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Geo-spatial sensing of apparent electrical conductivity: a leeway to agricultural soil assessment

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ABSTRACT

The demand for economical means of evaluating soil nutrients' unpredictability triggered the use of physical factors against the costlier, laborious, and time-consuming chemical approach. This drive led to resolving its capability in evaluating intricate soil properties as a productivity checker. This study aimed at assessing the efficiency of apparent electrical conductivity as a useful alternative to the conventional chemical examination of available nutrients. A petrographic examination was conducted on four rock samples for their classification as the source of soil formation. Apparent Electrical Conductivity (EC_a) measurements were seasonally executed in the wet (912-station) and dry (906-station); the ArcGIS 10.2 programme was used in generating the EC_a maps for classifying the EC_a into low, moderate, and high sections. Ten cored (*in-situ*) soil samples were subjected to permeability test to ascertain water infiltration rate and retention. Twenty soil samples were examined for pH, Electrical Conductivity (EC), available phosphorus, acidity, Na, Mg, K, and Ca using standard soil science procedures. The mineralogical composition of six samples (two samples per EC_a region) was determined with X-ray diffraction. The soils EC_a were 10–344 µS/cm, categorized as low (1–49 µS/cm), moderate (50–99 µS/cm), and high (>100 µS/cm). The EC_a distribution varied from moderate (61%) to high (64%), suggesting a heterogeneous pattern of soil attributes. The infiltration rate was slow in high EC_a ($5.56x10^{-5}$-$1.67x10^{-4}$ cm/s), signifying good retention capability, whereas the low and moderate EC_a (moderate-moderately rapid) sections promote nutrient leaching. 'Positive correlation was observed between CEC and EC_a in the low EC_a (2.99 cmol/kg), the same was observed in the moderate and high EC_a (3.30-4.85 cmol/kg) segments'. The base cation saturation varied from high (81.38%), moderate (73.34%) and low (71.89%), characterizing the high EC_a as the higher fertility status. Soils with moderate and high EC_a have a greater ability to adsorb cations onto their surfaces than soils with low EC_a; similarly, the deduction from base saturation showed that more cations are available in soils with high EC_a. The high EC_a region had low quartz (41.3%) and microcline (15.7%), but high kaolinite (31.1%) had an affinity to adsorb more cations compared to other EC_a regions in terms of quantity. The rock is biotite granite gneiss, containing plagioclase (22%), microcline (24%), orthoclase (4%), quartz (25%), biotite (7%), and others (18%). EC_a variability is practicable in predicting the spatial distribution of soil properties and delineating the management zones. Thereby reducing the cost that would have been expended on geochemical sampling of the entire farm.

Keywords: electrical conductivity, soil composition, mineral assemblages, nutrient variability, agricultural soil assessment, cation exchange capacity, spatial distribution

Detección geoespacial de la conductivad eléctrica aparente: una posibilidad para la evaluación de suelos agrícolas

RESUMEN

La demanda de medios económicos para evaluar la imprevisibilidad de los nutrientes del suelo ha llevado a que el uso de factores físicos prevalezca sobre los factores químicos, más costosos, laboriosos y demandantes de tiempo. Este enfoque condujo a resolver su capacidad de evaluar propiedades complejas del suelo como verificador de productividad. Este estudio se enfoca en medir la eficiencia de la conductividad eléctrica aparente como una alternativa útil a la examinación química convencional de los nutrientes disponibles. Para esto se realizó un análisis petrográfico en cuatro muestras rocosas para su clasificación como fuente de formación del suelo. Las medidas de Conductividad Eléctrica Aparente (EC_a) se llevaron a cabo durante la temporada de húmedad (912 estaciones) y la temporada seca (906 estaciones); el programa ArcGIS 10.2 se utilizó para la generación de mapas de clasificación de la EC_a que permitiera su clasificación en secciones baja, moderada y alta. Diez muestras de suelo (*in-situ*) fueron sometidas a pruebas de permeabilidad para determinar el índice de infiltración de agua y de retención. A veinte muestras de suelo se les examinó el potencial de hidrógeno (pH), la Conductividad Eléctrica, el fósforo disponible, la acidez, el sodio, el magnesio, el potasio y el calcio a través de procedimientos estándares de las ciencias del suelo. La composición mineralógica de seis muestras (dos muestras por cada región ECa) se determinó con difracción por rayos X. El rango EC_a de los suelos osciló en 10–344 µS/cm, categorizados como bajos (1–49 µS/cm), moderados (50–99 µS/cm) y altos (>100 µS/cm). La distribución EC_a varía de moderada (61 %) a alta (64 %), lo que sugiere un patrón heterogéneo de atributos del suelo. El grado de infiltración fue bajo en la región alta de EC_a (5.56x10-5-1.67x10-4 cm/s), lo que significa una buena capacidad de retención, mientras que las regiones baja y moderada de EC_a (moderado-moderadamente rápido) promueven la filtración de nutrientes. Se observó una correlación entre la Capacidad de Intercambio de Cationes (CTC) con la ECa; la CTC baja (2.99 cmol/kg) ocurre en la región baja de la EC_a, al igual que la moderada (3.30-4.85 cmol/kg) ocurre en la región moderada de la ECa y la alta ocurre en la región alta de la EC_a. La saturación base del cation varía entre alto (81.38 %), moderado (73,34 %) y bajo (71,89 %), lo que caracteriza la región alta de EC_a como la de mayor estatus de fertilidad. Los suelos de las regiones moderada y alta de EC_a tiene una mayor capacidad de absorber los cationes en sus superficies que los suelos de la región baja EC_a; igualmente, la deducción de la saturación base muestra que más cationes están disponibles en suelos de la región alta de la EC_a. La región alta de la EC_a tiene un bajo porcentaje de cuarzo (41,3 %) y microclina (15,7 %), pero la alta caolinita (31,1 %) tiene una afinidad de absorber más cationes en comparación con otras regiones de la EC_a en términos de cantidad. La roca es un gneis granítico de biotita que contiene plagioclasa (22 %), microclina (24 %), ortoclasa (4 %), cuarzo (25 %), biotita (7 %), y otros (18 %). La variabilidad de la EC_a es práctica para predecir la distribución espacial de las propiedades del suelo y delinear las zonas de manejo. Además sirve para reducir el costo que se gastaría en la realización de un muestreo del área completa de trabajo.

Palabras clave: Conductividad eléctrica; composición del suelo; conjuntos minerales; variabilidad de nutrientes; evaluación del suelo agrícola; capacidad de intercambio de cationes; distribución espacial.

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1. Introduction

Soil is developed from the parent rock material which is influenced by the climatic condition, topography, and living organisms acting on it; and tends to exhibit varying textural classes based on the mineral composition of the parent rocks (McCauley *et al.*, 2005; Botta, 2015; Jaja, 2016). The soil horizon is developed from the continuous weathering of the parent rock leading to the development of a vertical section of soil known as the soil profile (Gregory *et al.,* 2009). The chemical content of soil and its formation depend on the nature of the bedrock as derived from weathering processes, biological components acting on it, and the introduction of external materials from other sources. Oftentimes, the nutrient content of soil is dependent on the bedrock, and its variability depends on the conditions in which the parent rock is in the soil's formation. This in turn affects the weathering rates, resulting in different soil horizons with varying physical, chemical, and mineralogical compositions (Demir et al., 2022). Demir et al. (2022) suggested that soil nutrient evaluation should be determined from its physico-chemical and mineralogical properties in order to reveal its composition. Evaluating soil nutrients' capacity has been done through a geochemical approach but it's laborious, and time-consuming and the cost of analysis is expensive; although detailed information would be available at the end of the exercise. Considering the number of samples that would be required for a detailed assessment, often time farmers embarked on a smaller number of sampling points to get around the problem of cost, but this would not allow the production of a detailed and accurate map of soil nutrients' variability.

The quality of soil type is determined by the proportions of the clay, silt, and sand combination; this invariably dictates the porosity/permeability, nutrient catchment capacity, water retention, and electrical conductivity which are essential for plants' performance. Soil nutrient is derived from the chemistry of the parent rock. The petrographic evaluation of rock serves as a way to examine the optical properties of minerals and possibly determines the expected product when it weathers. Minerals in rock exhibit specific texture and colour, which can be identified from their optical properties. The rock's mineralogy dictates the resultant soil mineral contents and colour, this in turn influences the soil's productive capacity.

