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Soil Mapping and Assessment of the Agricultural Capacity of the Land at Kouh-Est in the Logone Oriental (Southern Chad)

Ngaro M'Baïti[1], Jean-Claude Doumnang Mbaigane[1], Achille Bienvenue Ibrahim[2]

[1]Laboratoire de Géologie, Géomorphologie et Télédétection, Département de Géologie, F.S.E.A., Université de N'Djamena, N'Djamena, Tchad
[2]Faculté d'Agronomie et des Sciences Agricoles (FASA), Université de Dschang, Dschang, Cameroun
Email: nmbaiti@gmail.com, doumnang@gmail.com, achille_ibrahim@yahoo.com

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Abstract

Agriculture is the main source of income and survival for the population of East Kouh. Population growth has led to an increase in arable land, a reduction in fallow periods and migration in search of arable land, with the corollary of soil degradation. So understanding the spatial distribution of surface conditions through mapping and knowing the agricultural capacity of the land are essential challenges for the ecosystem services they provide. However, the department of Kouh-Est does not yet have an exhaustive geographical coverage of soil properties that will enable them to be used wisely in the long term. The aim of the study is to understand the surface condition of Kouh-Est's soils and assess their fertility levels. Remote sensing and geographic information systems have revealed that the terrain is relatively flat and gradually rising, the hydrographic network converges from the outside towards the centre, and three types of soil have been identified, including ferrallitic soils, ferruginous soils and alluvial soils. Bare soil occupies a large part of the study area (50.92%), the high plateaux are reserved for agriculture (32.21%) and, finally, vegetation, water and forest occupy a tiny, predominantly low-lying area (17.02%). Soil fertility indices and nutrient ratios were used to assess the level of fertility of the various soils in the study area. These parameters range from 0.7 < ISS < 17.27; 8.33 < IF < 704; 0.16 < L/A < 1.53; 3.94 < C/N < 1912.83; 0 < NT/pH < 0.02; 11.02 < S/T < 116.29; 0 < N/P < 2.5; 0 < C/P < 66; 0.75 < Ca/Mg < 9.26; 0.16 < Mg/K < 184; CEC/A ≤ 0.41. Four soil fertility classes are identified. The physical parameters of the soil are acceptable, but there are shortcomings in terms of chemical fertility. Organic and mineral amendments are essential to improve soil fertility.

Keywords

Mapping, Soils, Land Capacity, Kouh-Est, Logone Oriental, Amendment

1. Introduction

Agriculture is an essential part of the economy of all African countries. It therefore has a role to play in resolving the continental priorities of eradicating poverty and hunger, boosting intra-African trade and investment, rapid industrialisation and economic diversification, sustainable management of resources and the environment, job creation and food security [1].

Chad is an agro-pastoral country, with over 75% of its population dependent on agriculture. The primary contribution of Chadian agriculture to the economy is its large share of Gross Domestic Product (GDP), estimated at 23%, of which 20% comes from food production and 3% from cash crops [2]. It is also a major provider of employment, employing 2/3 of the working population. The second fundamental contribution of agriculture is the production of food, which is an immediate response to the issues of food insecurity and poverty in particular. The third contribution of agriculture to overall growth is the supply of raw materials to the agri-food industries.

The increase in urban populations around the world is particularly affecting developing countries [3] [4]. This urban growth leads to increased demand for food products [5].

Chad has experienced galloping population growth in recent decades. The Eastern Logone, which is the subject of this study, has not stood still: the population was estimated at 44,300 in 1993 [6] and 796,453 in 2009 [7]. This rise in population is automatically accompanied by an increase in food requirements, which in turn leads to the over-exploitation of agricultural plots, a decline in soil fertility, and migration in search of good soil, resulting in food insecurity.

As it happens, the soil is an environment that is not easily mastered because it is often obscured by vegetation. Yet knowledge of the soil is essential if it is to be used wisely. Soil is an ecologically vital asset that continually renews its yield capacity. Soil suffers if its needs are not taken into account: it loses vitality and becomes more sensitive to weather conditions and erosion [8].

Low soil fertility is considered to be one of the major constraints limiting the productivity of sub-Saharan agriculture [9]. Low crop productivity due to the combined effects of poor farmland management, coupled with temporal and spatial variations in climatic conditions, leads to rapid soil nutrient depletion [10]. However, the development and judicious use of soils in agriculture depends on their prior knowledge, both in terms of cartography, which provides a synoptic view of the entire study area, and physico-chemical characterisation, which enables the fertility status to be assessed.

Mapping has served as a springboard for many authors to gain an overall view of the study areas and to benefit from its judicious use:

Over the last few decades, many authors have written about soil fertility, including: [2] [3] [9] [11]-[31].

Recent soil surveys in Chad have revealed a very significant decline in the productive capacity of the soil over recent decades [32]-[35]. It seems essential to rethink soil restoration in Chad, particularly in the Logone Oriental region, with a view to increasing agricultural production and ensuring the sustainability of agriculture, which is a significant source of income. The research on "Soil mapping and assessment of the agricultural capacity of the Kouh-Est lands in the Logone Oriental (southern Chad)" was undertaken in order to gain a better appreciation of the surface conditions of the soils and to assess the fertility status of the soils in the Logone Oriental in southern Chad. The specific aim of the study is to map the surface conditions of the study area using Landsat images, Digital Terrain Models (DTMs) and existing map backgrounds, and to use the results of physico-chemical soil analyses to determine the soil's suitability for cultivation. The results obtained in this way will serve as a basis for developing strategies for restoring the soils of the Logone Oriental and, by extension, increasing agricultural production.

2. Location of the Study Area

The Eastern Logone lies between the 8th and 11th parallels, in the extreme south of Chad and covers an area of 130,000 km^2; It comprises six (6) departments, namely Pendé, Nya, Nya Pendé, Mont de Lam, Kouh-Ouest and the department of Kouh-Est. The department of Kouh-Est, which is the subject of this study, covers an area of 1017.3 km^2 and is located between latitudes 8˚08' and 8˚20' North and between longitudes 16˚80' and 17˚20' East. It is bounded to the south by Baïbokoum, to the north-west by Doba, to the East by Moyen Chari and to the west by Béboto (**Figure 1** below).

3. Materials and Methods

For this work, we used maps in the field:

- the topographic map of Koumra (NC-33-06) at a scale of 1:200,000

- landsat TM (Type 2, Path: 185, Row: 54) dated 21 May 2022, recorded at 08H30'54" (Chad time)

- Den,

- Sampling bag,

- GPS.

Laboratory methods

- The physico-chemical analyses were carried out at the Laboratory of Soil Analysis and Environmental Chemistry of the Faculty of Agronomy and Agricultural Sciences (FASA) of the University of Dschang in Cameroon.

- Measuring instruments used: turbidimeter, conductimeter, pH meter, spectrophotometer, mineraliser, distiller and oven.

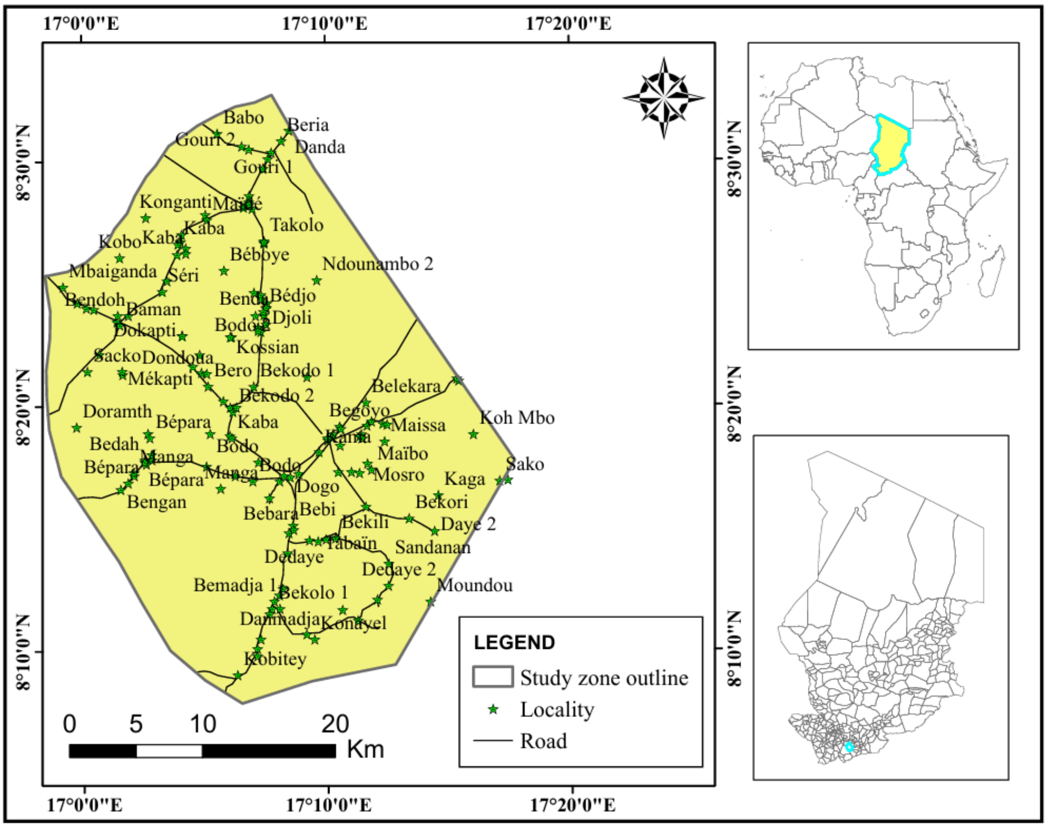

Figure 1. Location map of the study area.

4. Sampling

Field methods

The location of our study area was determined using the topographic map of Koumra (sheet NC-33-06) at a scale of 1:200,000 and GPS. After several field trips, a representative transect for soil study was selected. Before opening the soil profiles, auger samples were taken and compared with the soil comparator to avoid redundancy in sampling. The helical auger was used to take surface samples as it is suitable for the sandy soils in the study area. Thus, after gridding the sampling area, systematic samples were taken.

The procedure undertaken was as follows: Select the main diagonals of the area to be sampled, then take samples with an auger every 100 meters along the diagonals. For each sampling point, three (3) samples were taken every 20 meters, *i.e.*, at 20 meters, 40 meters, and 60 meters. After a morphological description of these different samples, they were submitted to the pedocomparator to determine the representative samples that will be used for surface sampling. It was also at the end of these comparisons that the opening points for the soil profiles were chosen.

The choice of these different sampling sites is guided by the local availability of their soils, their accessibility, and their wide geographical spread within the locality.

The detailed description of the soil pits covered depth, colour, texture, structure, presence of nodules, biological activity and the boundary between horizons. After the description, samples were air-dried and sieved using a 2 mm sieve. Next, 1 kg of the fine soil obtained from the sieving was taken and packaged in a labelled plastic bag for laboratory analysis. Figure 2 below shows the various sampling points.

Table 1 below clarifies the sampling sites and the context of land use:

Table 1. Sampling sites and land use context.

