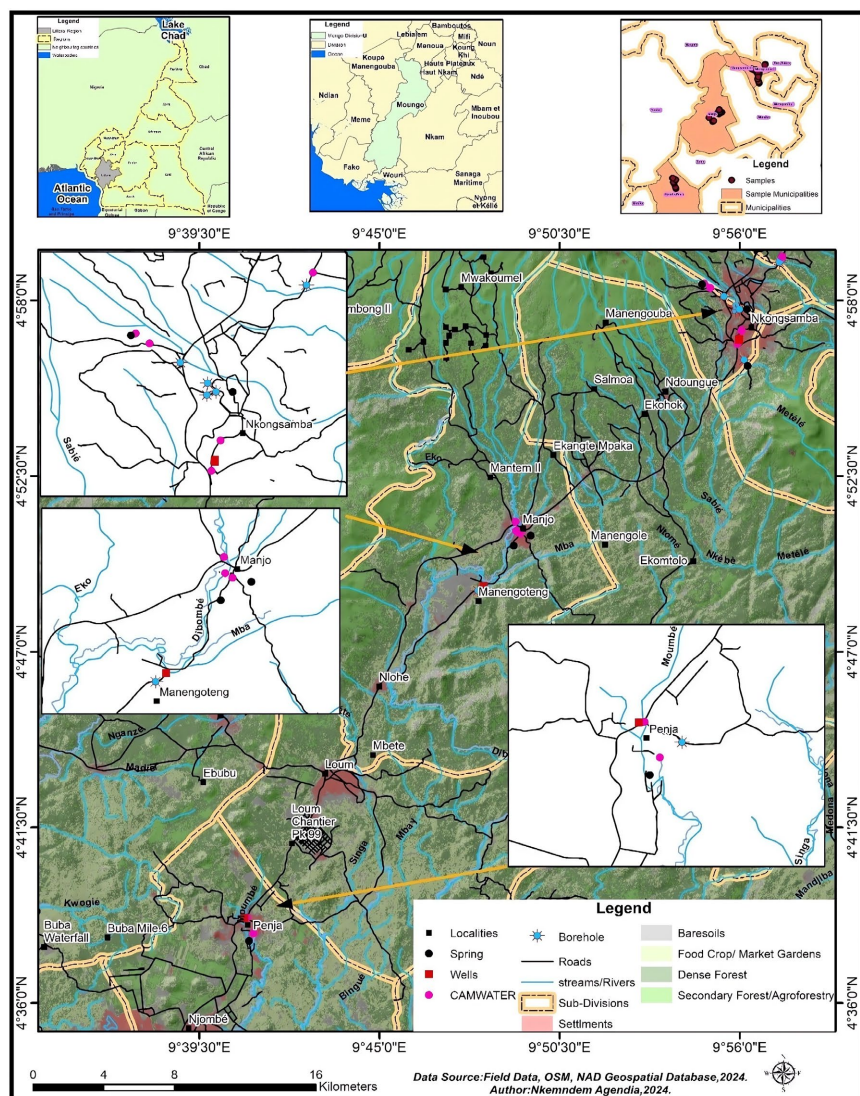


Figure 2. Land use map showing sampling points and three (03) study sites (Nkongsamba, Manjo, and Penja) modified after [30].