Apparent electrical conductivity (EC_a) serves as an alternative for dense sampling and offers a way to reduce the cost, coupled with a good correlation with soil variables (Costa *et al.* 2014). Soil electrical conductivity is useful in assessing soil mineralogy, soil texture, nutrients, temperature, field holding capacity, chemical properties, and soil moisture; these variables play a vital role in plant development. The flow of electrical charges through a material enables the conduction of charged particles; soil also displays electrical properties based on its physical and chemical properties such as texture, and water content (Samouëlian *et al.*, 2005). Field measurement of soil apparent electrical conductivity (EC_a) is a simple and inexpensive method and can be correlated with the other soil properties such as soil texture, cation exchange capacity, drainage conditions, organic matter level, salinity, water holding capacity, temperature and elevation (Grisso *et al.*, 2009; Siqueira *et. al.*, 2014; Mertzanides *et al.*, 2020; Fagbemigun *et al.*, 2021). Swileam *et al.* (2019) studied the spatial inhomogeneity of soil properties using electrical resistivity approach, the variabilities observed in resistivity study were correlated with moisture and bulk density; soil of low resistivity was noted with high soil moisture and bulk density, it was expressed with curvilinear models. They opined that the study could be used for soil irrigation and salinity management. Negative relationship occurred between moisture content and electrical resistivity, and aids in delimiting the spatial variability of the moisture content being extrapolated from the resistivity distribution (Mertzanides *et al.*, 2020). Electrical resistivity has been found useful in monitoring of herbicide contamination in soil as a bioremediation device capable of evaluating its varying concentration (Balwant *et al.* 2021). Mohammed *et al.* (2022) carried out a study on a natural agricultural oasis of Al-Ahsa region in Saudi Arabia using electrical resistivity tomography and electromagnetic induction. The techniques classified the hydrogeological conditions being influenced by soil textural and moisture content variations. Areas with soil degradation requiring attentions were delineated and this affirms the use of electrical method as a viable tool in agricultural soil administration. Electrical resistivity technique (VES and 2-D) is effective in characterizing the soil horizons and depicting structural inhomogeneity, the findings of Ganiyu *et al.* (2019) revealed the soil horizon and suitable crop that could be grown on soil as delineated by the physical parameters. Thereby, enhancing its soil management capability in agricultural discipline.

Electrical conductivity (EC) has been reported by USDA (2011) to be a functional tool in assessing soil productivity, such that high EC value has been linked with high concentrations of P, K, Ca, Mg, Mn, Zn, and Cu and nitrate. Africa's rainfall pattern is torrential which is responsible for the leaching of soil nutrients beyond the root zone and blanket use of fertilizer may be injurious to plants (Adewole and Adeoye, 2014). The clay minerals play a vital role in their ability to adsorb cations onto their surfaces and determine the quantity of cation exchange capacity sites. Exchangeable cations are electrostatically bound or attached to the clay surface, although few anions are in a diffuse layer due to electrostatic repulsion (Al-Ani and Sarapää, 2008).

The inception of this study was prompted by meticulous field observations conducted on cacao trees cultivated concurrently within the same parcel of land in year 2000. Evident disparities in cocoa pod development rates among these trees spurred a quest for deeper insights into the underlying factors driving such variations in soil productivity. This observational imperative underscores the need for an in-depth exploration of the physical determinants shaping these differences.

In this pursuit, we draw inspiration from the burgeoning field of agrogeophysics, which serves as a conduit for interconnecting diverse interdisciplinary tenets aimed at tackling challenges inherent to agricultural soil dynamics. Recognizing the potential of physical properties, we have integrated them into comprehensive agroecosystem assessments, perceiving them as enduring tools for assessing the mutable nature of soil nutrient content.

The crux of our study revolves around the pivotal role of spatial apparent electrical conductivity as a predictive gauge for soil properties. This foundational insight empowers us to venture into new realms, where the relationship between electrical conductivity and soil permeability is elucidated, unraveling how the latter inherently impacts productivity dynamics. Furthermore, we embarking on an effort to identify rock types, deciphering soil mineralogy, and conducting chemical assessments. This holistic undertaking is designed to affirm the credibility and utility of physical properties as a robust alternative avenue for soil analysis.

As we delve into the depths of this investigation, our ultimate goal is to leverage the conclusions drawn from our study to guide future practices. The implications extend to actionable recommendations that can shape agricultural approaches, enhance productivity, and inform decision-making processes. These include adopting spatial apparent electrical conductivity as a strategic tool in predictive soil assessment, optimizing the correlation between electrical conductivity and permeability for enhanced productivity outcomes, and validating the reliability of physical property assessments through comprehensive chemical and mineralogical analyses.

2. Material and Methods

2.1 General Features of the Field Study

The area spans 99 meters by 78 meters and falls within the geographical coordinates of Latitudes 7°13′15.9″N to 7°13′19.6″N and Longitudes 3°51′40.1″E to 3°51′43″E. The study area's location rests upon a migmatite complex within Ibadan, encompassing the Cocoa Research Institute of Nigeria (Fig. 1). The rock samples were obtained from outcrops around the farm and they were situated between Latitudes 7°13′10.2″N and 7°14′04.6″N, and Longitudes 3°51′34.8″E and 3°51′55.6″E.

2.2 Rock Analysis

The thin sectioning of the rock samples into slides was carried out in the Department of Earth Sciences at Ajayi Crowther University Oyo, using Hillquist thin section machine, and the petrographic studies were conducted via Brunel petrographic microscope. The rock samples were prepared into thin section via the approach stated below:

1. The rock samples obtained were prepared into small sizes of about 8 mm thick.
2. One of its surfaces was polished using 400-grade carborundum on the glass plate.
3. The polished surface mounted on the glass slide using Araldite epoxy resin.

4. The mounted slide set for 30 minutes and the chip cut into a size of 90 microns.
5. The sample surface was ground using four grades (90, 400, 600, and 800) of carborundum until it reached 30-micron size.
6. Excess Araldite removed and the slide was covered using Araldite epoxy resin on the hot plate.
7. The mineral properties through the cross and plane polarised light were examined; and modal analysis for the relative mineral composition.

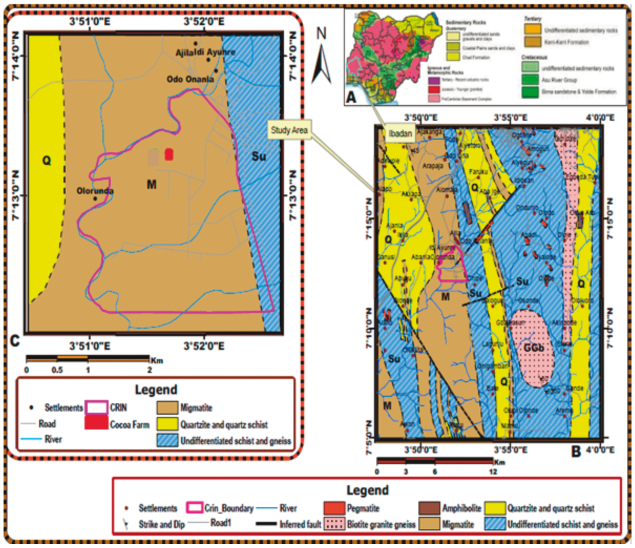

Figure 1. Geological map of the research vicinity (NGSA, 2009).

2.3 Electrical Resistivity Procedure

The basic principle of electrical resistivity involves the measurement of the resistance (R) of a conductor which opposes the flow of electric current when a voltage is applied across the two ends and its unit is Ohm (Ω). Resistance is the ratio of the potential difference (V) to the resulting current flow (I) as defined by Ohm's Law (Equation 1):

$$V = IR \quad (1)$$

The apparent electrical resistivity (ρ_a) is the multiplication of the resistance (R) with the geometric factor (k). The 'K' for the Wenner array is 2Πa, where 'a' is the spacing between adjacent electrodes. The apparent electrical resistivity (ρ_a) was converted into apparent electrical conductivity (σ_a) using the inverse relationship between them as noted in Equation 2.

$$\sigma_a = \frac{1}{\rho_a} \quad (2)$$

The apparent electrical conductivity was used in generating the conductivity maps of the farm.