Soil type	Profile name	Code	Land use context	Depth (meter)	Coordinate	
Ferralsols	Bébara	PBB	sorghum	4.05	N08˚14'56.6"	E017˚07'55.2"
	Bélekara	PBKA	cotton	3.40	N08˚20'11.4"	E017˚11'29.1"
	Bédouada	PBD	sorghum	4.20	N08˚19'20"	E17˚06'45"
	Kouh	PKH	peanut	0.30	N08˚09'38.2"	E17˚03'57.4"
	Bédjo	PBDJ	penicillary	0.35	N08˚25'03.2"	E17˚07'20.8"
	Békoye	PBKY	white millet	0.25	N08˚26'56.3"	E17˚07'23.9"
Alluvial soils	Bémou	PBM	cotton	3.20	N08˚16'24.2"	E017˚07'42.0"
	Béro	PBR	red millet	3.30	N08˚20'48.3"	E017˚05'07.9"
	Bépara	PBP	sesame	4.00	N08˚17'44.3"	E017˚02'35.0"
	Békodo II	PBKO	sesame	4.15	N08˚19'20"	E17˚06'32"
	Béyama	PBYA	corn	4.24	N08˚19'17"	E17˚04'25"
	Takapti	PTKT	haricot	0.30	N08˚23'44,5"	E17˚01'51,1"
	Sandana	PSDN	penicillary	0.35	N08˚13'25.6"	E17˚12'44.5"
	Dedaye	PDD	various associated	0.30	N08˚14'31.6"	E17˚10'42.6"
	Daye	PDY	red millet	0.25	08˚14'47.3"	17˚14'36.8"
Brunisols	Kaba	PKB	various associated	3.00	N08˚18'38.3"	E017˚06'04.1"
	Bodo	PBO	white millet	1.50	N08˚16'51.1"	E017˚08'14.6"
	Gouri	PGO	white millet	4.18	N08'19'09"	E17˚09'41"
	Békorbe	PBKB	haricot	0.30	N08˚13'39"	E17˚08'10"
	Békolo	PBKL	sesame	0.20	N08˚11'11.7"	E17˚07'25.6"
	Kobetey	PKBY	sorghum	0.40	N08˚09'11.4"	E17˚06'39.4"
	Sacko	PSCK	penicillary	0.30	N08˚21'56,0"	E17˚00'31,2"
	Seri	PSR	white millet	0.25	N08˚24'53.2"	E17˚03'30.9"
	Djoli	PDJL	corn	0.20	N08˚24'43.0"	E17˚04'04.5"
	Békori	PBKR	sesame	0.20	N08˚15'23.4"	E17˚13'05.0"

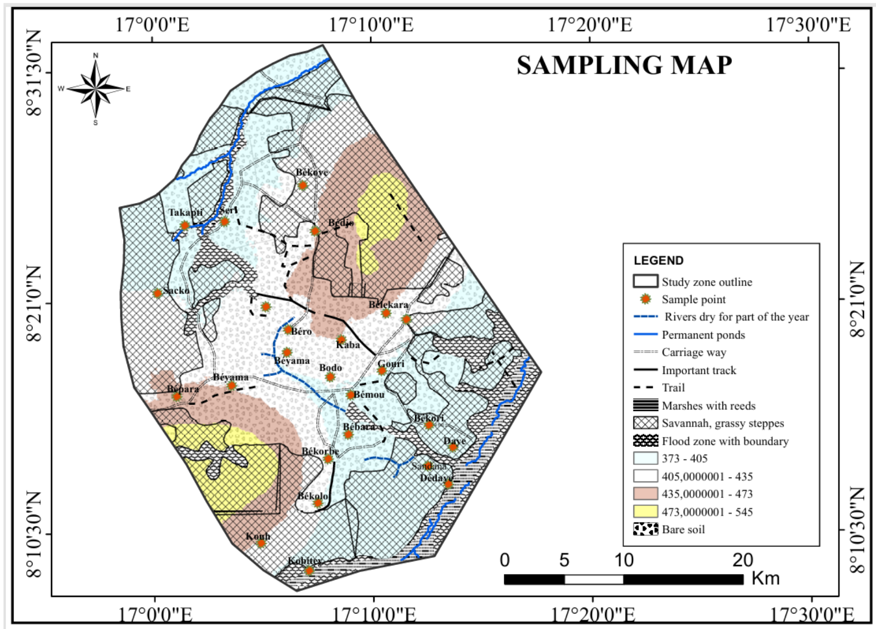

Figure 2. Sampling map (obtained by superimposing the 1:200000 topographical map of Koumra (NC-33-06) and the DTM).

5. Mapping

Remote sensing and GIS were used to produce maps using satellite images (Landsat and DTM) and the various base maps (topographic, geological and soil) of the locality available at different scales.

5.1. Choice and Characteristics of Landsat Images

Several Landsat scenes were observed, but given the objective, which was to produce a land cover map, the scene shown in **Figure 1** was chosen. This choice is guided by the fact that the scene is recent and does not require as much processing as the other scenes. It is the Landsat 8 image. Landsat 8/LDCM images include spectral bands from the OLI (Operational Land Imager) instrument and spectral bands from the TIRS (Thermal Infrared Sensor) instrument. The OLI instrument comprises 9 bands ranging from the visible to the mid-infrared and the TIRS instrument bands correspond to bands 10 and 11 (**Table 2**).

5.2. Landsat8/LCDM Image Acquisition and Processing

The scene used for land cover mapping is that of Landsat TM (Type:2, Path: 185, Row: 54) of 21 May 2022, captured at 08H30'54" (Chad time). It is freely accessible and provided by the United States Geological Survey (USGS) after registering on the site at the following address: http://earthexplorer.usgs.gov/ or http://glovis.usgs.gov/. The scene captured is in Geotiff format. Chad is located in zone 33 North of the Universal Transverse Mercator (UTM, zone 33 N) map projection, and the reference geodetic system is WGS 84. **Figure 3** below shows the extraction process for the study area.

Table 2. Landsat-8/LDCM band characteristics.

Sensors	Spectral resolution	Band color	Spatial spatiale (m)	Stage dimensions	Revisit time
	Band 1: 0.433 - 0.453	Aérosol	30 m		
	Band 2: 0.450 - 0.515	Blue	30 m		
	Band 3: 0.525 - 0.600	Green	30 m		
	Band 4: 0.630 - 0.680	Red	30 m		
OLI	Band 5: 0.845 - 0.885	Near infrared	30 m		
	Band 6: 1.560 - 1.660	Medium infrared 1	30 m	170 Km × 170 Km	16 days
	Band 7: 2.100 - 2.300	Medium infrared 2	30 m		
	Band 8: 0.500 - 0.680	Panchromatic	30 m		
	Band 9: 0.360 - 1.390	Cirrus	30 m		
TIRS	Band 10: 10.30 - 11.30	Medium infrared	100 m		
	Band 11: 11.50 - 12.50	Medium infrared	100 m		

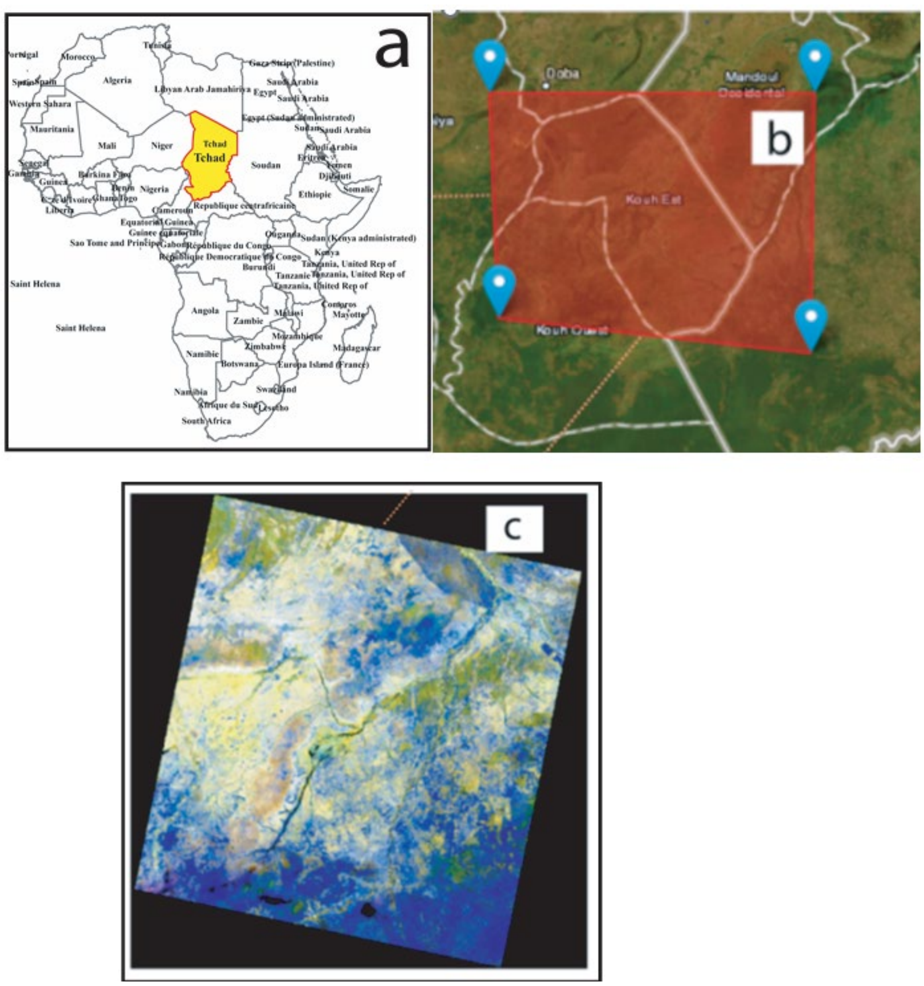

Figure 3. Location of the study area: (a): Map of Africa showing the position of Chad's Logone Oriental, (b) and (c): Location and extraction of Landsat-8/LDCM scene 185-54.

After acquisition, the Landsat 7 image was processed using ENVI 4.5 software, then ArcGis 10.8 software was used to produce the various maps.

5.3. Statistical Processing of the Data

Different types of analysis were carried out to process the results of the physico-chemical analyses. These included analysis of the inter-element correlation matrices, which were used to characterise the various parameters of dispersion (coefficient of variance, standard deviation), central tendency (mean and median) and range (minimum, maximum).

- Principal component analysis

This is a descriptive statistical analysis method used to establish a relationship between the parameters of a data matrix. This technique has been widely used to show the relationships that exist between different soil fertility parameters by many authors: [36] [37].

Table 3 below shows the different combinations of Landsat 8 bands:

Table 3. Band combination for Landsat 8.

Compound name	Band
Natural color	4 3 2
False color	7 6 4
Infrared color (vegetation)	5 4 3
Agriculture	6 5 2
Vegetation	5 6 2
Soil/Water	5 6 4
Natural with atmospheric elimination	7 5 3
Short-wave infrared	7 5 4
Vegetation analysis	6 5 4

6. Laboratory Work

The physico-chemical analyses were carried out at the Laboratoire d'Analyse des Sols et de Chimie de l'Environnement of the Faculté d'Agronomie et des Sciences Agricoles (FASA) of the University of Dschang in Cameroon. The analyses were carried out on soil surface samples (0 - 20 cm). They focused mainly on sand, clay and silt content, pH in an aqueous (pH-H_2O) and saline (pH KCl) environment, organic carbon (CO) content, total nitrogen (Ntot) content, exchangeable base content (Ca, Mg, K and Na), Cation Exchange Capacity (CEC) and assimilable phosphorus content (P Bray II), Sum of Exchangeable Bases (SBE) and saturation rate (V).

The physico-chemical and chemical parameters contained in the soils were determined using the methods recommended by [27] and complying with ISO, AFNOR NF and EN standards. These were as follows.

Total nitrogen: mineralisation by acid etching of 2 g of sample, distillation by steam distillation and determination with sulphuric acid (Kjeldahl method, standard NF ISO 1161).

Organic matter (OM) content was obtained from organic carbon (OC) using the Sprengel factor (OM = OC × 1.724) (Walkey & Black, 1934).

Assimilable phosphorus: ammonium molybdenum blue calorimetry after extraction with Bray II acid solution (HCl + NH4F) of 2.5 g of the sample and reading at wavelength 665 mm (standard NFX31-130).

Potassium and sodium: flame emission spectrometry by direct reading in the ammonium acetate extract at pH 7 of the sample (AFNOR standard NF T 90-019).

CEC: by extraction of exchangeable cations, washing with alcohol, replacement of NH_4 + ions by K + ions from 1N KCl, steam distillation and determination with 0.01 N sulphuric acid (standard NF EN ISO 23470).

Calcium and magnesium: complexometry and titrimetric method of an ammonium acetate extract of the sample at pH 7 (AFNOR standard NF U 44 - 146).