2-mm sieve, and analyzed for routine parameters in the Environmental and Analytical Chemistry Laboratory of the University of Dschang (Cameroon) in duplicate. Particle size distribution, cation exchange capacity (CEC), exchangeable bases, electrical conductivity (EC), and pH were determined by standard procedures [30]. Soil pH was measured both in water and KCl (1:2.5 soil/water mixture) using a glass electrode pH meter. Part of the soil was ball-milled for organic carbon (OC) using the Walkley and Black method and Kjeldahl-N after Pauwels *et al.* [30]. Available P was determined by the Bray I method and exchangeable cations were extracted using 1 N ammonium acetate at pH 7. Potassium (K) and sodium (Na) were determined using a flame photometer, and complexometric titration helped to obtain magnesium (Mg) and calcium (Ca). Exchangeable acidity was extracted with 1 M KCl followed by quantification of Al and H by titration [30]. Effective cation exchange capacity (ECEC) was determined as the sum of bases and exchanged acidity. The apparent CEC (pH = 7) was directly determined as outlined by Pauwels *et al.* [30]. For the determination of soil mineralogical phases, the fine particles (<63 μm) of three (03) representative samples (from each study site) were sent to ACME Laboratories, Ontario-Canada for X-ray Diffractometry (XRD). X-ray diffraction patterns were obtained using a Bruker Advance D8 diffractometer (Cu-K α radiation, 40 kV and 30 mA), 1.0 min^{-1} scanning speed, and 5 - 40° of 2 θ interval. Identification of mineral phases was done according to the position of the (001) series of the basal reflections on the air-dried and glycolated XRD diffractograms. Soil variability was assessed by calculating the coefficient of variation (CV) using the following formula: $CV = Sd/x (100)$ where: Sd = standard deviation; = K arithmetic mean of soil properties [31].

3.2. Data Analysis

The data were subjected to statistical analysis. Soil properties were assessed for their variability using the coefficient of variation (CV) and comparison with standard variability classes in **Table 1**.

Table 1. Summary of soil properties (coefficient of variation and critical nutrient values).

Properties	Critical values				
	Very low	Low	Medium	High	Very high
OM (%)	<1	1 - 2	2 - 4.2	4.2 - 6	>6
Total N (%)	< 0.5	0.5 - 1.25	1.25 - 2.25	2.25 - 3.0	>3.0
CV (%)	CV<10 (low variability); CV = 10 - 14 (Moderate variability); CV > 35 (high variability)				
C/N	<10 = good; 10 - 14 = medium; >14 = poor				
Ca (cmol/kg)	<2	2 - 5	5 - 10	10 - 20	>20
Mg (cmol/kg)	<0.5	0.5 - 1.5	1.5 - 3	3 - 8	>8
K (cmol/kg)	<0.1	0.1 - 0.3	0.3 - 0.6	0.6 - 1.2	>1.2
Na (cmol/kg)	<0.1	0.1 - 0.3	0.3 - 0.7	0.7 - 2.0	>2
pH	5.3 - 6.0 (moderately acid); 6.0 - 7.0 (slightly acid); 7.0 - 8.5 (moderately alkaline)				
CEC7 (cmol/kg)	0 - 20	21 - 40	41 - 60	61 - 80	81 - 100

Principal component analysis (PCA) using Microsoft Excel 2021 and the SPSS statistical package 25.0 helped to identify the factors that trigger the variation of soil properties. Varimax rotation served as a tool to correct auto-correlation problems and to reduce the effect of soil factors on the orthogonal principal components. Analysis of the correlation- and variation coefficients was equally conducted to identify the soil factors that correlate or differ significantly.

4. Results and Discussion

4.1. Soil Textural Characteristics and Suitability for Agriculture

The measured physico-chemical properties of soils in the study area vary considerably (Appendix 1). Forty five percent (45%) of soils are of loam texture, 15% are silt clay, silt loam (15%) and clay loam (15%). Ten percent (10%) of soils are of the sandy- and silt clay loam textural classes. The silt content in soils of the study area is generally high (it varies from 32.0% to 84.5% with an average of 45.5%) as shown in **Table 2**. These results suggest that the area is suitable for agriculture since the soil texture provides good aeration, retention and good supply of nutrients and water [32] [33]. This situation is similar to the work done by Salami *et al.* [34] in the northern savannah in Nigeria.