The study was carried out during the wet (August 2016) and dry (March 2017) seasons; the electrodes were fixed on a wooden frame to facilitate the same penetration depth and inter-electrode spacing was 40 cm (Fig. 2). The effective depth of investigation is approximately 31 cm (Edwards, 1977) which is situated within the root zone. The resistivity measurements were taken at every 3 m along a profile (99 m long) and inter-profile spacing of 3 m was adopted for 27 profiles; 912 and 906 resistivity stations were investigated for soil variability during the wet and dry seasons, respectively. The EC_a data set which were regularly spaced on the field were input as CSV file (comma delimited). Interpolation of the data enables the prediction for all the points in the study area. The EC_a data were related to one another via kriging and the correlation function was used for interpolating the data as provided by the ArcGIS 10.2 program. The approaches have been reported and found useful in generating the apparent electrical conductivity maps (Oladunjoye, 2022; Olaojo and Oladunjoye, 2023). This revealed the spatial heterogeneity in the soil EC contrast on which further inferences could be determined.

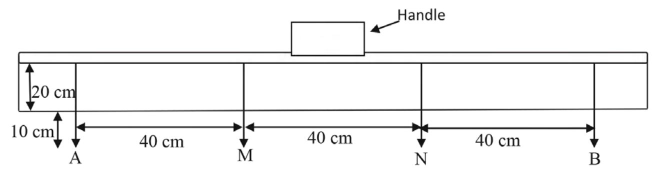

Figure 2. Fixed electrodes on a wooden frame

2.4 Procedure for the Modified Constant Head Permeability Techniques

Ten undisturbed soil samples were taken at the root zone (0.3 m) with the aid of a cylindrical metallic core barrel (diameter 7 cm and height 7 cm). They were saturated in water for 24 hours to ensure water rose through the capillary fringes. This analysis was conducted at the Department of Agronomy, the University of Ibadan using a modified Wageningen constant head permeameter. The pressure head difference was established by clamping an empty metallic core cutter tightly on top of the core with a soil sample and then filled with water. The water flows through the soil sample and is collected at the down end through outlet tubing onto a funnel seated on a beaker. The volume of water was quantified using a measuring cylinder while the time taken for the water to pass was measured with a stopwatch.

Darcy's law was used in ascertaining the hydraulic conductivity, parameters measured include; the volume of the water (Q) that flows through the soil column (cm^3), the cross-sectional area (A) of flow through the soil column (cm^2); time interval (t), length of soil (L) column (cm) and the hydraulic head difference (ΔH) in cm. Saturated hydraulic conductivity was determined using Equation 3 (Hillel 2004).

$$K_{sat} = QL/At\Delta H \quad (3)$$

2.5 Geochemical and Mineralogical Assessments of the Soils

2.5.1 Determination of Soil Chemistry

The field apparent electrical conductivity aided in demarcating the farm into different EC_a zones from which soil-sampling stations were selected. Geochemical analyses were conducted on twenty soil samples (low EC_a -9, moderate EC_a-5, and high EC_a-6 segments). The electrical conductivity and pH of soil samples were determined using the Hanna EC meter by weighing 10 grams of <75 µm soil particles into an extraction cup mixed with distilled water (10 ml). The spectrophotometry analysis was engaged for the determination of available phosphorus, the acidity in the soil was evaluated using titration method, the potassium and sodium were determined with a flame photometer (Jenway FP640) while calcium and magnesium via Atomic Absorption Spectrophotometer AAS (Buck scientific 210/211 model). The Cation Exchange Capacity (CEC) was computed from the addition of cations (Ca+Mg+Na+K) plus the acidity. All the analyses were executed at the Department of Agronomy, University of Ibadan.

2.5.2 Determination of Primary Mineral

X-Ray Diffraction (XRD) analysis was carried out on six soil samples via the Malvern PaNalytical empyrean XRD system at the College of Petroleum Engineering and Geosciences, King Fahd University of Petroleum and Minerals, Saudi Arabia. Two soil samples were chosen from each of the EC_a regions ((low EC_a -2, moderate EC_a-2, and high EC_a-2 segments) to ascertain the mineralogical composition. A fine fraction (< 45 µm) of soil was packed into a hollow-cavity sample mount and the quantitative XRD analysis is achieved employing a whole-pattern fitting method utilizing a measured and calculated XRD scan. Minerals identification was carried out by comparing calculated d-spacing with a library of standard d-spacing.

3. Results and Discussion

3.1 Geological Mapping of Basement Rock

The gneiss exhibited pronounced foliation, discernible through the alternating or banded arrangement of mafic (dark) and felsic (light) mineral constituents (Fig. 3a). Concordant with the host rock, the quartzo-feldspathic segregations exhibited striking patterns between 359^0 and 6^0 degrees, with a maximum length of 4 meters (Fig. 3b). The distribution of these segregations encompassed varying areas, spanning from 20 m² to 300 m². Additionally, these outcrops were characterized by a medium-grained texture. Primary mineral constituents comprised quartz, feldspar, and mica, with biotite-rich mica and muscovite predominating. Within this mineral composition, mafic components exhibited prominence over their felsic counterparts, rendering a gneissic appearance.

An understanding of the rock composition is vital in determining soil mineral constituents that would result from the weathering of the parent rock. This would serve as an indirect approach in evaluating the soil nutrient that would be available for plant uptake and ensure proper management of agricultural soil.

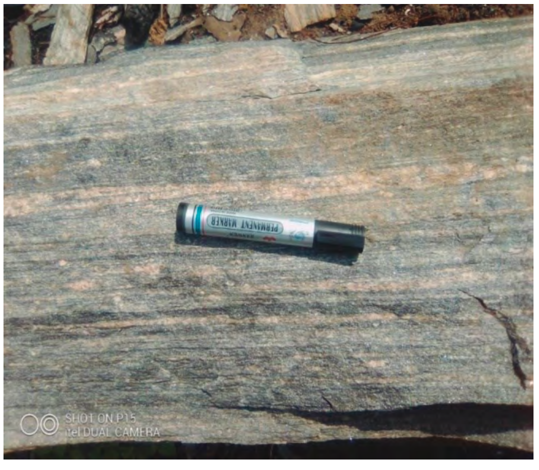

Figure 3a. Banding of mafic and felsic mineral components

Figure 3b. Outcrop intruded with quartzo-felspathic vein

3.2 Petrographic Investigations of Rocks

In the examination of thin-sectioned rock samples, a complex interlocking arrangement of minerals was revealed, encompassing feldspars (plagioclase, microcline, and orthoclase), mica (biotite and phlogopite), quartz, and the accessory mineral zircon. Cross and plane polarised light microscopy unveiled distinctive features, notably elongated quartz crystals exhibiting a preferred alignment alongside present biotite minerals (Figs. 4 and 5).

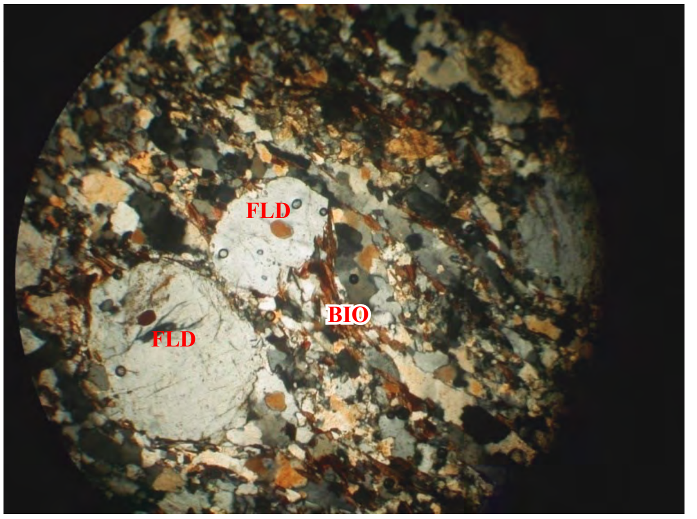

Figure 4. Photomicrograph showing the porphyroclast of feldspar grains in the matrix of biotite quart and medium grain feldspar minerals (cross polar) at location 1. Mag. x100.