Granulometry (sand, clay and silt): Robinson-Kôhn pipette method after destruction of organic matter with hydrogen peroxide and iron oxides and carbonates with hydrochloric acid (standard NFX 31 - 107).

Organic carbon: oxidation of 0.5 g of sample with potassium dichromate ($K_2Cr_2O_7$) and determination of the remaining dichromate with ferrous sulphate heptahydrate ($FeSO_4$, 7 H_2O) (AFNOR standard NFU 44 - 051).

pH: potentiometry using a "Hanna Instruments" pH meter in aqueous soil extract at a ratio of 1:2.5 (ISO standard 10390).

7. Assessment of Soil Fertility Levels

Soil fertility levels were assessed using the [38] criterion. Depending on the abundance or deficiency of chemical elements in the soil, four fertility classes are identified:

Class 1) high fertility: Soils in this class have no or only slight limitations.

Class 2) medium fertility level: Soils in this class have no more than 3 moderate limitations, possibly combined with slight limitations.

Class 3) low fertility level: Soils are in this class when their characteristics present more than 3 moderate limitations associated with only one severe limitation.

Class 4) very low fertility level: Soils in this class have more than one severe limitation.

Table 4 below elucidates the assessment criteria for soil fertility classes.

Table 4. Evaluation criteria for soil fertility classes [38].

Elements	Fertility Level				
	Very High (no limitations)	High (low limitation)	Medium (medium limitations)	Low (severe severe)	Very Low (very very severe)
	Degree 0	Degree 1	Degree 2	Degree 3	Degree 4
OM (%)	>2	2 - 1.5	1.5 - 1	1 - 0.5	<0.5
N (%)	>0.08	0.08 - 0.06	0.06 - 0.045	0.045 - 0.03	<0.03

Continued

P_{ass} ($cmol^+/kg$)	>20	20 - 15	15 - oct		<5
K^+ ($cmol^+/kg$)	>0.4	0.4 - 0.3	0.3 - 0.2	0.2 - 0.1	<0.1
Sum of bases ($cmol^+/kg$)	>10	10 - 7.5	7.5 - 5	5 - 2	<2
V (%)	>60	60 - 50	50 - 30	30 - 15	<15
CEC ($cmol^+/kg$)	>25	25 - 15	15 - 10	10 - 5	<5
pH	5.5 - 6.5 6.5 - 8.2	5.5 - 6.0 6.5 - 7.8	5.5 - 5.3 7.8 - 8.3	5.3 - 5.2 8.3 - 8.5	<5.2 >8.5

Table 5. Soil fertility class evaluation [11].

Caractéristique	Level 1 (no limitation)	Level 1 I (moderate limitation)	Level 1 II (severe limitation)	Level 1 V (very severe limitation)
OM (%)	>2	100 - 2	0.5 - 1	<0.5
N (%)	>0.08	0.045 - 0.08	0.03 - 0.045	<0.03
P (ppm)	>20	10 - 20	5 - 10	<5
K ($cmol^+/kg$)	>0.4	0.2 - 0.4	0.1 - 0.2	<0.1
S ($cmol^+/kg$)	>10	5 - 10	2 - 5	<2
S/CEC (%)	>60	40 - 60	15 - 40	<15
CEC ($cmol^+/kg$)	>25	10 - 25	5 - 10	<5
pHe	>5.5	5.1 - 5.5	4.75 - 5.1	<4.75
IB	≤1.4	1.6 - 1.4	1.8 - 1.6	≥1.8
IF	>1.5	-	-	<1.5
ISS	>9	7 - 9	5 - 7	<5
M (%)	<20	20 - 40	40 - 60	>60

7.1. Structural Stability Index (SSI)

The structural stability index is a physical parameter that determines the degree of degradability and erodibility of a soil [26].

$$ISS = (1.724 \times OC)/((L + A)) \times 100;\ 0 \leq ISS \leq \infty$$

with, MO: soil organic matter content, A: soil clay content. L: silt content in the soil. ISS > 9% indicates soils with stable structure; 7% < ISS ≤ 9% indicates soils with low risk of structural degradation; 5% < ISS ≤ 7% indicates soils with high risk of structural degradation; and 5% < ISS indicates soils with degraded structure.

7.2. Forestry Index (FI)

The Forestier index provides information on the reserve of exchangeable bases in the soil. It is given by the following relationship:

$$IF = S^2/((A + Lf))$$

where S: soil sand content, A: soil clay content and Lf: soil fine silt content. For

IF > 1.5: the reserve of exchangeable bases is good; for IF < 1.5: the reserve of exchangeable bases is low.

8. Results and Discussion

8.1. Cartographic Aspects

8.1.1. Relief Map

The relief of Kouh-Est department is in the form of two contiguous, convex half-oranges, oriented NNE-SSW. The SE-NW extremities and the middle part of the relief form a depression. The relief rises gradually from 370 m in the south and north to 546 m. **Figure 4** below highlights the elevation level of Kouh-East.

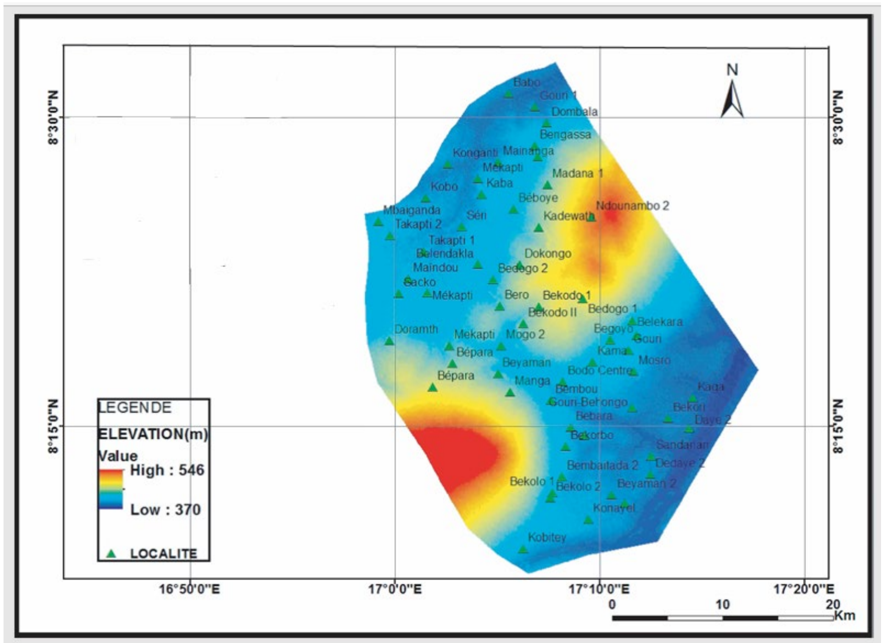

Figure 4. Relief map of East Kouh department based on DTM (USGS, 2022) processing.

8.1.2. Hydrographic Network Map

The hydrographic network of Kouh-Est is closely dependent on rainwater collected during the short rainy seasons. The various seasonal watercourses in the locality are the Daye, the Kou and the Mbo. These temporary watercourses are dependent on the topography of the area and are generally drained in a south-easterly and north-westerly direction, as well as in the centre of the study area, which are considered to be the lowest parts of the locality (**Figure 5**).

8.1.3. Soil Map

The soil map used is that of Bouteyré, 1965 at a scale of 1:200,000, Feuille de Koumra, published by the Cartographic Service of ORSTOM, Fond Topographique de l'I.G.N (Institut Géographique National) at a scale of 1:200,000, Feuille NC-33-V.

Various types of soil are found in East Kouh department. These are raw erosion mineral soils, cuirassés; raw mineral input soils; alluvial soils with pronounced hydromorphic characteristics; weakly ferrallitic red ochre modal soils; weakly ferrallitic red modal soils; truncated leached ferruginous soils and leached tropical ferruginous soils [39] (**Figure 6**).

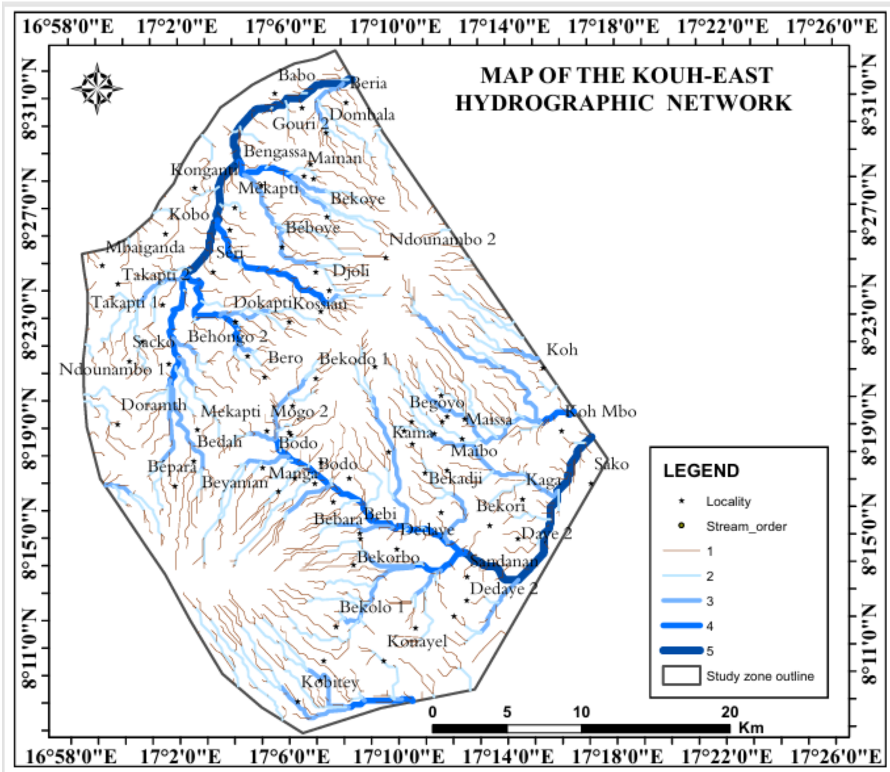

Figure 5. DTM-processed map of the Kouh-Est hydrographic network.

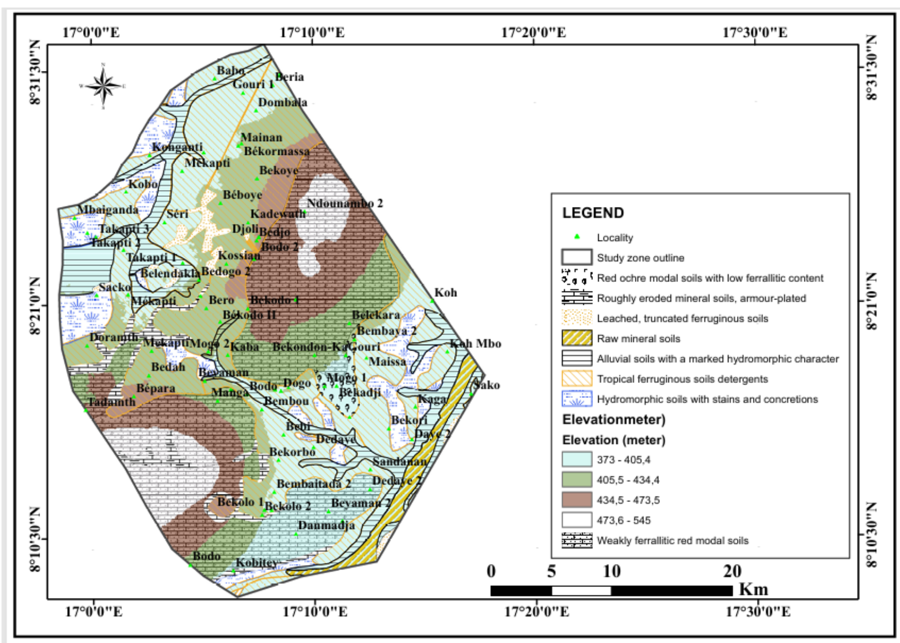

Figure 6. Soil map of Kouh-Est extracted from the Koumra soil map [39] and the DTM [USGS, 2022].