4.2. Variation of pH (H₂O), pH (KCl) and Acidic Nature of Soils

The pH (H₂O) and pH (KCl) of studied soils range from 4.60 to 5.70 and 4.20 to 5.50 respectively as shown in **Table 2**. The average value of pH (H₂O) = 5.29 is higher than that of pH (KCl) = 4.66. Consequently pH (H₂O) > pH (KCl) and their variation [Δ pH (pH (KCl) – pH (H₂O))] is throughout negative. This indicates that soils in Penja-Manjo-Nkongsamba are moderately acidic, with a dominance of cation exchange (Ca⁺, Mg⁺, Al³⁺, H⁺), less weathered, and comparable to tropical soils from areas with moderate rainfalls [29] [35].

Table 2. Summary of the physico-chemical properties and statistical parameters of twenty (20) soil samples from the study area.

Variable	Minimum	Maximum	Mean	Std. deviation	Variance
Clay (%)	4.50	45.00	31.25	8.90	79.14
Sand (%)	0.50	35.00	23.00	9.06	82.00
Silt (%)	32.00	84.50	45.45	15.25	232.66
pH (H ₂ O)	4.60	5.70	5.29	0.29	0.08
pH (KCl)	4.20	5.50	4.66	0.36	0.13
Bulk density(g/cm ³)	1.01	1.25	1.09	0.06	0.00
OC (%)	0.46	8.23	2.72	2.14	4.59
OM (%)	0.79	14.19	4.69	3.69	13.63
N (%)	0.03	0.13	0.11	0.03	0.00
C/N	5.54	111.70	27.01	24.35	593.16

Continued

Ca (Cmol/kg)	0.48	3.92	2.01	1.00	1.00
Mg (Cmol/kg)	0.16	1.88	0.95	0.53	0.28
K (Cmol/kg)	0.52	5.07	2.49	1.36	1.84
Na (Cmol/kg)	0.01	0.59	0.14	0.12	0.01
SBE (Cmol/kg)	1.94	8.45	5.59	1.91	3.63
CEC (Cmol/kg)	8.25	12.23	10.60	1.14	1.30
TSB (%)	20.99	74.47	52.19	14.98	224.54
AP (mg/kg)	3.32	159.78	32.15	38.15	1455.30

4.3. OC-, OM-, and N contents and C/N as Indicators of Soil Quality

The calculated OC values in the studied soils vary from 0.46 to 8.23% with a mean of 2.72 % while a large range of variation (0.79% - 14.19%) is observed for OM (Table 2 and Table 3). On the other hand, the close range of variation (from 0.03 to 0.13%) of total nitrogen (N) differs from the large range (5.54 - 111.70) of C/N ratios. The combination of these results indicates that the amount of carbon-rich materials (use of organic manure by farmers) in soils predominate compared to the nitrogen input because of its high mobility [33]. Moreover, the high C/N values that have been recorded for soils of the study area support the hypothesis of organic carbon enrichment, thus the soil suitability for agriculture [32]. Similar results were obtained in the research work of Dohrmann [35].

4.4. P-, Ca-, Mg Concentrations and Soil Quality

Available phosphorus (AP), calcium (Ca) and magnesium (Mg) have been determined and the values are summarized in appendix 1 and Table 2. AP in the studied soils varies between 3.32 and 159.78 mg/kg with an average value of 32.15 mg/kg. These values are higher than the required minimum AP (16 mg/kg). It is an indication that soils in the area of study can ensure adequate phosphate supply to plants [33]. Moreover, low Ca (0.48 - 3.92 cmol/kg) and Mg (0.16 - 1.88 cmol/kg) infer the soil category with $\text{pH} \leq 5.5$ to the Penja-Manjo-Nkongsamba area Landon [33]. Ca and Mg deficiencies could be linked to the fact that

Table 3. Soil properties variability classes based on the coefficient of variation.