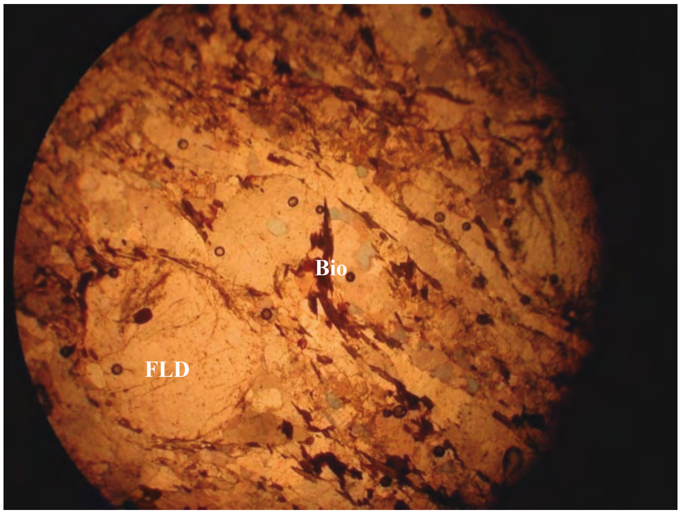

Figure 5. Photomicrograph showing the biotite (Bio), porphyroclast of feldspar (FLD) grains in the matrix of others minerals (plane polar) at location 1. Mag.x100.

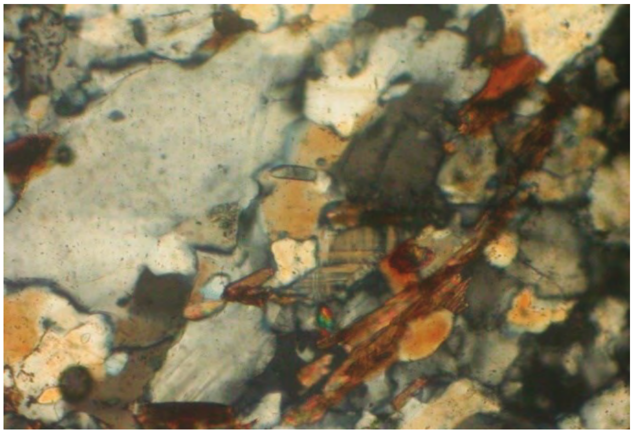

Figure 6. Photomicrograph showing zircon as an accessory mineral, biotite, quart and feldspar under cross polar at location 1. Mag. x100

Quantitative modal analysis provided insight into the mineral composition distribution at each location (Table 1). Through comparison with Egesi (2019), Ibrahim et al. (2015), and Parsons and Zwanzig (2003), the rock formations observed in the study location were classified as biotite granite gneisses. These rock constituents are destined to weather into soil under the influence of temperature and pressure differentials from their formation conditions.

The subsequent transformation of rock constituents into soil components was discussed, particularly the alteration of plagioclase, microcline, orthoclase, and biotite into kaolinite due to weathering. The varying susceptibilities to weathering were highlighted; plagioclase and biotite undergo more rapid weathering than microcline and orthoclase, with quartz demonstrating higher resistance (White et al., 2001; Wilson, 2004).

The mineralogical characteristics of the rock have profound implications for the potential clay content of the resultant soil after weathering. This composition significantly influences soil productivity, particularly in terms of adsorption and nutrient holding capacity. Kaolinite's distinctive attribute, its relatively lower Cation Exchange Capacity (CEC) compared to illite and montmorillonite, underscores its role (Sonon et al., 2014).

3.2 Electrical conductivity of Soil

The apparent electrical conductivity (ECa) data of the soil were subjected to statistical analysis, as presented in Table 2. The coefficient of variation (CV) was utilized to determine the variability of the ECa values. During both rainy and dry periods, moderate (61%) and high (64%) variability in ECa were observed, respectively, as highlighted by Warrick and Nielsen (1980). Molin and Faulin (2013) emphasized the significance of CV in identifying spatial variability, serving as an initial indicator. Consequently, ECa can be considered a valuable tool for evaluating soil quality and assessing the suitability of subsequent study sites. The measured ECa values were found to fall within the non-saline class according to USDA (2011), suggesting that crops would not face water stress.

Spatial distribution analysis of apparent electrical conductivity of soil was conducted using ArcGIS 10.2 software. The data points were interpolated using a correlation function known as kriging. The agricultural area was classified into distinct ECa zones: low ECa zone ranging from 0 to 49 µS/cm, moderate ECa zone ranging from 50 to 99 µS/cm and high ECa zone with a conductivity of 100 µS/cm and above. The most conductive regions (highlighted in red) were primarily concentrated in three areas: north/northeast, southwestern, and central portions of the map (Fig. 7). Moderate ECa zones (depicted in light brown) extended from high ECa areas and gradually transitioned into low ECa areas, notably in the southeastern, central, and northern parts of the map. Low ECa terrain (shown in blue) was prominently observed in the southeast, southern section, central, and northwest/north-northwest (NNW) regions of the map. Similar distribution patterns of electrical conductivity were observed during the dry season as well (Fig. 8).

Table 1. Modal analysis of analysed rock samples in the study area

Rock samples from the study area							**Previous works used for comparison**			
Mineral (%)	**L1**	**L2**	**L3**	**L4**						
	7°13'12.8" 3°51'55.6"	**7°13'10.2" 3°51'53.3"**	**7°13'54.5" 3°51'48.5"**	**7°14'04.6" 3°51'34.8"**	**Range**	**Average**	**Parsons and Zwanzig (2003) Composition of Granite Gneiss**	**Egesi (2019) Average Composition of Granite Gneiss**	**Ibrahim et al. 2015 Hornblende Granite Gneiss**	**Yusof & Zabidi (2016) Granitic Compositional Range**
Plagioclase	25.2	23.6	18.0	19.3	18.0-25.2	21.5	35	20	35	40.0-70.0
Microcline	28.1	27.0	21.3	20.8	20.8-28.1	24.3	21	30	-	
Orthoclase	3.4	4.0	-	-	3.4-4.0	3.7			-	
Quartz	23.3	23.7	26.0	27.5	23.3-27.5	25.1	24	27	30	5.0-30.0
Biotite	14.0	14.2	33.2	31.4	14.0-33.2	23.2	7	7	5	
Zircon	5.3	6.5	-	-	5.3-6.5	5.9	-	-	-	
Hornblende	-	-	-	-	-	-	0-24	6	15	20.0-40.0
Cummingtonite										
Muscovite	-	-	-	-	-	-	-	5	-	
Opaque Mineral	-	-	-	-	-	-	-	2	10	
Total	99.3	99.0	98.5	99.0						

L1-Location

Table 2. Statistical assessment of soil apparent electrical conductivity (EC_a) of cacao field

Season	**Number of points**	**Range (µS/cm)**	**Mean (µS/cm)**	**Standard Deviation**	**Coefficient of Variation (%)**
Wet	912	13-344	68	41	61
Dry	906	10-267	45	29	64

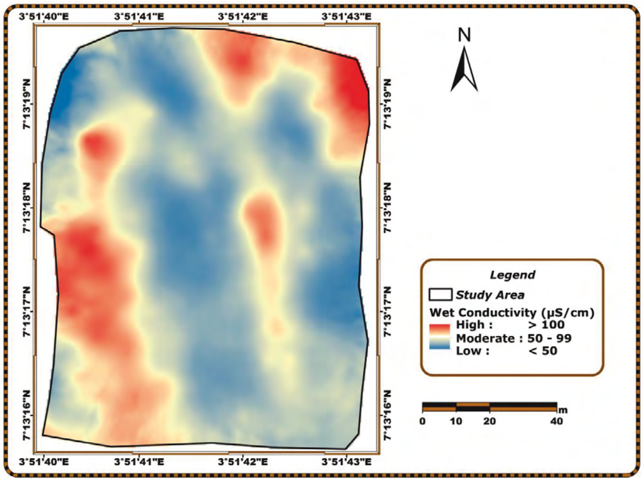

Figure 7. Apparent electrical conductivity distributions within the cacao field during wet season

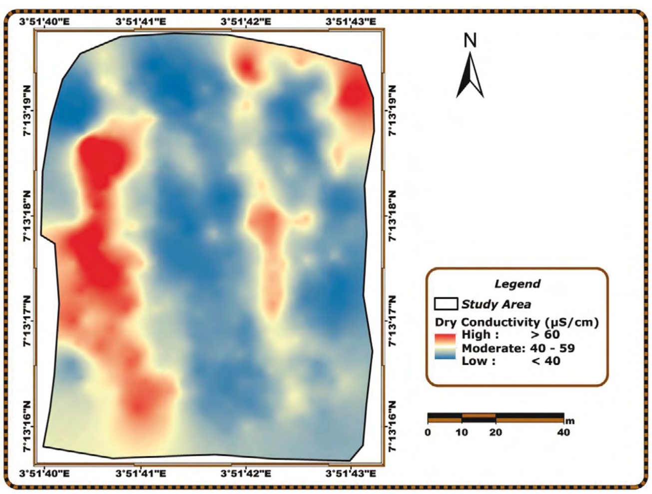

Figure 8. Apparent electrical conductivity distributions within the cacao field during dry season

However, numerical values were reduced in segments corresponding to high ECa (> 60 µS/cm), moderate EC_a (40-59 µS/cm), and low conductive sections (< 40 µS/cm) compared to the wet season. The noticeable difference between the two seasons was the distinct presence of low ECa segments during the dry season.