8.1.4. Geological Map

The geological formations encountered in the study area are essentially sedimentary with fluvio-lacustrine superficial layers found in most of southern Chad. Three (3) formations have been identified in the department of Kouh-Est:

* Continental Terminal sandstones;
* the sub-actual to present alluvial series dating from the Quaternary;
* the recent Quaternary sandy series.

Figure 7 below shows the various geological formations in the study area.

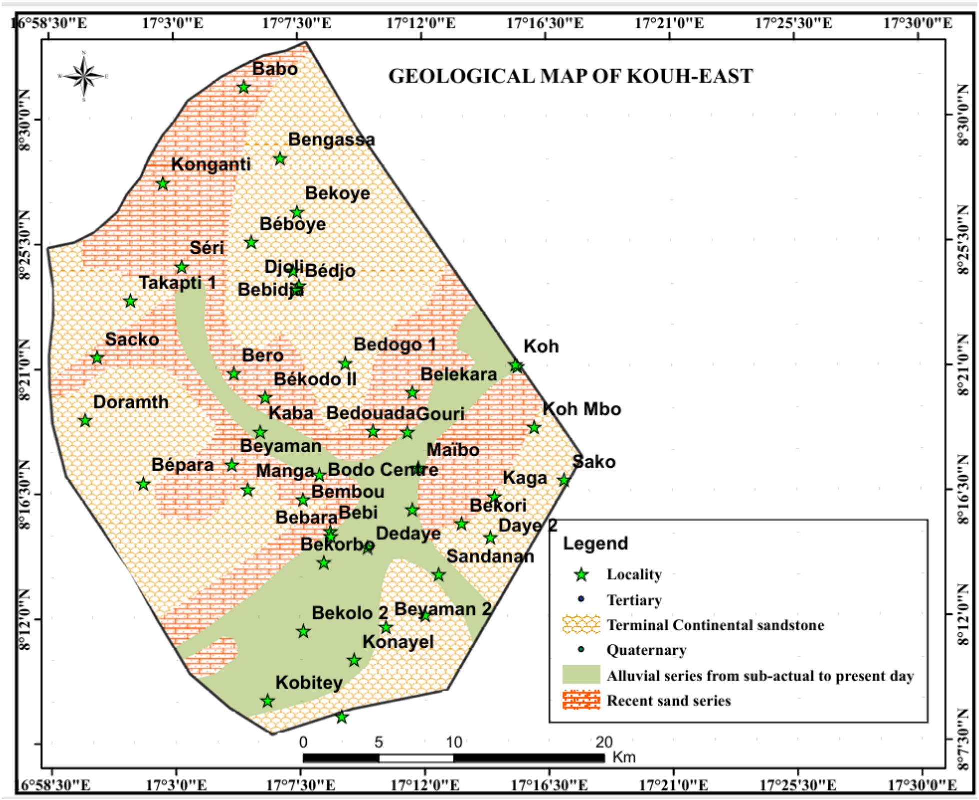

Figure 7. Map of the geological formations of Kouh-East [40].

8.1.5. Land Use Map

The land cover map is a cartographic document produced on the basis of satellite images, possibly in combination with additional information gathered in the field or from a raw image. It is based on the general principle that pixels with the same properties are assigned to a class, thus defining the type of land cover. The set of classes is predefined in the case of supervised classification. For this work, the Landsat imagewas downloaded via the Earth Explorer channel after registering on the USGS website. Figure 8 below shows the different land use elements in the study area.

Image Processing

The various land cover elements identified in this work are as follows:

* Bare soil: all surfaces not covered by any vegetation at the time the image was acquired.

Acquisition Date

* Cultivable area: includes all areas cultivated on the date the image was acquired.

* Vegetation: covers areas that are generally cultivated and where natural vegetation is left to grow spontaneously and uncontrolled at the time the image is acquired.

* Forest: includes areas covered by dense shrub vegetation on the date of image acquisition.

May 21, 2022

* Water: all areas covered by water, in particular ponds, marigots and mayo (watercourses) in the locality as seen on the date the image was acquired.

Statistically, the following characteristics emerge from this occupation map: the predominance of bare soil covering 517.99 km^2 out of a total of 1017.3 km^2 (surface area of the study area), *i.e.* 50.92%; arable land covers 327.66 km^2, *i.e.* 32.21%; vegetation covers 138.05 km^2, *i.e.* 13.57%; forest covers 32.31 km^2, *i.e.* 3.17%; and finally, water is represented by the string of ponds covering 1.29 km^2, *i.e.* 0.28%.

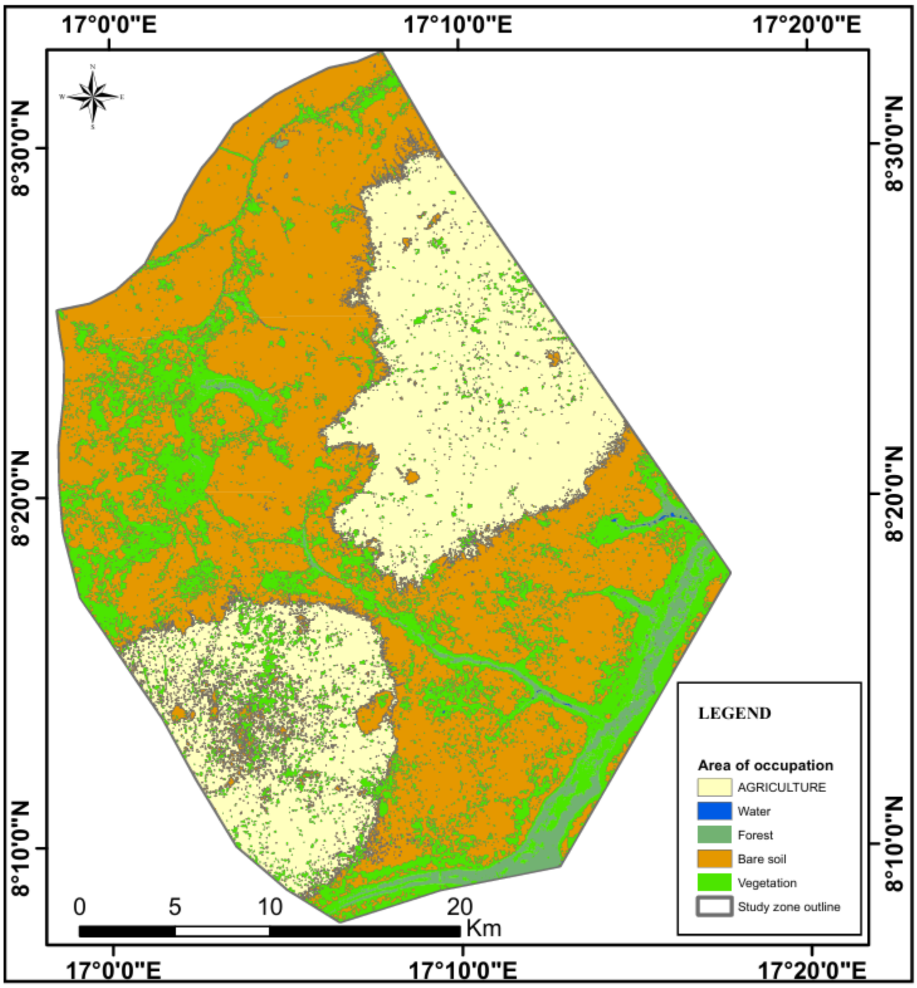

Figure 8. Land cover map of Kouh-Est county based on Landsat 2022 [41].

8.2. Fertility Aspect

8.2.1. Fertility Level of Ferralsols

Soil fertility indices and nutrient ratios were used to assess the fertility status of ferralsols in the study area. Structural stability index (SSI) values ranged from 0.81 to 7.45, with the lowest values observed in PBDJ soils and the highest values in PBKA soils. Intermediate SSI values were observed in PBB (1.33), PBD (2.27), PBKY (2.51) and PKH (3.25) soils. Forester's Index (FI) ratios range from 15.95 to 71.27, with the lowest levels found in PBKY and the highest in PBD. The following soils have intermediate FI values: PBB (17.52), PBDJ (18.51), PBKA (23.29) and PBKH (22.49). Silt/clay ratios range from 0.16 to 0.98, with low values for PBD and extreme values for PBKA. C/N ratios range from 4.36 to 1912.83, with the highest values in PBKA and the lowest in PBDJ. Intermediate C/N ratios are observed in the following soils: PBB (7.73), PBD (14.5), PBKY (11.33) and PKH (25.18).

NT/pH (total nitrogen/hydrogen potential) ratios are very low and virtually stationary overall, ranging from 0.00 to 0.01. S/T ratios range from 22.79% to 116.29%, with the lowest ratios found in PBKY soils and the highest S/T ratios in PBKA soils, and intermediate ratios in PBB (52.48), PBDJ (26.37), PBD (24.48) and PKH (44.91) soils. The nitrogen mineralisation index or N/P ratio ranged from 0.00 to 2.50, with low levels in PBDJ, PBD, PBKY and PBKA soils and high levels in PKH soils. The phosphorus mineralisation index, represented by the C/P ratio, ranged from 0.01 to 66.00, with low mineralisation index levels in PBDJ soils and high levels in PKH soils. Intermediate mineralisation indices were found in PBB (0.04), PBD (0.04), PBKY (0.05) and PBKA (0.12) soils. Ca/Mg ratios vary from 1.89 to 9.26, with the lowest values found in PBB soils and the highest values in PBKA soils. Intermediate values are found in PBDJ (2.63), PBD (5.29), PBKY (2.88) and PKH (2.07) soils.

Mg/K ratios range from 0.58 to 2.85, with low ratios in PBKY soils and high values in PKH soils, and intermediate ratios in PBB (1.26), PBDJ (1.24), PBD (2.55) and PBKA (0.63) soils. The CEC/A ratios range from 0.41 to 1.10, with the lowest ratios in PBD soils and the highest ratios in PBKA soils, and intermediate ratios in PBB (0.95), PBDJ (0.60), PBKY (0.90) and PKH (0.78) soils. Table 5 below shows the values of the various indices and ratios used to assess the level of soil fertility. Table S1 in the appendix clarifies the level of fertility ratios and indices of the ferralsols studied.