Location	Less variable (CV < 15%)	Moderately variable (15 < CV ≤ 35%)	Highly variable (CV > 35%)
Nkongsamba	pH (H ₂ O), Bulk density, CEC, clay	pH (KCl), N, silt	OC, OM, P, C/N, Ca, Mg, K, Na, SBE, TSB, sand
Penja	pH (H ₂ O), pH (KCl), Bulk density, Na, CEC, clay, silt	N, SBE, TSB	OC, OM, C/N, Ca, Mg, K,
Manjo	pH (H ₂ O), pH (KCl), Bulk density, CEC	SBE, TSB	N, OC, OM, P, C/N, Ca, Mg, K, Na, clay, silt, sand

amphibole, olivine, pyroxene, dolomite, and phyllosilicate (sources of Mg and Ca in soils) are rare in the area of study [36].

4.5. Cation Exchange Capacity (CEC) and Base Saturation (ECEC) as Soil Fertility Indicators

The CEC values for the soil in the study area vary from low (8.25 cmol/kg) to medium (12.23 cmol/kg) with a mean value of 10.60 as shown in **Table 2** and **Table 3**. ECEC values for the same soil range from 1.94 to 8.45 meq/100g, whereas the minimal requirement for adequate ECEC is 4 meq/100g (FAO) [37]. These suggest that these soils might have a limited amount of weathered minerals (1:1 clay and sesquioxide) and the capacity to hold nutrients against leaching implying high fertility [29] [35].

4.6. Coefficient of Variation (CV) and Soil Properties

The variability of soil properties in the area of study was assessed based on of the obtained variability classes (**Table 3**).

From the results OC, OM, C/N, Ca, Mg and K are highly variable ($CV > 35\%$) in soils of the entire study area. SBE and TSB values in soils around Penja-Manjo-Nkongsamba tie with moderate CV ($15 < CV \leq 35\%$) whereas bulk density and CEC are less variable ($CV < 15\%$). The moderate variability of SBE and TSB can refer to the use of organic and/or inorganic fertilizers. In the three study sites, pH (H_2O) has low variability ($CV < 15\%$) and differs from pH (KCl) whose increase ($15 < CV \leq 35\%$) is observed in Nkongsamba. The variability of soil pH is similar to that of alfisols in Nigeria [38], vertisols for rice cultivation in Northern Cameroon [38], and animal waste-rich soils in Uyo, Nigeria [39]. CEC is constantly low ($CV < 15\%$). Clay, sand and silt highly vary in soils of the area of the study. This could be attributed to the Pan African geologic processes (igneous-volcanic, metamorphic, and sedimentary activities) that have probably affected the soil characteristics and landscape features [18] [22]. These geologic processes, including weathering, might have equally contributed to the fertility of soils in the area of study and other parts of Cameroon [40].

4.7. Soil Parameters and the Type of Soil

The relationship between paired physico-chemical parameters of soil of the study area was computed and summarized in a Pearson correlations matrix (Appendix 2). The coefficients of correlation (r) vary between -0.844 and 0.976 although most of the values are less than 0.500. Strong positive correlations are observed for OM/OC ($r = 0.976$), TSB/SBE ($r = 0.960$), CN/OC ($r = 0.933$), CN/OM ($r = 0.933$) and SBE/Mg ($r = 0.731$). Fair correlations vary from $r = 0.500$ to 0.679 and exist between SBE/K, TSB/K, Mg/Ca, TSB/Ca, TSB/Mg, CEC/SBE and Ph (H_2O)/clay. Negative correlations were obtained for silt/clay ($r = -0.831$), silt/sand ($r = -0.844$) and N/pH KCl ($r = -0.529$). These could indicate the same source and non-homogenous distribution of organic matter and other parameters in soils

[36]. However these findings are different from the results that were obtained on inceptisols in Ethiopia by Yerima *et al.* [29]. These differences could be attributed to contrasting geologic history [28]. Furthermore, the results of factor analysis are presented as Varimax factors (Appendix 3) from which five (05) PCI factors were extracted (Table 4). Factor 1 (SBE, TSB, Mg, Silt, CEC, Sand, Clay, Ca, and K) has a strong positive load for SBE (0.859), TSB (0.769), Mg (0.757), silt (0.756), CEC (0.687); moderate positive load for Ca (0.530) and K (0.513) but moderate negative load for sand (−0.629) and clay (−0.627).