It can be inferred that zones with high EC_a usually have more fine soil fractions than those with low EC_a (Mzuku *et al.*, 2005; Rodríguez-Pérez *et al.*, 2011; Gholizadeh *et al.*, 2012; Fagbemigun *et al.*, 2021; Mohammed *et al.*, 2022), regions with low EC_a loses water faster than other regions resulting in variability of water content (Costa *et al.*, 2014; Swileam *et al.*, 2019) as the water drains through it.

3.3 Constant Head Permeability Assessment of Soils in the Cacao Farm

The constant head permeability test (Table 3) revealed varying permeability; low permeability ($5.56\text{x}10^{-5}$-$1.67\text{x}10^{-4}$ cm/sec) in high EC_a segment, moderate in the moderate EC_a (0.00128 cm/sec) whereas high permeability ($6.67\text{x}10^{-4}$-$2.86\text{x}10^{-3}$ cm/sec) in the low EC_a section.

Soils of high EC_a have low relative permeability classified as silty sand; sand/fine sand (medium relative permeability) in the moderate EC_a segment and low EC_a is sand/fine sand to silty sand with a low to medium range relative permeability (Terzaghi and Peck, 1967).

Soil Infiltration Rate in the Cacao Plot

Scherer *et al.* (2013) established the infiltration rate in the soil as the amount of water absorbed by the soil over a given time. The rate at which water moves through soil units in high EC_a ranged from moderately slow to slow whereas moderate infiltration in the region of moderate EC_a. Soil materials in the low EC_a segment indicate a moderate to moderately rapid infiltration rate (Table 4).

Table 3. Permeability (k) coefficients of some selected soil samples from cacao farm

S/N	Coordinates		EC_a of sample selection point	k_{sat} (cm/sec)	Wet Season	Dry Season
	Northing	Easting			EC_a (µS/cm)	EC_a (µS/cm)
1	7°13′18.5″N	3°51′40.6″E	High	$8.33\text{x}10^{-5}$	133	112
2	7°13′16.8″N	3°51′40.6″E	High	$8.33\text{x}10^{-5}$	159	89
3	7°13′16.2″N	3°51′41.1″E	High	$5.56\text{x}10^{-5}$	118	81
4	7°13′17.7″N	3°51′41.6″E	Low	$6.67\text{x}10^{-4}$	23	20
5	7°13′19.3″N	3°51′41.4″E	Low	$1.61\text{x}10^{-3}$	40	15
6	7°13′16.4″N	3°51′41.9″E	Low	$2.86\text{x}10^{-3}$	49	30
7	7°13′16.6″N	3°51′42.9″E	Medium	$1.28\text{x}10^{-3}$	51	36
8	7°13′17.8″N	3°51′42.3″E	High	$1.11\text{x}10^{-4}$	114	85
9	7°13′17.9″N	3°51′41.9″E	Low	$7.50\text{x}10^{-4}$	48	26
10	7°13′19.0″N	3°51′43.0″E	High	$1.67\text{x}10^{-4}$	136	103

Table 4. Classification of soil moisture infiltration rate (Modified after Scherer *et al.*, 2013)

S/N	Classification	Infiltration Rate (inches/hour)	Infiltration Rate (cm/s)
1	Very slow	less than 0.06	$< 4.233\text{x}10^{-5}$
2	Slow	0.06 to 0.2	$4.233\text{x}10^{-5}$ to $1.411\text{x}10^{-4}$
3	Moderately slow	0.2 to 0.6	$1.411\text{x}10^{-4}$ to $4.233\text{x}10^{-4}$
4	Moderate	0.6 to 2.0	$4.233\text{x}10^{-4}$ to $1.411\text{x}10^{-3}$
5	Moderately rapid	2.0 to 6.0	$1.411\text{x}10^{-3}$ to $4.233\text{x}10^{-3}$
6	Rapid	6.0 to 20.0	$4.233\text{x}10^{-3}$ to $1.411\text{x}10^{-2}$
7	Very rapid	greater than 20.0	$> 1.411\text{x}10^{-2}$

3.3.1 Correlation Analysis between Permeability (k) Coefficients and EC_a of the Soils

The plot of permeability coefficients with the EC_a (Fig. 9) showed that its determination coefficient is 0.460 in which 46.0% of the variables were related linearly and also exhibits a strong negative correlation coefficient (0.68) in the wet season. The degree of interaction revealed that 50.1 % of these variables have linear dependence as suggested by the determination coefficient while a negatively strong correlation (0.708) in the dry period (Fig. 10). Positive correlation exists between electrical resistivity and hydraulic conductivity (Fagbenro and Woma, 2013); this deduction also validates the negative correlation obtained from the plot as a result of an inverse relationship between electrical resistivity and conductivity. Kayode *et al.* (2022) engaged electrical resistivity in assessing soil inhomogeneity and the technique was reported to be efficient in characterizing the soil moisture and void distribution, thus useful in agricultural management programmes. Mary *et al.* (2020) monitored the root water uptake using electrical method via a controlled infiltration process. The permeability evaluations agreed clearly that soils of high EC_a are characterized by low permeability at both seasons and vice versa. It can be inferred that there is the presence of more fine particles in the high EC_a section than in the moderate and low EC_a segments. This promotes the adsorption of essential nutrients onto its surface due to its large surface area.

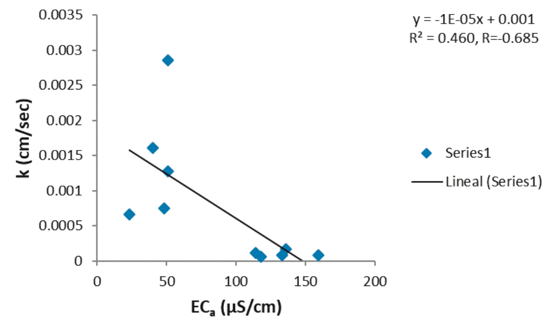

Figure 9. Plot of permeability (CHP) versus EC$_a$ in the cacao farm during the wet season

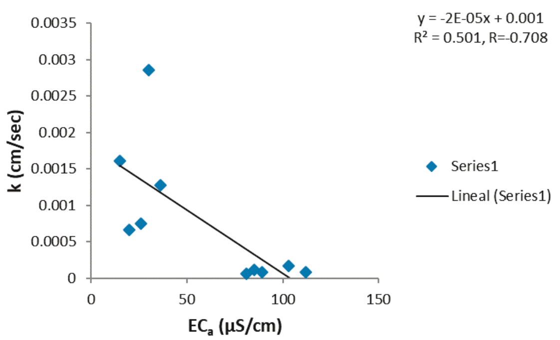

Figure 10. Plot of permeability (CHP) versus EC$_a$ in the cacao farm during the dry season

3.4 Soil Chemical Assessment

3.4.1 Assessment of Physical and Chemical Properties of Soil in the Farms

Soil pH: Overall pH values range from 6.1 to 7.1 with a mean concentration of 6.71, the average pH in the low EC$_a$ (6.1-6.8) horizon is 6.62; the moderate EC$_a$ section (pH: 6.6-6.8) has a mean value of 6.70 while the high EC$_a$ segment has the mean pH level (6.4-7.1) of 6.80. All the mean pH recorded falls in the neutral (6.6-7.3) category (Horneck *et al.*, 2011). The measured pH at all the zones is within the required concentration (6.0–7.5) which favours the availability of soil nutrients for most crops (Moral and Rebollo, 2017; Khadka *et al.*, 2018). The soil nutrients would be available for cacao consumption since pH values are close to either side of neutrality, not likely subjected to Al_{3+} toxicity which can limit root growth, restraining access to soil water and nutrient since the pH is considerably above 5.5 (FAO, 2008; Ribeiro *et al.,* 2013; Botta, 2015).