8.2.2. Fertility Level of Alluvial Soils

The nutrient ratios of alluvial soils and the soil fertility indices were used to assess the fertility status of the soils. Structural stability index (SSI) values ranged from 0.76 to 17.27, with the lowest values observed in PBR soils and the highest values in PBK soils. Intermediate SSI values were observed in PBM (1.97), PBY (9.92), PTKT (4.89), PSCK (3.28), PDY (2.89), PSDN (2.92), PDD (2.10) and PBP (2.61) soils. The Forester's Index (FI) ratios range from 9.14 to 704.00, with the lowest contents in PBP and the highest in PBK. The following soils have intermediate FI values: PBM (9.14), PBR (13.38), PBY (630.75), PTKT (24.93), PSCK (22.50), PDY (29.44), PSDN (23.29) and PDD (13.38). Silt/clay ratios range from 0.31 to 1.53, with low values in PSDN and extreme values in PDD. Intermediate silt/clay ratios are found in PBM (0.78), PBR (0.55), PBY (0.50), PBK (0.57), PTKT (0.67), PSCK (0.92), PDY (0.71) and PBY (0.64). C/N ratios ranged from 4.45 to 199.76, with the highest levels found in PBP and the lowest in PBR. Intermediate C/N ratios were observed in the following soils: PBM (15.93), PBD (23.00), PBK (36.60), PTKT (19.00), PSCK (10.86), PDY (16.52), PSDN (15.48) and PDD (17.30). NT/pH (total nitrogen/hydrogen potential) ratios are very low and virtually stationary overall, ranging from 0.00 to 0.02. S/T ratios ranged from 12.43% to 116.07%, with the lowest ratios found in PBK soils and the highest in PSDN soils. Intermediate values were observed in PBM (30.60%), PBR (41.06%), PBY (20.33%), PTKT (22.65%), PSCK (53.65%), PDY (76.34%), PDD (60.50%) and PBP (40.53%) soils. The nitrogen mineralisation index or N/P ratio varies from 0.00 to 0.01. The phosphorus mineralisation index, represented by the C/P ratio, varies from 0.01 to 0.18. The low mineralisation index levels are found in PSDN soils and the high levels are found in PBK soils, intermediate mineralisation indices are found in PBM (0.04), PBR (0.02), PBY (0.02), PTKT (0.09), PSCK (0.13), PDY (0.06), PDD (0.10) and PBP (0.02) soils. Ca/Mg ratios range from 0.75 to 6.67, with low values in PTKT soils and high values in PDD soils, and intermediate values in PBM (2.00), PBR (2.44), PBY (2.29), PSCK (3.26), PDY (2.50), PSDN (2.62) and PBP (3.39) soils. Mg/K ratios vary from 0.16 to 184.00, with low ratios in PDY soils and high values in PBP soils, and intermediate ratios in PBM (5.69), PBR (2.04), PBY (28.00), PBK (11.20), PTKT (3.80), PSCK (0.37), PBM (0.22) and PDD (0.22) soils. The CEC/A ratios range from 0.50 to 2.24, with the lowest ratios found in PSDN soils and the highest ratios found in PBK soils, and intermediate ratios found in PBM (0.93), PBR (0.76), PBK (1.50), PTKT (0.76), PSCK (0.71), PDY (0.94), PBD (1.21) and PBP (0.94) soils. Table 6 below shows the values of the various indices and ratios used to assess the level of soil fertility. Table S2 in the appendix shows the ratios of the physicochemical parameters and fertility indices of the alluvial soils studied.

8.2.3. Level of Fertility of Brown Soils

The soil fertility indices calculated and the nutrient ratios were used to assess the fertility levels of the various brown soils in the study area. Structural stability index (SSI) values ranged from 0.70 to 5.55, with the lowest values observed in PSR soils and the highest values in PKB. Intermediate SSI values were observed in PBDO (3.50), PGO (3.79), PDJL (2.58), PKBY (0.71), PBKR (1.98), PBKL (1.41) and PBKB (3.51) soils. The Forester's Index (FI) ratios range from 8.33 to 630.75, with the lowest contents in PBKB and the highest in PBDO. The following soils have intermediate FI values: PKB (8.53), PGO (185.14), PDJL (33.49), PSR (28.96), PKBY (31.41), PBKR (23.29) and PBKL (22.25). Silt/clay ratios range from 0.22 to 1.31, with low values in PGO and extreme values in PBKB. Intermediate silt/clay ratios are found in PKB (0.57), PBDO (0.50), PBDJL (0.70), PSR (0.49), PKBY

(0.80), PKBR (0.66) and PBKL (0.62) soils.

C/N ratios ranged from 3.94 to 39.62, with the highest levels in PBKB and the lowest in PSR. Intermediate C/N ratios were observed in the following soils: PKB (32.12), PBDO (4.80), PGO (15.50), PDJL (8.97), PKBY (4.24), PBKR (9.69) and PBKL (14.53). The NT/pH (total nitrogen/hydrogen potential) ratios are very low and virtually stationary overall, at around 0.01. S/T ratios ranged from 11.02% to 93.62%, with the lowest ratios found in PGO soils and the highest in PDJL soils. Intermediate values were observed in PKB (39.01%), PBDO (26.33%), PSR (18.58%), PKBY (68.70%), PBKR (49.44%), PBKL (11.21%) and PBKB (59.51%) soils. The nitrogen mineralisation index or N/P ratio varies from 0.00 to 0.01. The phosphorus mineralisation index, represented by the C/P ratio, varies from 0.00 to 0.18. The low mineralisation index levels are found in PSR soils and the high levels in PKB soils, Intermediate mineralisation indices are found in PBDO (0.04), PGO (0.12), PBDJL (0.02), PKBY (0.03), PBKR (0.07), PBKL (0.03) and PBKB (0.05) soils. Ca/Mg ratios ranged from 0.82 to 3.86, with the lowest values found in PGO soils and the highest values are found in PBDO soils, with intermediate values found in PKB (3.79), PDJL (2.31), PSR (1.03), PKBY (1.09), PBKR (2.69), PBKL (0.92) and PBKB (1.76) soils. Mg/K ratios vary from 0.16 to 8.80, with low ratios in PDJL soils and high values in PGO soils, and intermediate ratios in PKB (0.42), PBDO (4.31), PSR (4.29), PKBY (3.28), PBKR (0.51), PBKL (1.14) and PBKB (3.69) soils. The CEC/A ratios range from 0.70 to 1.40, the lowest ratios being those of PKB soils and the highest ratios being those of PBDO soils, while the intermediate ratios are those of PGO (0.77), PDJL (1.00), PSR (1.03), PKBY (0.82), PBKR (0.84), PBKL (0.76) and PBKB (0.86) soils. Table 7 below shows the values of the various indices and ratios used to assess the level of soil fertility. Table S3 in the appendix highlights the levels of the physicochemical parameters and fertility indices of the Brunisols studied.

Table 6 below highlights the fertility parameters of the soils studied:

Table 6. Statistical summary of fertility indices and chemical element ratios for the soils studied.

	Min	Max	Moy	Ecart type
ISS	0.70	17.27	3.60	3.56
IF	8.33	704.00	104.86	210.65
L/A	0.16	1.53	0.68	0.30
C/N	3.94	1912.83	98.73	379.85
NT/Ph	0.00	0.02	0.01	0.00
S/T	11.02	116.29	45.56	30.06
N/P	0.00	2.50	0.10	0.50
C/P	0.00	66.00	2.70	13.19
Ca/Mg	0.75	9.26	2.90	1.93
Mg/K	0.16	184.00	10.86	36.53
CEC/A	0.41	2.24	0.94	0.37

8.2.4. Element Levels in the Different Soils Studied

* Soil particle size

Clay content ranged from 7% to 47.50% (mean = 33.86%; SD = 11.32%), with the Kaba (PKB) soils having the highest percentage of clay and the lowest percentage in the PBK soils. The percentage of silt varies from 4% to 42.50% (mean = 22.77%; SD = 10.83%), with the highest percentage of silt in PBKB and the lowest in PBK. The percentage of sand varies from 25.00% to 88% (mean = 43.65%; SD = 18.81%), with the PBK soils having the highest percentage and the PBKB soils the lowest.

Overall, the soils studied have a sandy-clay texture, with the exception of PBO, PBK, PBY and PGO, which have a sandy-clay texture.

Low and very low organic matter levels were observed in PKBY, PSR and PBO.

* Soil organic matter

The organic matter of the soils studied ranged from 0.41% to 4.62% (mean = 1.63%; SD = 1.06%). The highest organic matter values were found in PBKA and the lowest values in PSR and PKBY. The organic matter content is very high in PBKB, PKH, PSCK, PTKT, PBKA and PKB; the organic matter content of PSDN, PBKY, PDY, PBP and PBK Sandana is high; organic matter is average in PDD, PDJL, PBKR, PBM, PBD, PBY and PGO; PBKL, PBDJ, PBR and PBB have low organic matter contents and very low contents are observed in PKBY, PSR and PBO.

pH of the soils studied

The pH values studied ranged from 5.10 to 7.60 (mean = 6.22; SD = 0.59), compared with the standard range of 6.5 to 7.5. The highest pH was observed in PBKA and the lowest in PKB. Very high pH values were observed in PBKB, PBKL, PDD, PSDN, PBDJ, PBKY, PSR, PDJL, PBKR, PSCK, PTKT, PBR, PBM and PBY soils; high pH values were observed in PKBY, PBKA, PBP, PBB, PBO, PBD, PBK and PGO soils; PKH had an average pH; PDY had a low pH and PKB a very low pH.

* Nitrogen in the soils studied

Nitrogen content ranged from 0.00% to 0.11% (mean = 0.07%; SD = 0.02%), compared with the standard of 0.1% to 0.15%. The highest nitrogen values were found in PBKB and the lowest in PBKA. These values show that PBKY, PDJL, PSCK and PTKT have very high nitrogen levels; PKBY, PSDN, PBDJ, PBR, PKB and PBB have high nitrogen levels; PKH, PDD, PSR, PDY, PBM and PBO have medium nitrogen levels; PBKL, PBK, PBY and PGO have low nitrogen levels and PBKA, PBP and PBD have very low nitrogen levels.

* Calcium in the soils studied

Calcium content varied from 0.72 to 28.88 cmol+/kg (mean = 6.12%; SD = 5.51%) compared with the standard of 2.3 to 3.5 cmol+/kg. PBKA had the highest magnesium content and PGO the lowest. Apart from PBKL, PDD, PBDJ, PBKY, PDY, PBKR, PSCK, PTKT, PKB, PBO, PBK, PBY and PGO, the other soils have a high calcium content.

* Magnesium in the soils studied

Magnesium concentration ranged from 0.28 to 6.56 cmol+/kg (mean = 2.33%;

SD = 1.49%), compared with a reference range of 1 to 1.5 cmol+/kg. The highest magnesium content was found in PKBY soils and the lowest in PBY soils. Most of the soils studied have magnesium, with the exception of PBKL, PSR, PTKT, PBO, PBD, PBK, PBY and PGO.

* Potassium in the soils studied

Potassium concentration ranged from 0.01 to 20.09 cmol+/kg (mean = 3.44%; SD = 4.92%) compared with the standard range of 0.2 to 0.4 cmol+/kg. The highest potassium values were found in PDJL and the lowest in PBY. Very high potassium levels are found in PBKB, PBKL, PKBY, PKH, PDD, PSDN, PBDJ, PBKY, PSR, PDJL, PDY, PBKR, PSCK, PTKT, PBR, PBKA, PKB, PBM and PBB; average levels are found in PBD; PBO and PGO have low potassium levels; PBP, PBK and PBY have very low potassium levels.

* Assimilable phosphorus in the soils studied

The concentration of assimilable phosphorus ranged from 0.02 to 212.83 ppm (mean = 31.59%; SD = 44.05%), compared with the reference range of 10 to 15 ppm. PSR had the highest levels of assimilable phosphorus and PKH had the lowest. PBKB, PSDN, PBDJ, PBKY, PSR, PDJL, PTKT, PBKA, PBM, PBP and PBY had very high levels of assimilable phosphorus compared with the standard; PBKL and PDY had high levels; PKBY, PDD, PBKR, PSCK, PKB, PBB, PBR, PBO, PBD, PBK and PGO had low levels and PKH had very low levels of assimilable phosphorus.

* Sodium in the soils studied

The sodium concentration ranged from 0.03 to 0.24 cmol+/kg (mean = 1.66%; SD = 1.18%) compared with a reference of 0.3 to 0.7 cmol+/kg. The highest sodium content was observed in PDY and the lowest in PBY. With the exception of PBO, PBD, PBK, PBY and PGO, most of the soils studied contain sodium.

* Saturation rate of the soils studied

The saturation rate of the soils studied varied in general from 11.02% to 116.29% (mean = 45.56%; SD = 29.45%) against the norm of 40 to 60%. The highest saturation rate was observed in the Bélekara soils (PBKA) and the lowest in the Gouri soils. Very high saturation values were observed in PKBY, PDD, PSDN, PDJL, PDY and PBKA; high saturation values were observed in PBKB, PSCK and PBB ; medium saturation values are found in PKH, PBKR, PBR, PKB, PBM and PBP; low saturation values are found in PBDJ, PBKY, PSR, PTKT, PBO, PBD and PBY; very low saturation values are found in PBKL, PBK and PGO.