Table 4. Varimax Rotated of Factor Matrix (Five-Factor Model) of selected physico-chemical properties of soil samples from the study area.

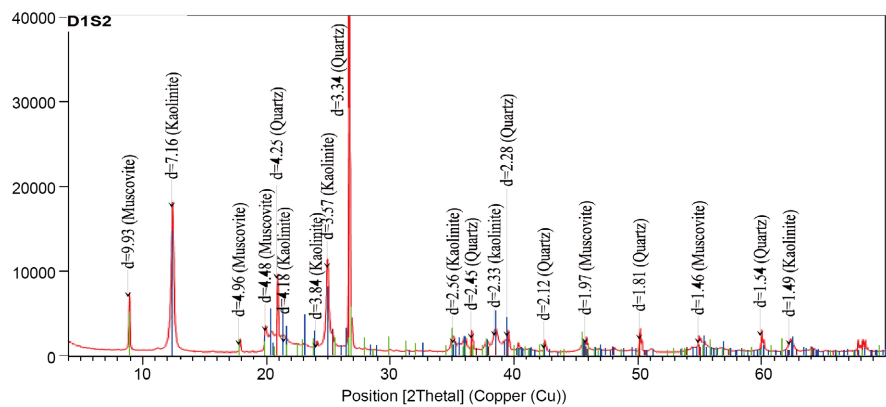
	Component Matrix				
	Component				
	1	2	3	4	5
SBE	0.859		0.391		
TSB	0.768		0.506		
Mg	0.757	0.341			
Silt	0.756		−0.401		
CEC	0.687			0.311	
Sand	−0.629			0.573	
Clay	−0.627		0.584		
Ca	0.530	0.393	0.320		−0.309
OC		0.905			
OM		0.904			
CN		0.897			
AvailableP		0.616		−0.337	
bulkdensity		−0.463	0.596	0.399	
pHWater	−0.376		0.545		−0.446
N	−0.344			−0.639	0.482
pHKCl	0.410		−0.310	0.575	−0.365
K	0.513				0.644
Na					0.445

The important positive load of SBE, TSB, Mg, and Ca suggests that Factor 1 is a base status factor [32]. Factor 2 is characterized by a very high load for OC (0.905), OM (0.904), and C/N (0.897), but a moderate load for P (0.616). This factor refers to organic matter from natural decomposition of vegetation and the application of organic manures in farms in the area of study [38]. Factor 3 comprises TSB (0.506), bulk density (0.596), pH_{H2O} (0.545), and clay (0.584), and insinuates weathering processes and associated moisture retention [4] [41]. Factor

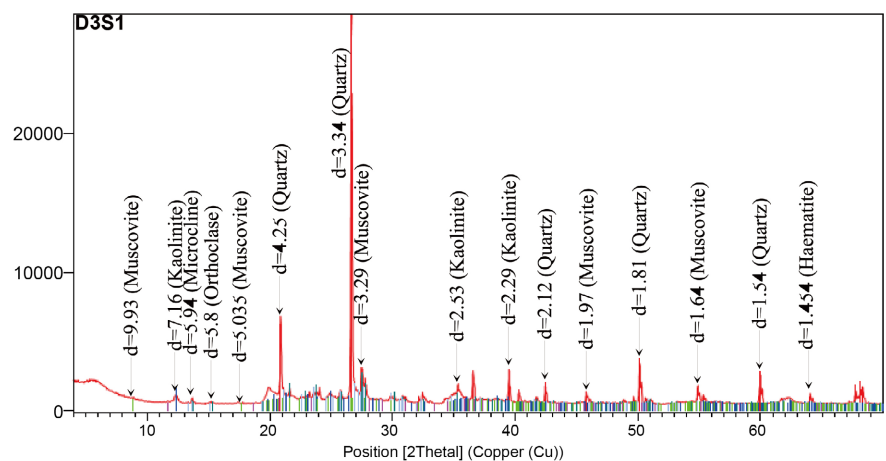
4 is made up of a moderate positive load for sand (0.573) and pH_{Kcl} (0.575). This factor reflects the state of erosion and N input in the study area since nitrogen can easily be leached in well drained soils [32]. These findings are in conformity with the studies of Tabi *et al.* [38]. Factor 5 is essentially composed of K and could be derived from the weathering of potassium-rich minerals such as muscovite [16]. Evidence of muscovite in the study area is confirmed by the soil mineralogical phases shown in **Figures 3(a)-(c)**. The occurrence of potassium in soil can equally be linked to the use of potassium rich fertilizers and is considered an essential nutrient for plant growth [15] [16].