Soil EC: The mean soil electrical conductivity value (30-180 µS/cm) in the farm is 62 µSc/m. The low EC$_a$ section (30-70 µS/cm) has an average conductivity of 48 µS/cm, and those in the moderate class (30-80 µS/cm) have an average value of 54 µS/cm. The most conductive section (50-180 µS/cm) has the highest conductivity (90 µS/cm). There is the presence of more conductive ions in the high EC$_a$ region than in the other sections. EC values measured in soil samples were regarded as non-saline (Botta, 2015). The measured EC values were in a low category (<1.0 dS/cm) which is suitable for optimum plant growth, in essence, the cacao trees can uptake the soil solution without resulting in water stress (Horneck *et al.* 2011).

Available phosphorus: The average concentration of available phosphorus across all the investigated sections (6.0-12.71 mg/kg) is 8.89 mg/kg. Region of low EC$_a$ has the highest mean concentration of available P (9.52 mg/kg) and its concentration is between 8.32 mg/kg and 12.71 mg/kg. Its mean proportion in the moderate EC$_a$ areas (7.32-10.51 mg/kg) is 8.32 mg/kg. The least mean concentration (8.23 mg/kg) was noticed in the high EC$_a$ region (6.0-10.51 mg/kg). The mean concentration of available P (8.89 mg/kg) across the whole farm was below the critical limit (12 mg/kg) needed to maximize crop productivity (Horneck *et al*., 2011; van Vliet *et al*., 2015), and classified as low category (<20).

Acidity of soil: The average acidic cation across the farm (0.64-1.20 cmol/kg) is 0.82 cmol/kg. Zone of low EC$_a$ (0.64-0.96 cmol/kg) had a mean concentration of 0.78 cmol/kg, moderate EC$_a$ segment (0.64-1.04 cmol/kg) had a common concentration of 0.85 cmol/kg. Its concentration in high EC$_a$ portion stretched from 0.64 to 1.20 cmol/kg with an equal strength of 0.87 cmol/kg.

Soil acidification in the high EC$_a$ was ranked highest due to the preferential consumption of base cations by cacao trees and organic acid being derived from the decomposition of litter (Watanabe *et al*., 2015). It is not a useful nutrient for plant survival but it could be toxic to plants if the pH is below 5.5 (Botta, 2015). The pH values across the soils were within the neutral level (Horneck *et al*., 2011), therefore acidic cation content is not harmful to the growth of the cacao plant.

Soil Calcium Content: The average concentration of Ca (0.46-3.72 cmol/kg) across the entire field was 1.29 cmol/kg. Its mean distribution in the low EC$_a$ (0.46-1.28 cmol/kg) was 0.93 cmol/kg, the moderate EC$_a$ zone (0.77-1.34 cmol/kg) had 1.02 cmol/kg while its specific proportion in the high EC$_a$ segment (1.27-3.72 cmol/kg) was 2.05 cmol/kg.

There is no significant difference in the concentration of Ca in the low EC$_a$ (0.93 cmol/kg) and moderate EC$_a$ (1.02 cmol/kg) sections but twice their values were noted in the high EC$_a$ segment (2.05 cmol/kg). These mean values fall within the low category (<5.0) class (Proffitt, 2014). Botta (2015) and White and Broadley (2003) reported that the deficiency of Ca is not a common phenomenon but its excessive can restrict adequate growth. Its deficiency is noted in soils having low base saturation and high acidic content (White and Broadley, 2003; Horneck *et al*., 2011).

Magnesium Content: Magnesium concentration on the average was 0.76 cmol/kg in the low EC$_a$ (0.25-1.97 cmol/kg), mean distribution in the moderate EC$_a$ zone (0.37-1.38 cmol/kg) was 0.94 cmol/kg while the most electrically conductive zone (0.58-2.65 cmol/kg.) has its mean concentration to be 1.37 cmol/kg. The average concentration computed from the entire cacao soils (0.25-2.65 cmol/kg) was 0.99 cmol/kg. The mean proportion of Mg in low EC$_a$ and moderate EC$_a$ regions was within the low class (<1.0 cmol/kg); the moderate category (1-5 cmol/kg) was noted in the high EC$_a$ (Proffitt, 2014) which is approximately twice and one-half the contents in the low EC$_a$ and the moderate EC$_a$ sections. Thus, the quantity of Mg content in the high EC$_a$ region plays a greater role in photosynthesis because it was an essential element for chlorophyll pigment (Botta, 2015).

Potassium Content: Potassium content in all soil samples ranged from 0.14 cmol/kg to 0.44 cmol/kg indicating that its distribution was categorized between low (<0.4 cmol/kg) and medium (0.4-0.6 cmol/kg). Its mean value is 0.27 cmol/kg was classified to be low by Horneck *et al.* (2011). Region of low EC$_a$ has its specific potassium concentration (0.14-0.44 cmol/kg) to be 0.28 cmol/kg in the low category. Similar mean concentrations were observed in the moderate and high EC$_a$ sections to be 0.24 cmol/kg and 0.30 cmol/kg respectively classified as low. The quantity of potassium available in high EC$_a$ for plant consumption was greater than those from other regions. Thus aiding a better regulation of nutrient uptake, water, flowering, and seed-bearing, and ensuring resistance to stress (Wodaje and Abebaw, 2014; Botta, 2015) invariably contributing to the productivity in that section.

Sodium Content: The mean proportion of exchangeable sodium was 0.24 cmol/kg in the low EC$_a$ segment (0.2-0.27 cmol/kg). In soils of moderate EC$_a$, its mean concentration (0.21-0.34 cmol/kg) was 0.25 cmol/kg. The mean fraction in the highly conductive segment (0.23-0.30 cmol/kg) was 0.27 cmol/kg. These mean concentrations were classified as low (<0.3 cmol/kg) at all the EC$_a$ segments (Proffitt, 2014). The mean concentration computed in the entire farm was 0.25 cmol/kg. Sodium is not considered an essential soil nutrient for plants (Horneck *et al*., 2011; Botta, 2015). The high EC$_a$ section has the highest sodium content contributing to the cacao productivity than the other two segments.

Cation Exchangeable Capacity (CEC) of soils: The ability of the soil to adsorb cations onto its surface is regarded as CEC. The mean cation exchangeable capacity (CEC) in the low EC$_a$ (1.92-4.53 cmol/kg) was 2.99 cmol/kg. In the moderate EC$_a$ region, it varied from 2.45 to 4.13 cmol/kg with an average capacity of 3.30 cmol/kg and in the high EC$_a$ section (2.94-8.28 cmol/kg) has a representative value of 4.85 cmol/kg. The CEC in the low

EC_a segment was classified as low (<3.0 cmol/kg) while the mean capacity in the moderate and high EC_a sections was considered as moderate (3.0-10.0 cmol/kg) by Proffitt (2014). The clay type deduced from the mean CEC falls within the kaolinite (3.0-15.0 cmol/kg) class (Sonon *et al*., 2014). The high EC_a region has a presence of more cations being held by the soil against leaching and retains more soil nutrients indicating higher fertility status than low CEC soils (Arévalo-Gardini *et al*., 2015).

Percentage Base Saturation: This is the percentage proportion of basic cations in overall CEC. An increase in base saturation suggests that the soil cations are becoming more available in soil. The percentage concentration of base cation in the soils of low EC_a ranged from 57.52 to 82.34% with a mean saturation of 71.80%. The section of moderate EC_a (64.08-82.04%) has a mean saturation percent of 73.34% while the high EC_a (78.23-85.51%) was ranked with the highest mean saturation (81.38%). High percentage base saturation signifies more fertile soil with little or no acidic cation that will hinder crop growth, buffered against acidic cation and a greater amount of basic cation for plant consumption (Sonon *et al*., 2014).

Ca:Mg Dispersion: When the concentration of Mg is relatively high compared to the Ca, it would result in sealing the soil surface, thereby creating water run-off instead of infiltration. The ratio of Ca:Mg in the low EC_a region stretched from 0.6 to 2.6 with an average ratio of 1.5. Its mean ratio was 1.2 in the moderate EC_a zone (0.9 to 2.1), whereas the mean dispersion ratio in the high EC_a section (0.8 to 2.7) was 1.7. Soils in this farm have Ca:Mg ratios to be less than 2 indicating that the soils are not well structured (Botta, 2015). The closest ratio to this value was 1.7 in the high EC_a soil suggesting that it is fairly structured than other segments. High Mg concentration can have a negative effect on soil physical properties thereby sealing the soil surface leading to infiltration decrease, and promoting run-off leading to erosion during rainfall (Dontsova and Norton, 2001). Mg has greater hydration energy than Ca, resulting in a larger hydration radius/shell which in turn causes a higher distance of separation between clay layers with less surface attraction making it flocculate (Dontsova and Norton, 2001). Mg-dominated soils have a greater proportion of exchangeable Na accumulating on their surface than Ca-dominated soils (He *et al*., 2013).