* Cation Exchange Capacity (CEC) of the soils studied

The Cation Exchange Capacity (CEC) content of the soils studied ranged from 11.20 to 42.32 cmol+/kg (mean = 28.53%; SD = 8.61%) (**Table 3**), compared with a reference value of 10 to 25 cmol+/kg. The highest CEC contents were found in the Bépara soils (PBP) and the lowest values in the Bodo soils (PBO). Very high CEC values are found in PBKB, PBKL, PKBY, PKH, PDD, PBDJ, PBKY, PDJL, PSR, PDY, PBKR, PTKT, PBR, PBKA, PKB, PBM, PBP and PBB; high CEC values are found in PSDN, PSCK, PBK and PGO; medium CEC values are found in PBO, PBD and PBY Bodo.

* Sum of exchangeable bases (SBE) of the soils studied

The sum of exchangeable bases in the soils studied ranged from 1.44 to 39.82 cmol+/kg (Avg = 13.54%; SD = 9.65%), compared with the reference range of 5 to 10 cmol+/kg. The sum of exchangeables was highest in PBKA and lowest in PBY. Very high exchangeable base sums were observed in PBKB, PKBY, PKH, PDD, PSDN, PDJL, PDY, PBKR, PSCK, PBR, PBKA, PKB, PBM, PBP and PBB; high exchangeable base sums are observed in PBKY and PSR; PBDJ and PTKT show average SBE; the SBE of PBKL, PBO, PBD and PBK, PBY and PGO show very low SBE.

8.2.5. Results of Correlations between Parameters

A significant and positive two-way correlation at the 0.01 level was observed between clay and CEC ($R^2 = 0.711$), and between silt and CEC ($R^2 = 0.707$) (**Figure 9**). The higher the clay and silt content of the soil, the greater the CEC. This relationship is antagonistic between CEC and sand, which shows a strong two-way correlation that is significant and negative at the 0.01 level ($R^2 = 0.822$). As soil sand content increases, CEC decreases.

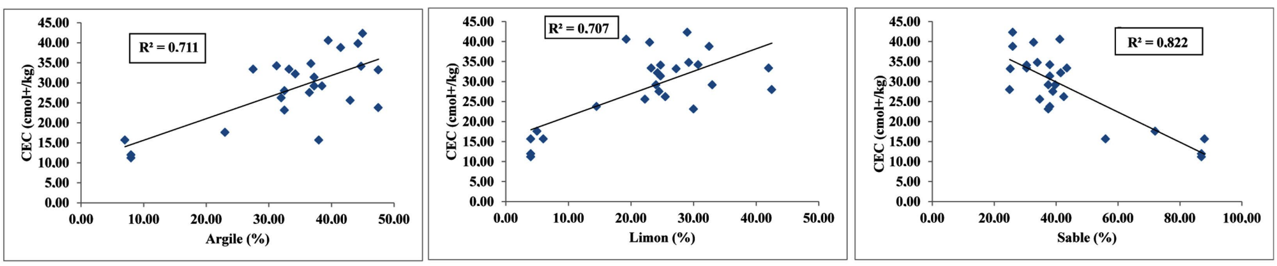

Figure 9. Elemental correlation between CEC and granulometry.

A significant and positive two-way correlation at the 0.01 and 0.05 level was observed respectively between OM and Ca ($R^2 = 0.564$) and between SBE and OM ($R^2 = 0.429$). An increase in OM led to an increase in Ca and SBE and vice versa. **Figure 10** below shows the correlation between organic matter and exchangeable bases:

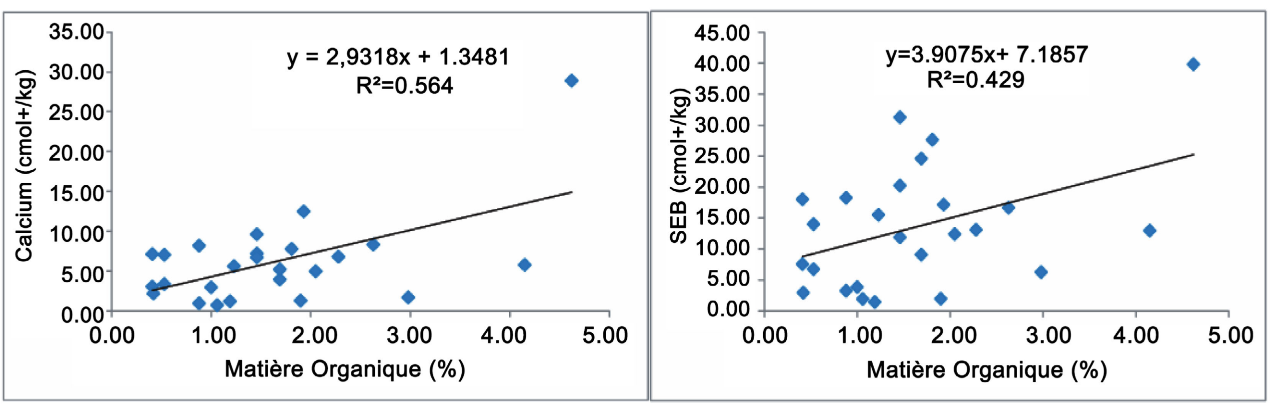

Figure 10. Elemental correlation between organic matter and chemical bases.

A significant and positive two-way correlation at the 0.01 level was observed between SBE and the following parameters: silt (R^2 = 0.520), Ca (R^2 = 0.812), Mg (R^2 = 0.542), K (R^2 = 0.720), Na (R^2 = 0.689). The increase in the content of these elements also leads to an increase in the SBE. Figure 11 below shows the correlation between the sum of exchangeable bases and exchangeable bases:

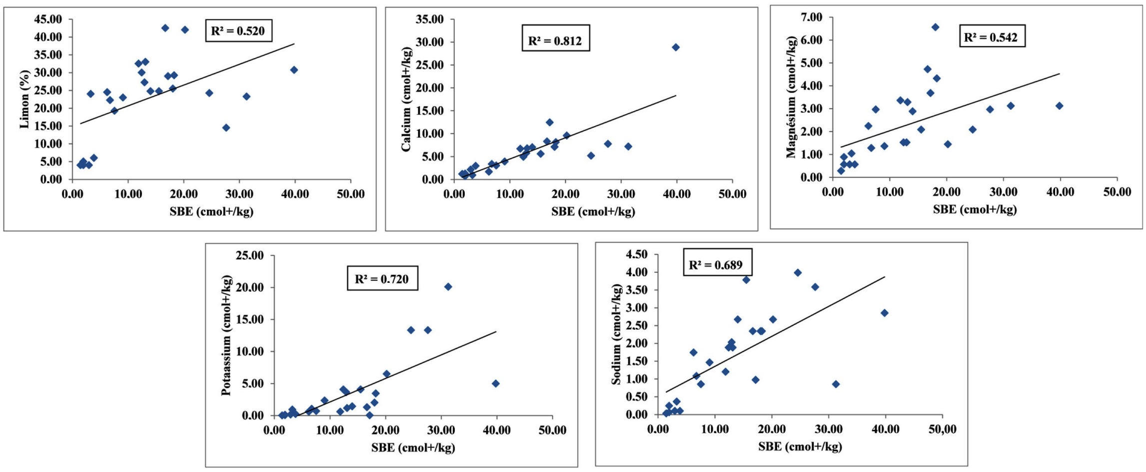

Figure 11. Elemental correlation between SBE and chemical bases.

The same trend was observed between the saturation rate V at the 0.01 threshold with the following chemical parameters Ca (R^2 = 0.713), K (R^2 = 0.748), Na (R^2 = 0.687) and SBE (R^2 = 0.949). Figure 12 below shows the correlation between the saturation rate and exchangeable bases:

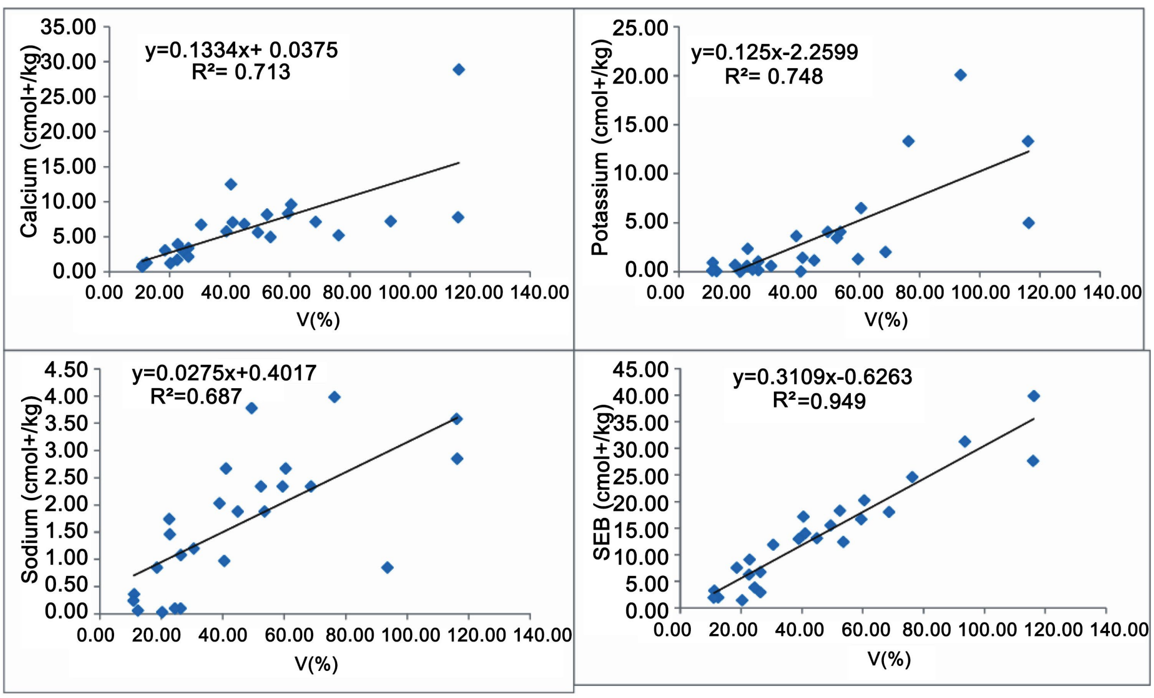

Figure 12. Elemental correlation between V and chemical bases.

Figure 13 below shows the various correlations that exist between the physico-chemical parameters of the soils in the study area.

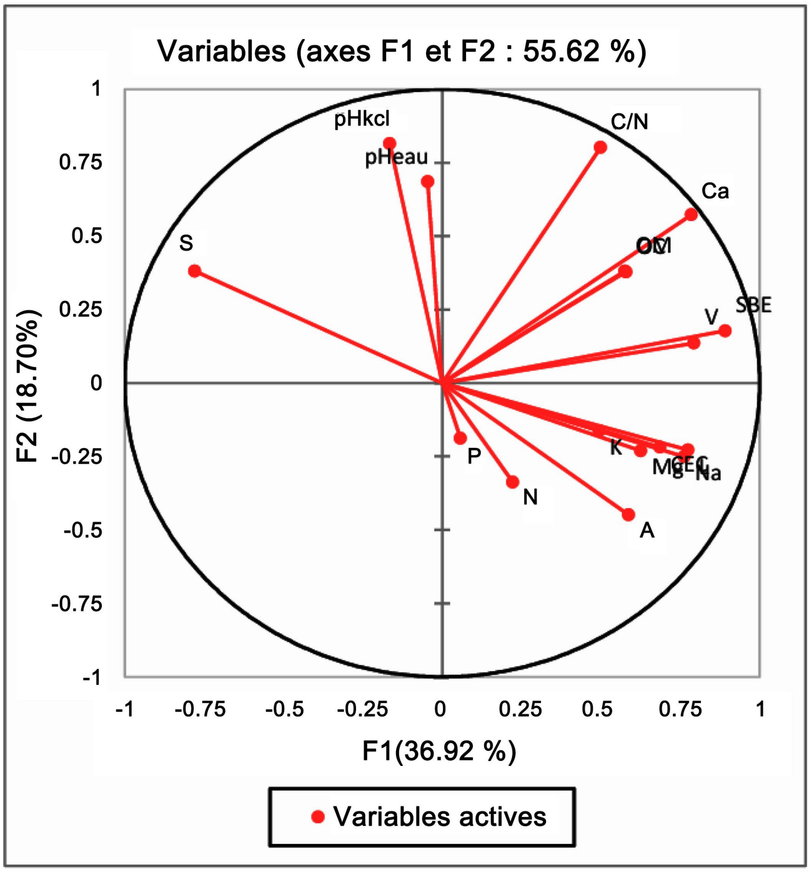

Figure 13. Correlation circle for physico-chemical parameters.