4.8. Soil Mineralogy and Formation

Different mineral phases compose the studied soils (**Figure 3**) and their proportions (%) are summarised in **Table 5**. Quartz (~50%), kaolinite (40%), and muscovite (10%) have been identified in soils from Penja (**Figure 3(a)**). The same minerals are the main phases in the Manjo area, but quartz (~45%) and kaolinite (20%) are depleted compared to Penja, and the proportion of muscovite has increased from 10% to 35% (**Figure 3(b)**). Contrary to the Penja and Manjo areas, soils in Nkongsamba are composed of six (06) mineral phases namely quartz



(a)



(b)

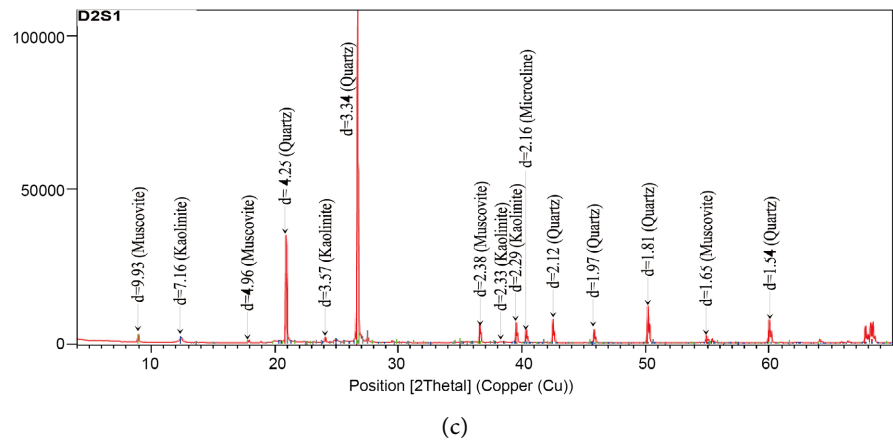


Figure 3. X-ray diffractograms showing different mineral phases in the study area. (a) Sample D1S2 from Penja; (b) Sample D3S1 from Manjo and (c) sample D2S1 at Nkongsamba.

Table 5. Different mineral phases (%) found in three (03) soil samples from three study sites.

Mineral phase	D1S2 (Penja)	D2S1 (Manjo)	(D3S1) Nkongsamba
Quartz	(~50%)	(~45%)	(~40%)
Muscovite	(~40%)	(~35%)	(~35%)
Kaolinite	(~10%)	(~20%)	(~10%)
Microcline	-	-	(~5%)
Orthoclase	-	-	(~5%)
Haematite	-	-	(~5%)

(~40%), muscovite (35%), kaolinite (10%), microcline (~5%), orthoclase (~5%), and haematite (~5%) in **Figure 3(c)**.