Exchangeable Sodium Percentage (ESP): Soils in the region of low EC_a (4.99-11.17%) have a mean ESP to be 8.36%. Zone of moderate EC_a has ESP in soils varying from 5.57% to 8.60% with an equitable percentage of 7.71%. The ESP in the soils of high EC_a ranged from 3.26% to 7.82% and its average percentage was 5.99%. The low EC_a and moderate EC_a areas were classified as marginally sodic (>6%) and their aggregate is susceptible to dispersion when wet (Proffitt, 2014; Botta, 2015), therefore they tend to have poor drainage, aeration, and susceptible to erosion. Soils in the high EC_a portion are categorized as non-sodic (<6%), they are generally stable, have good aeration, and drainage and are not vulnerable to erosion.

3.4.2 Soil Nutrients Influencing the Measured Field Electrical Conductivity in the Soils

A positive correlation (R) exists between the field EC_a data and laboratory-determined EC (Figs. 11 and 12), having coefficients of 0.8 and 0.7 in the wet and dry seasons respectively. The coefficient of determination (R_2) shows that 60.5% and 42.4% of the data were involved in the correlation during the wet and dry seasons respectively. Thus, it validates the effectiveness of the field EC_a data as a useful proxy for assessing soil productivity.

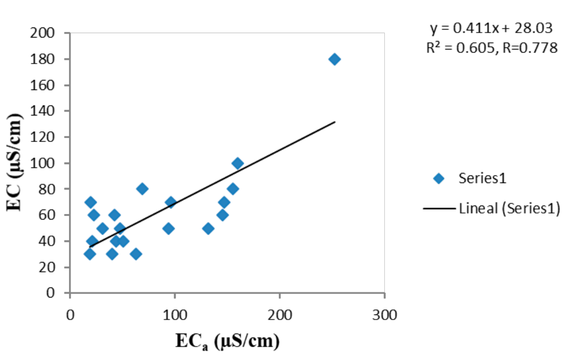

Figure 11. Relationship between field EC_a and laboratory EC in the soils of cacao farm during the wet season

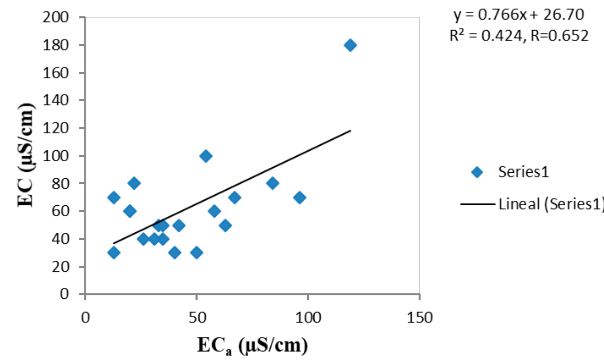

Figure 12. Relationship between field EC_a and laboratory EC in the soils of cacao farm during the dry season

The field EC_a was influenced strongly by Mg, Ca; weakly influenced by acidic cation; very weak influenced by Na, K, and an inverse relationship with available P (Figs. 13 and 14).

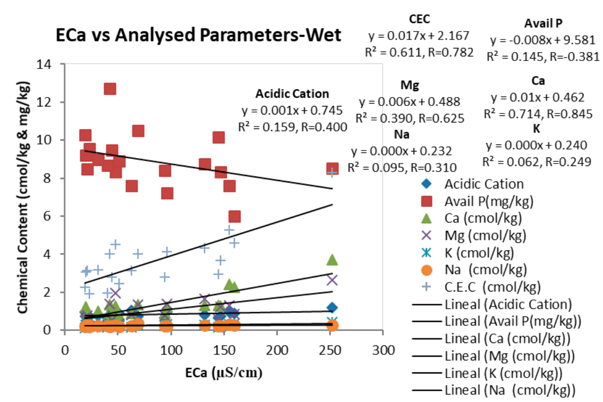

Figure 13. Chemical constituents influencing the measured field ECa during wet season

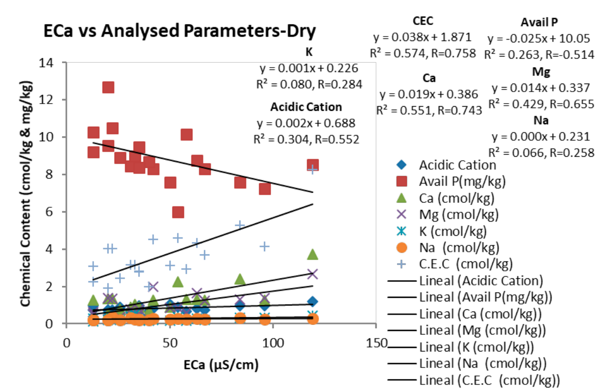

Figure 14. Chemical constituents influencing the measured field ECa during dry season

A negative correlation was observed from the interaction of available phosphorus with EC_a, indicating that is not contributing to the measured EC_a, though moderate coefficients were generated in the wet (-0.4) and dry (-0.5) seasons (Figs. 13 and 14). Kim *et al*. (2007) observed that the concentration of phosphorus increases under anaerobic conditions and for a direct relationship to occur between phosphorus concentration and EC, denitrification must take place in advance before the release of phosphorus.

Positive interaction was observed between the acidic cation and EC_a with moderate coefficients of 0.4 and 0.6 in the wet and dry periods respectively (Figs. 13 and 14). The presence of acidic cations aids the conductivity of the media but the percentage of the cation involved in the interaction is between

15.9% and 30.4%. Soil acidity tends to build up hydrogen and aluminium cations in soil when the base cations are leached and replaced by aluminium or hydrogen ions (FAO & ITPS, 2015) but pH in the farm is within the tolerance range for plant growth.

A strong positive relationship was noticed between calcium and EC_a in the wet and dry seasons with the coefficient of 0.9 and 0.7 respectively (Figs. 13 and 14). 71.4% and 55.1% of the data were perfectly engaged in the correlation in which there was a great chunk of the ions participating in the fluid conductivity (Peralta and Costa, 2013; Heil and Schmidhalter, 2017; Medeiros *et al*., 2018). This suggests that Ca is one of the dominant divalent ions in soil solution as a result of its large hydrated radius responsible for its easy dislodge from soil charges-CEC (Gransee and Führs, 2013).

Positive coefficients (0.6-0.7) were generated from the interaction (Figs. 13 and 14) between Mg and EC_a (Korsaeth, 2005; Rodríguez-Pérez *et al.,* 2011). The group II metals are characterised by S-P hybridisation in which the S and P electron shells overlap, thus availing the metal access to the unfilled P-subshell and finally aiding its electrical conductivity (Garcia and Damask, 1991). Magnesium has a smaller ionic radius compared to Ca, K and Na, and its hydrated radius is larger, this made magnesium to be less strongly bounded to soil charges which were responsible for higher magnesium concentration in soil solution with increasing mobility and the mobility leads to electrical conductivity (Gransee and Führs, 2013).

A weak positive correlation was established from the interaction of potassium ions with the EC_a, resultant coefficients of 0.3 were generated from the interaction at both seasons (Figs. 13 and 14). This indicates that it has less influence on the conductivity of the medium as deduced from the percentage (6.2-8.0%) of data involved in the interaction. Its strong adsorption onto clay surface was due to a decrease in hydrated radius compared to other cations ($<Na^+<Ca^{2+}<Mg^{2+}<Al^{3+}$), thereby reducing its mobility (Gransee and Führs, 2013; Olson-Rutz and Jones, 2018).

The contribution of Na_+ ions to the conductivity of soil unit was regarded as weak; its coefficient was 0.3 in both seasons (Figs. 13 and 14). 6.6% to 9.5% of the data fit perfectly, thus its influence on the conductivity of soil solution is less. UNSW (2007) reported that cations with small hydrated radii are strongly adsorbed onto clay surfaces because adsorption strength increases with decreasing the hydrated radius of the cation.

Correlating the CEC with the EC_a (Figs 13 and 14), a strong positive relationship was deduced with resultant coefficients of 0.8 at both seasons (Korsaeth 2005; Peralta and Costa 2013). Data interaction showed a good matched (57.4%-61.1%), suggesting a greater influence on the measured EC_a.