Table 7 below shows the degree of limitation of the physicochemical parameters and the fertility level of the ferralsols studied.

Table 7. Degree of limitation of physico-chemical parameters and level of soil fertility in ferralsols.

Characteristics	PBB	PBD	PBKA	PKH	PBDJ	PBKY
MO (%)	Severe limitation	Medium limitation	Unlimited	Unlimited	Severe limitation	Low limitation
N (%)	Low limitation	Very severe limitation	Very severe limitation	Medium limitation	Low limitation	Unlimited
Pass (cmol+/kg)	Severe limitation	Severe limitation	Unlimited	Very severe limitation	Unlimited	Unlimited
K+ (cmol+/kg)	Unlimited	Medium limitation	Unlimited	Unlimited	Unlimited	Unlimited
SBE (cmol+/kg)	Unlimited	Severe limitation	Unlimited	Unlimited	Medium limitation	Low limitation
CEC (cmol+/kg)	Unlimited	Medium limitation	Unlimited	Unlimited	Unlimited	Unlimited

Continued

V (%)	Low limitation	Severe limitation	Unlimited	Medium limitation	Severe limitation	Severe limitation
pH	Low limitation	Low limitation	Low limitation	Medium limitation	Unlimited	Unlimited
Limiting factors	OM, N, P, V, pH	OM, N, P, K V, SBE, CEC, pH	N, pH	N, P, V, pH	OM, N, SBE, V	OM, SBE, V
Soil class	IV	IV	III	III	IV	III
Fertility level	Very low fertility level	Very low fertility level	Low fertility level	Low fertility level	Very low fertility level	Low fertility level

Table 8 below shows the degree of limitation of the physicochemical parameters and the fertility level of the Brunisols studied.

Table 8. Degree of limitation of physico-chemical parameters and level of soil fertility in brown soils.

Characteristics	PBKB	PBKL	PKBY	PGO	PKB	PBO	PSR	PDJL	PBKR
OM (%)	Unlimited	Severe limitation	Very severe limitation	Medium limitation	Unlimited	Very severe limitation	Very severe limitation	Medium limitation	Medium limitation
N (%)	Unlimited	Severe limitation	Low limitation	Severe limitation	Low limitation	Medium limitation	Medium limitation	Unlimited	Low limitation
Pass (cmol+/kg)	Unlimited	Low limitation	Severe limitation	Severe limitation	Severe limitation	Severe limitation	Unlimited	Unlimited	Severe limitation
K+ (cmol+/kg)	Unlimited	Unlimited	Unlimited	Severe limitation	Unlimited	Severe limitation	Unlimited	Unlimited	Unlimited
SBE (cmol+/kg)	Unlimited	Severe limitation	Unlimited	Severe limitation	Unlimited	Severe limitation	Low limitation	Unlimited	Unlimited
CEC (cmol+/kg)	Low limitation	Unlimited	Unlimited	Low limitation	Unlimited	Medium limitation	Unlimited	Unlimited	Unlimited
V (%)	Very severe limitation	Very severe limitation	Unlimited	Very severe limitation	Medium limitation	Severe limitation	Severe limitation	Unlimited	Medium limitation
Ph	Unlimited	Unlimited	Low limitation	Low limitation	Very severe limitation	Low limitation	Unlimited	Unlimited	Unlimited
Limiting factors	V	OM, N, P, SBE, CEC, V	OM, N, P, pH	OM, N, P, K, SBE, CEC, V, pH	N, P, V, pH	OM, N, P, K V, SBE, CEC	MO, N, SBE, V	MO	OM, N, P, V
Soil class	I	IV	IV	IV	IV	IV	IV	II	III
Fertility level	High level of fertility	Very low fertility level	Very low fertility level	Very low fertility level	Very low fertility level	Very low fertility level	Very low fertility level	Medium fertility level	Low fertility level

Table 9 below shows the degree of limitation of the physicochemical parameters and the fertility level of the alluvial soils studied.

Table 9. Degree of limitation of physico-chemical parameters and level of fertility in alluvial soils.

Characteristics	PSCK	PTKT	PBR	PDD	PDY	PBM	PBP	PSDN	PBK	PBY
OM (%)	Unlimited	Unlimited	Severe limitation	Medium limitation	Low limitation	Medium limitation	Low limitation	Low limitation	Low limitation	Medium limitation
N (%)	Unlimited	Unlimited	Low limitation	Medium limitation	Medium limitation	Medium limitation	Very severe limitation	Low limitation	Severe limitation	Severe limitation
P_{ass} (cmol$^+$/kg)	Severe limitation	Unlimited	Severe limitation	Severe limitation	Severe limitation	Unlimited	Unlimited	Unlimited	Severe limitation	Unlimited
K^+ (cmol$^+$/kg)	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	Very severe limitation	Unlimited	Very severe limitation	Very severe limitation
SBE (cmol$^+$/kg)	Unlimited	Medium limitation	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	Very severe limitation	Very severe limitation
CEC (cmol$^+$/kg)	Limitation faible	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	Low limitation	Low limitation	Medium limitation
V (%)	Low limitation	Severe limitation	Medium limitation	Unlimited	Unlimited	Medium limitation	Medium limitation	Unlimited	Very severe limitation	Severe limitation
pH	Unlimited	Unlimited	Unlimited	Unlimited	Severe limitation	Unlimited	Low limitation	Unlimited	Low limitation	Unlimited
Limiting factors	CEC, V	SBE, V	OM, N, P, V	OM, N, P	OM, N, P, pH	OM, N, V	OM, N, K, V, pH	OM, N, CEC	OM, N, P, K V, SBE, CEC	OM, N, K, SBE, CEC, V
Soil class	III	III	IV	III	III	III	IV	II	IV	IV
Fertility level	Low fertility level	Low fertility level	Very low fertility level	Low fertility level	Low fertility level	Low fertility level	Very low fertility level	Medium fertility level	Very low fertility level	Very low fertility level

The map in Figure 14 below shows the different types of soil and their level of fertility.

9. Discussion

Soil fertility indices and nutrient ratios were used to assess the fertility status of the soils in the study area. The various soils studied (ferralsols, alluvial soils, and brunisols) have structural stability index (SSI) values ranging from 0.7 to 17.27. The highest values were found in the grey soils and the lowest in the brown soils. These structural stability index values show that the soils studied have very limiting to limiting levels of structure overall, with the exception of the PBK and PBY soils [26]. All the soils have the Forestier Index (IF > 1.5), these values show that the exchangeable base reserves are acceptable for crops (Forestier, 1960). Silt/clay ratios range from 0.16 to 1.53, with low values for PBD and extreme values for PDD. These ratios suggest two processes: 1) soils with low ratios (<0.75) (PBDJ, PBKY, PBR, PBY, PBK, PTKT, PDY, PSDN, PBP, PKB, PBDO, PGO, PDJL, PSR, PKBY, PBKR and PBKL); 2) soils with moderate ratios (>0.75) (PBB, PBD, PBKA, PKH, PBM, PSCK, PDD, PBKB). The first category (silt/clay < 0.75) suggests an ancient pedogenetic process while and the second a pedogenetic process of moderate age [29].

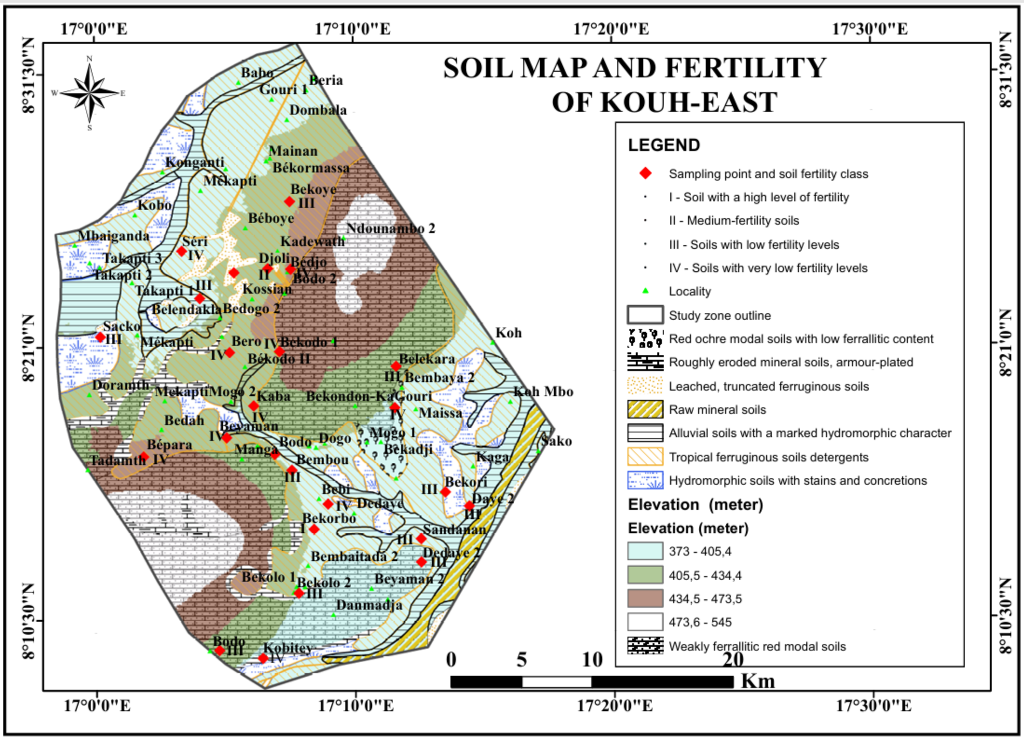

Figure 14. Soil map and fertility status of Kouh-Est soils.

C/N ratios range from 3.94 to 1912.83, the highest contents are in PBKA and the lowest are in PSR, intermediate C/N ratios are observed in the following soils: PBB (7.73), PBD (14.5), PBKY (11.33) and PKH (25.18).

These ratios are generally high, suggesting slow decomposition and a low rate of mobilisation of organic matter [20]. NT/pH (total nitrogen/hydrogen potential) ratios are very low and almost stationary overall, ranging from 0.00 to 0.01. Similar results were found by [28]. The S/T ratios vary from 11.02% to 116.29%, the low ratios are for BMP soils and the highest S/T ratios are for PBKA soils. These values show that more than 40% of the soils studied are below the saturation threshold. These results corroborate those of [42]. The nitrogen mineralisation index or N/P ratio varies from 0.00 to 2.50, with low levels in PBDJ, PBD, PBKY and PBKA soils respectively and high levels in PKH soils. The phosphorus mineralisation index, represented by the C/P ratio, varies from 0.01 to 66.00, with low mineralisation index values in PBDJ soils and high values in PKH soils. Intermediate mineralisation index values are found in PBB (0.04), PBD (0.04), PBKY (0.05) and PBKA (0.12) soils.