Role of quartz in soil formation and stability

According to Böhmann *et al.* [17] quartz is a resistant mineral with low reactivity with other chemical substances and plays a significant role in soil formation and stability. From our finding's quartz, muscovite, kaolinite and feldspars (microcline and orthoclase) are common in igneous (granite), metamorphic (gneiss), sedimentary rocks (halloysite) and can influence soil properties and fertility [22] [24] [42] [43] within the study area. Quartz is the dominant mineral in soils from the Penja-Manjo-Nkongsamba area and its presence influences the soil texture, whose importance (sandy texture enhancing aeration and water infiltration) is known for agricultural practices, drainage, and nutrient availability [44]. Furthermore, quartz's resistance to weathering equally ensures long-term soil stability. The situation in the study area is in conformity with the results that were obtained by Churchman and Lowe [11].

Contribution of muscovite to soil fertility and plant growth

Muscovite is a rock-forming mineral in igneous (granite), metamorphic (gneiss), and sedimentary rocks (Halloysite) and can influence soil properties

and fertility [22] [24] [42] [43]. Muscovite is a phyllosilicate mineral from the mica group, composed of potassium-, and aluminum, and characterized by its perfect cleavage and pearly to vitreous luster [42] [45]. Moreover, due to the weathering of muscovite, trace elements and potassium (nutrients for plant photosynthesis and growth) are released into the soil to enhance its structure (important for water retention) and boost its CEC [42]. The proportion of muscovite (from 10 to 40% with a high CEC mean value of 12.23 Cmol/kg) combined with available Ca^+ , Mg^+ , K^+ suggests that the studied soils are fertile and favorable for plant growth [6] [42]).

Kaolinite and muscovite as indicators of crop productivity, soil porosity, and pollution

According to Weaver [46] and Wilson [8] kaolinite is a major component of the kaolin group of minerals; it is a highly porous mineral that can enhance soil structure (aeration) and root growth. Kaolinite is obtained from the weathering of muscovite rich granite from the Precambrian granite-gneissic basement within the study area [22] [43]); Kaolinite serves as a buffer to maintain an optimal pH range for plant growth and acts as a catalyst for chemical reactions that activate the nutrient availability in soils [6]. Kaolinite can also retain essential elements for plant growth in soil such as potassium, calcium and magnesium (Hillier [47]). Kaolinite (10% - 20%) is one of the major mineral phases found in the studied soils which can improve soil fertility/crop productivity in the area. However, as low-activity clay mineral with generally low CEC, kaolinite cannot retain pollutants and therefore can expose these soils (ecosystem) to contamination [6]. On the other hand, the occurrence of barren plagioclase and microcline-rich pegmatite is known in the Njombe-Penja area [48]. Consequently the presence of feldspar minerals such as microcline (5%) and orthoclase (5%) in soils from the study area is justified and increases their potassium content. These can help to reinforce the soil structure, regulate the soil pH and increase soil porosity (aeration) after Hillier [47]. Moreover, the soil's water-retention capacity can increase and soil erosion can be reduced [47]. This context is similar to the results obtained by [6] [49].

4.9. Soil Properties and Mineralogy as Ecosystem Health Indicators

Soil is a habitat for numerous organisms, medium for plant growth (it plays a vital role in nutrient cycling), functioning as a water filter or a carbon sink [50]. According to Brady *et al.* [51], soil mitigates climate change, and represents a key component of the ecosystem. From our findings the studied soils are composed of kaolinite and muscovite (low-activity clay minerals having an impact on soil fertility, crop productivity, and ecosystem health) and contain good indicators for plant growth (average CEC = 12.23 Cmol/kg, significant Ca^+ , Mg^+ , K^+). This combination is essential for photosynthesis and favorable for crop productivity, land use and ecosystem conservation. The situation can be compared with the results of Girma *et al.* [3] and Yaseen *et al.* [4].

5. Conclusions

We have investigated the physico-chemical characteristics and mineralogy of the soils of Penja-Manjo-Nkongsamba, and the following conclusions have been drawn:

The silt content in soils of the study area varies from 32.0% to 84.5% with an average of 45.5%. Forty-five percent (45%) of soils are of loam texture, 15% are silt-clay; silt loam (15%) and clay loam (15%), whereas 10% are of the sandy- and silt-clay loam textural classes.