Ca/Mg ratios range from 0.75 to 9.26, with the lowest values found in PTKT soils and the highest values in PBKA soils. Most of the soils studied have ratios of 1 < Ca/Mg < 5, with the exception of the PDD and PBKA soils, which have Ca/Mg > 5 ratios. These results corroborate those of [20] according to whom for values of 1 < Ca/Mg < 5, these soils are in nutritional balance in terms of calcium and magnesium, and for values of Ca/Mg > 5, these soils show a deficiency in Mg in relation to Ca, which would indicate a nutritional imbalance indicating an excess of Ca in the soil in relation to Mg. The Mg/K ratios vary from 0.16 to 184.00, the low ratios being those of the PDJL soils. Three classes of Mg/K ratios are observed: 1) soils with Mg/K ratios < 1; 2) soils with ratios 1 < Mg/K < 4 and 3) soils with Mg/K ratios > 4. The first class reflects an imbalance between Mg-K, the second class reflects a nutritional balance between Mg-K and the third class reflects a deficiency in Mg compared with K. Similar results have been found by [43] [44] in the past. CEC/A ratios range from 0.41 to 1.10, with the lowest ratios found in PBD soils and the highest ratios in PBKA soils, and intermediate ratios found in PBB (0.95), PBDJ (0.60), PBKY (0.90) and PKH (0.78) soils.

All the soils have low Ca/Mg/K ratios compared with the ideal nutritional balance values of 76% Ca, 18% Mg and 6% K. Similar results were found by [24].

CEC is an indicator of potential soil fertility. The soil's cation exchange capacity represents the size of the reservoir for reversibly storing certain cationic fertilising elements (potassium, magnesium, calcium, etc.). It is linked to the clay-humus complex. The Cation Exchange Capacity content of the soils studied ranged from 11.20 to 42.32 cmol+/kg, compared with the benchmark of 10 to 25 cmol+/kg. The proportions of clay and silt largely dominate that of sand in all locations (88%). The soils have a sandy-clay to sandy-clay texture. Clay is the most active granulometric fraction because it has multiple functions (association with organic matter, cohesion of aggregates, fixing of cations and anions on exchange sites, water retention [45] [46]. Similar results were found by [36] [47].

Soils in the various localities have calcium levels ranging from 0.72 to 28.88 cmol+/kg, compared with the standard of 2.3 to 3.5 cmol+/kg. Over 52% of the soils have a calcium content below the reference level. Exchangeable calcium deficiencies normally only occur in soils with a low pH ≤ 5.5, which is the case for the sites studied [48]. Magnesium changes from 0.28 to 6.56 cmol+/kg against the reference varying from 1 to 1.5 cmol+/kg. More than 32% of the soils studied are magnesium deficient. Potassium concentration varied from 0.01 to 20.09 cmol+/kg, compared with a reference of 0.2 to 0.4 cmol+/kg. More than 20% of the soils studied were below the threshold. Alkaline and alkaline-earth elements play a major role in plant nutrition, and their deficiency is not without incident [49] [50].

Nitrogen levels range from 0.00% to 0.11%, compared with the norm of 0.1% to 0.15%. More than 28% of soils have a nitrogen deficit. The work of [25] has highlighted the importance of nitrogen in soil fertility. This work shows that the carbon content of an organic matter relative to its nitrogen content determines mineralisation or immobilisation. Bacteria need nitrogen to decompose plants or other residues. The decomposition of carbon-rich organic matter will slow down until sufficient nitrogen is present. Soil bacteria will consume the bioavailable nitrogen to break it down, creating a risk of nitrogen deficiency during the season, as long as an unfavourable C/N ratio remains.

Organic matter is a good indicator of plant health. It contributes to soil fertility. In this study, soil organic matter varied from 0.41% to 4.62%. Over 72% of the soils studied had a high organic matter content, but 28% had a low content, which could be an obstacle to good productivity [11]. This could be due to insufficient organic amendments and chemical inputs, as well as overexploitation of the soil [42].

The pH values studied ranged from 5.10 to 7.60. The soils studied are slightly acidic to neutral. These pH values are typical of the ferrallitic and ferruginous soils of the Sahel [51]-[53]. For pH values below 5.5, as in the case of the ferrallitic and ferruginous soils in the locality, organic matter must be added in order to increase the pH, otherwise it will be a limiting factor for plant nutrition.

More than 48% of the soils studied had levels of assimilable phosphorus below the permitted threshold. Numerous authors have demonstrated the role played by phosphorus in plant nutrition. These studies reveal the importance of organic matter in the availability of assimilable phosphorus [54]. Organic matter is an important source of phosphorus in organic form, but it also contributes to the reversible storage of nutrients through mineralisation/immobilisation by microorganisms [55].

For conservation-based land management, erosion control measures should be considered, such as anti-erosion structures (dykes, terraces, stone barriers). Construction of stone terraces, fallow land grazed in rotation with cereals and peanuts, sorghum-cowpea combinations, micro-fallow land based on shrubs such as Piliostigma reticulata, dense tree parks based on Faidherbia albida, Vitellaria paradoxa (shea tree) or Proposopis Africana [56], and the practice of zaï [57]. Use the zaï technique, which is a soil conservation technique that involves digging 10 - 15 cm deep pits before the rains, adding organic fertilizer, and then sowing sorghum or millet.

To address nitrogen deficiency, crop rotation with legumes is essential, as they are known to increase soil fertility through their symbiotic nitrogen fixation. The combination of legumes and cereals is the second type of plant combination that promotes, among other things, soil fertility, provided that the legume density is high and that these plants fix nitrogen from the air effectively [58]-[60]. This combination was very common in the past in the Sahel, where staple cereals (millet, sorghum) were grown alongside low-density cowpeas. In this case, the aim is more to limit insect infestation of the cowpeas and to make better use of the available land and manual labor.

For [61], vegetation should be used for soil conservation. He lists the benefits of vegetation as follows:

1) Cela affaiblit la vitesse du vent dans le champ, réduisant ainsi les dommages causés par l'érosion éolienne et permettant l'accumulation du sol.

2) Grass plays a protective role and complements agricultural land conservation efforts, limiting runoff.

3) Trees absorb water at a depth beyond the reach of crops, as well as nutrients

washed down by leaching; they also return plant matter to the soil during defoliation.

4) Many legumes contain nitrogen fixers and thus return nutrients to crops.

5) Fallen leaves from trees are a source of organic matter, promoting the activity of microorganisms in the soil.

10. Conclusions

At the end of the study, the main objective was to map the surface conditions of the soils of Kouh-Est and to assess soil fertility. The various thematic maps produced using remote sensing and GIS tools show that the relief is in the form of two contiguous and convex half-oranges, oriented NNE-SSW; the hydrographic network is drained in a south-easterly and north-westerly direction, as well as in the centre of the study area; the pedology reveals a varied range of soils, including crude erosion mineral soils, cuirassés, crude mineral input soils, alluvial soils with pronounced hydromorphic characteristics, red ochre modal weakly ferrallitic soils, red modal weakly ferrallitic soils, truncated leached ferruginous soils and leached tropical ferruginous soils; geologically, three (3) formations have been identified, including Terminal Continental sandstones, the sub-actual to current alluvial series dating from the Quaternary and the recent Quaternary sandy series; land use shows that bare soil occupies 50.92%, arable land 32.21%, vegetation 13.57%, forest 3.17% and, lastly, water is represented by a string of ponds covering 0.28%.

The physico-chemical characteristics of the soils were used to assess their fertility status. Soil fertility indices and nutrient ratios for the different morphological varieties of soil in the study area, ferralsols, alluvial soils, and brunisols, showed four classes of fertility. On the whole, these soils have low to very low levels of fertility, with the exception of the Békorobe soils, which are class I, showing a good level of fertility, and the Sandana and Djoli soils, class II, with average fertility. Given the low organic matter content, organic and chemical amendments are needed to improve the quality of these soils.

Conflicts of Interest

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

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Appendix

Table S1. Parameters of ferralsol fertility level.

	PBB	PBDJ	PBD	PBKY	PBKA	PKH
ISS	1.33	0.81	2.27	2.51	7.45	3.25
IF	17.52	18.51	71.27	15.95	23.29	22.49
L/A	0.80	0.52	0.16	0.52	0.98	0.89
C/N	7.73	4.36	14.5	11.33	1912.83	25.18
NT/pH	0.01	0.01	0.01	0.01	0	0.01
S/T	55.48	26.37	24.48	22.79	116.29	44.91
N/P	0.01	0.00	0.00	0.00	0.00	2.50
C/P	0.04	0.01	0.04	0.05	0.12	66.00
Ca/Mg	1.89	2.63	5.29	2.88	9.26	2.07
Mg/K	1.26	1.24	2.55	0.58	0.63	2.85
CEC/A	0.95	0.60	0.41	0.90	1.10	0.78
Ca/Mg/K	8.16/4.32/3.44	3.36/1.28/1.03	2.96/0.56/0.22	3.92/1.96/2.33	28.88/3.12/4.97	6.8/3.28/1.15

Table S2. Alluvial soil fertility parameters.

	PBM	PBR	PBY	PBK	PTKT
ISS	1.97	0.76	9.92	17.27	4.89
IF	9.14	13.38	630.75	704.00	24.93
L/A	0.78	0.55	0.50	0.57	0.67
C/N	15.93	4.45	23.00	36.60	19.00
NT/pH	0.01	0.01	0.00	0.01	0.01
S/T	30.6	41.06	20.33	12.43	22.65
N/P	0.00	0.00	0.00	0.00	0.00
C/P	0.04	0.02	0.02	0.18	0.09
Ca/Mg	2.00	2.44	4.29	2.29	0.75
Mg/K	5.69	2.04	28.00	11.20	3.80
CEC/A	0.93	0.76	1.50	2.24	0.76
Ca/Mg/K	6.72/3.36/0.59	7.04/2.88/1.41	1.20/0.28/0.01	1.28/0.56/0.05	1.68/2.24/0.59
	PSCK	**PDY**	**PSDN**	**PDD**	**PBP**
ISS	3.28	2.89	2.92	2.10	2.61
IF	22.50	29.44	23.29	13.38	9.14
L/A	0.92	0.71	0.31	1.53	0.64
C/N	10.86	16.52	15.48	17.3	199.76
NT/pH	0.02	0.01	0.01	0.01	0.00
S/T	53.65	76.34	116.07	60.5	40.53
N/P	0.01	0.00	0.00	0.01	0.00

Continued

C/P	0.13	0.06	0.01	0.10	0.02
Ca/Mg	3.26	2.50	2.62	6.67	3.39
Mg/K	0.37	0.16	0.22	0.22	184.00
CEC/A	0.71	0.94	0.50	1.21	0.94
Ca/Mg/K	4.96/1.52/4.06	5.20/2.08/13.32	7.76/2.96/13.32	9.60/1.44/6.49	12.48/3.68/0.02

Table S3. Brown soil fertility level parameters.

	PKB	PBDO	PGO	PDJL	PSR
ISS	5.55	3.50	3.79	2.58	0.70
IF	8.53	630.75	185.14	33.49	28.96
L/A	0.57	0.50	0.22	0.70	0.49
C/N	32.12	4.8	15.5	8.97	3.94
NT/Ph	0.01	0.01	0.01	0.01	0.01
S/T	39.01	26.33	11.02	93.62	18.58
N/P	0.01	0.01	0.01	0.00	0.00
C/P	0.18	0.04	0.12	0.02	0.00
Ca/Mg	3.79	3.86	0.82	2.31	1.03
Mg/K	0.42	4.31	8.80	0.16	4.29
CEC/A	0.70	1.40	0.77	1.00	1.03
Ca/Mg/K	5.76/1.52/3.64	2.16/0.56/0.13	0.72/0.88/0.10	7.20/3.12/20.09	3.04/2.96/0.69
	PKBY	PBKR	PBKL	PBKB	
ISS	0.71	1.98	1.41	3.51	
IF	31.41	23.29	22.50	8.33	
L/A	0.80	0.66	0.62	1.31	
C/N	4.24	9.69	14.53	39.62	
NT/Ph	0.01	0.01	0.01	0.01	
S/T	68.7	49.44	11.21	59.51	
N/P	0.01	0.01	0.00	0.00	
C/P	0.03	0.07	0.03	0.05	
Ca/Mg	1.09	2.69	0.92	1.76	
Mg/K	3.28	0.51	1.14	3.69	
CEC/A	0.82	0.84	0.76	0.86	
Ca/Mg/K	7.12/6.56/2.00	5.60/2.08/4.06	0.96/1.04/0.91	8.32/4.72/1.28	