The soils in the study area are slightly acidic. The pH (H₂O) and pH (KCl) range from 4.60 to 5.70, and 4.20 to 5.50 respectively, with pH (H₂O) higher (5.29) than pH (KCl) = 4.66.

The organic carbon enrichment (N 0.03 to 0.13%; mean OC = 2.72 % with high OM (0.79% - 14.19%), AP (3.32 - 159.78 mg/kg) and C/N (54 - 111.70) ratios make the studied soils suitable for agriculture and can ensure adequate phosphate supply to crops and plants.

Most physico-chemical properties of soils (OC, OM, C/N, Ca, Mg, and K) are highly variable (CV > 35%) in the entire study area. SBE and TSB have moderate variability (15 < CV ≤ 35%) due to the use of organic and/or inorganic fertilizers, whereas bulk density and CEC are less variable (CV < 15%).

K input in soils results from leaching and weathering of potassium rich minerals (muscovite) or potassium rich fertilizers as an essential nutrient for plant growth in the study area.

Quartz (45% - 50%), kaolinite (20% - 40%) and muscovite (10% - 35%) are the dominant mineral phases in soils from Penja and Manjo. In Nkongsamba, quartz (~40%) and kaolinite (10%) are depleted contrary to muscovite (35%). Minor (~5%) microcline, orthoclase and haematite equally exist.

These low-activity clay minerals impact soil fertility and crop productivity but can also affect ecosystem health. Monitoring and control of agro materials are therefore necessary to protect this ecosystem.

Acknowledgements

This paper is the result of the research collaboration of lecturers of the Department of Environmental Sciences and Geology at the University of Buea, Cameroon. Our thanks are addressed to the laboratory technicians of FASA-Dschang, the Institute of Geology and Mining Research-Yaoundé (Cameroon) and at the Activation Laboratory in Ontario (Canada) for various analyses.

Authors' Contributions

For the **conceptualization**, Bih Linda Piezuh, Mboudou Germain Marie Monespérance, and Asongwe Godswill Azinwie; **methodology**, Bih Linda Piezuh, Mboudou Germain Marie Monespérance, and Asongwe Godswill Azinwie; **software**, Eyong Thomson Areakpoh, Penn Emile Nkeng, and Emmanuel Essey

Mengu Junior; **validation**, Bih Linda Piezuh, Mboudou Germain Marie Monespérance, Asongwe Godswill Azinwie, and Eyong Thomson Areakpoh; **formal analysis**, Bih Linda Piezuh, Mboudou Germain Marie Monespérance, and Asongwe Godswill Azinwie; **investigation**, Bih Linda Piezuh, Mboudou Germain Marie Monespérance, and Asongwe Godswill Azinwie; **resources**, Bih Linda Piezuh, Mboudou Germain Marie Monespérance, Eyong Thomson Areakpoh, and Emmanuel Essey Mengu Junior; **data curation**, Mboudou Germain Marie Monespérance, Asongwe Godswill Azinwie, Bewah Emilien Bih, and Okpara David Dicken; **writing of the original draft**, Bih Linda Piezuh, Mboudou Germain Marie Monespérance, and Asongwe Godswill Azinwie; **writing, review and editing**, Mboudou Germain Marie Monespérance, Asongwe Godswill Azinwie, and Bih Linda Piezuh; **visualization**, all authors; **supervision**, Mboudou Germain Marie Monespérance, Asongwe Godswill Azinwie, and Bih Linda Piezuh; **project administration**, Mboudou Germain Marie Monespérance and Asongwe Godswill Azinwie. All authors read and approved the final manuscript.

Conflicts of Interest

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

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Appendix

- 1) Measured physicochemical properties of twenty (20) soil samples from the study area
- 2) Pearson correlation matrix for selected physico-chemical parameters in soil of the study area: r (strong positive correlation); r (fair positive correlation); r (strong negative correlation)
- 3) Total variance from the physico-chemical properties of wetland soils in the study area