3.5 Soil X-Ray Diffraction (XRD) Assessment

XRD analysis reveals the prevailing clay mineral to be kaolinite and the occurrence of montmorillonite and nontronite as a trace. Non-clay minerals include quartz, microcline, albite, muscovite, biotite, oligoclase, corderite, and coquimbite.

3.5.1 Mineralogical Composition of Fine Fraction in the Cacao Soils

Kaolinite (4.7-11.3%) is the dominant clay mineral in the low EC_a section (Figs 15 and 16) with an equitable 8.0% occurring as subordinate whereas montmorillonite (0-0.1%) occurred as trace (Okunlola and Owoyemi, 2015). The mean quantity of quartz (61.1-67.2%) was 64.2% (dominant). Microcline content (14.2-24.6%) has a mean of 19.4% (subordinate). Other minerals include muscovite (2.9%-5.7%), corderite (0.4%-1.2%) and oligoclase (1.3%-5.4%).

Region of moderate EC_a (Figs 17 and 18) has 21.7% as the prevailing kaolinite content (14.9-28.4%) occurring as subordinate whereas nontronite (0-7.1%) occurred as the trace clay mineral. Quartz (49.2-51.2%) is the dominant mineral with a mean of 50.2%, while microcline fraction (15.3-16.1%) has an average of 15.7% (subordinate). Other minerals include corderite (0-9.3%), albite (0.4%-1.5%) and biotite (1.0%-4.0%).

The high EC_a section (Figs 19 and 20) has kaolinite (23.9-38.3%) as the abundant clay mineral with an average quantity of 31.1%, and montmorillonite (0-4.5%) occurred as a trace. Quartz (30.5-52.7%) has a mean percentage of 41.3% signifying an abundant fraction. Microcline (9.8-20.3%) has a common percentage of 15.1 (subordinate). Corderite and muscovite proportions varied from 0.5% to 6.4% and 0% to 10.1% respectively. Percentage contributions from oligoclase (0.4%), albite (1.7%) and biotite (1.0%) are regarded as trace in quantity.

Analysis of average mineral distributions showed that the quantity of quartz decreases from the region of low EC_a (64.2%) through the moderate EC_a (50.2%) section down to the high ECa segment (41.3%). The quantity of microcline is highest (19.4%) in the low EC_a section, intermediate (15.7%) in the moderate EC_a region, and low (15.1%) in the high EC_a. The quantity of kaolinite increases from the low EC_a area to the high EC_a segment; the kaolinite was 8% (low EC_a segment), 21.7% (moderate EC_a) and both contents are in the subordinate class (5-25%) whereas highest percentage of kaolinite (31.1%) was noted to be in abundant quantity (25-50%) in the high EC_a zone.

The ratio of kaolinite across the moderate EC_a and high EC_a sections was approximately three and four times respectively compared to the low EC_a segment. The average quartz content in the low EC_a region approximately doubles the fraction in the high EC_a area. Grisso *et al.* (2009) reported that the EC of sand is low and sand constitutes 85% of quartz. The quartz particles are good insulator of electric current (negligible conductivity of 58 nS/m by Manoucheri, 2002) and it dominates sand and silt fractions whereas clay fraction transmits current because of their clay mineral and organic matter (Allred *et al*., 2008). In furtherance to this, the EC of silt was regarded as a medium while that of the clay was high (Grisso *et al.,* 2009); kaolinite has its electrical conductivity to be 0.2 S/m (Kibria and Hossain, 2019).

The conclusion reached by Revil and Glover (1998) was that the surface conductance of clay is about four higher than that of quartz; clay has a large surface area with porous pores than the sandier material and soil having high clay content has higher EC reading (Hawkins *et al.,* 2017). The fraction with the greatest surface area controls the behaviour and performance (properties) of soil. Soil characterised with a high proportion of quartz will hold fewer soil nutrients compared to that with much more clay content. This accounted for the variation across the three segments, even when the segments were supplied with the same amount of water, the concentration of dissolved nutrients will vary, thereby impacting different plant productivity rates.

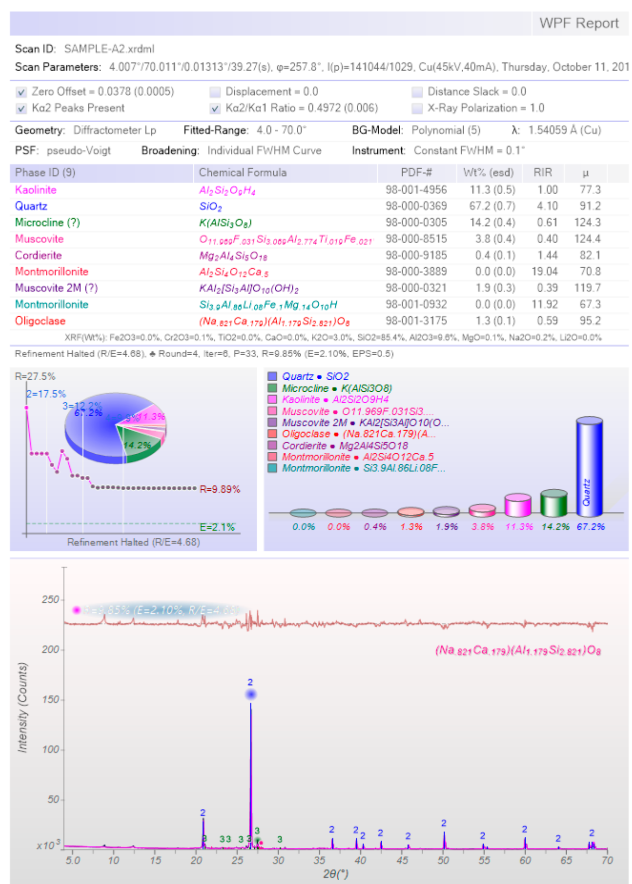

Figure 15. X-ray diffraction result of soil-fine fraction in the low EC_a region of cacao plot (Sample A2)

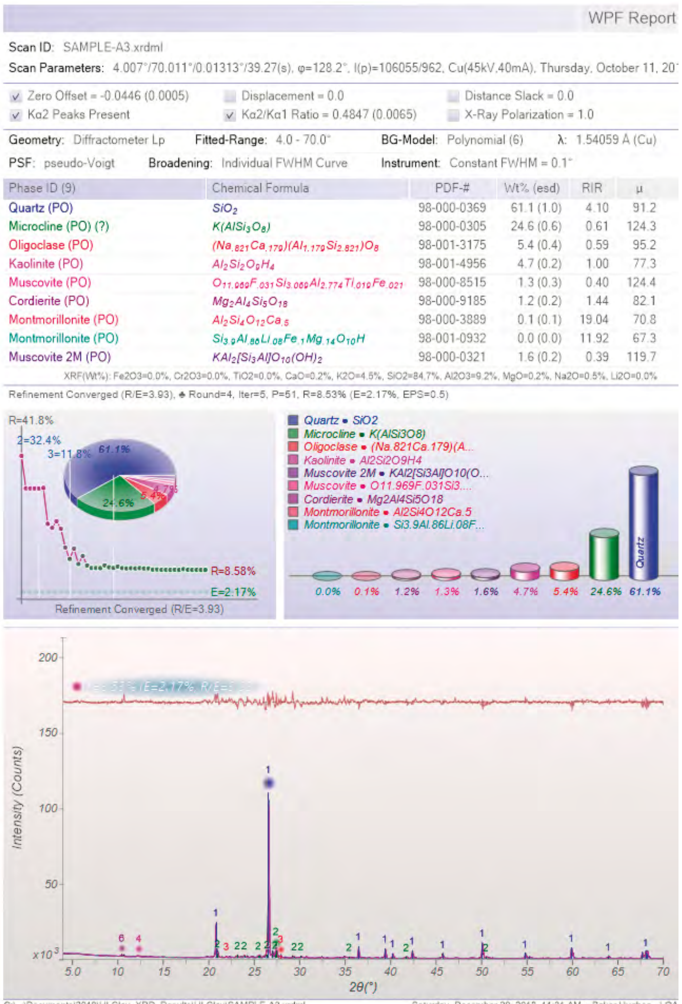

Figure 16. X-ray diffraction result of soil-fine fraction in the low EC$_a$ region of cacao plot (Sample A3)

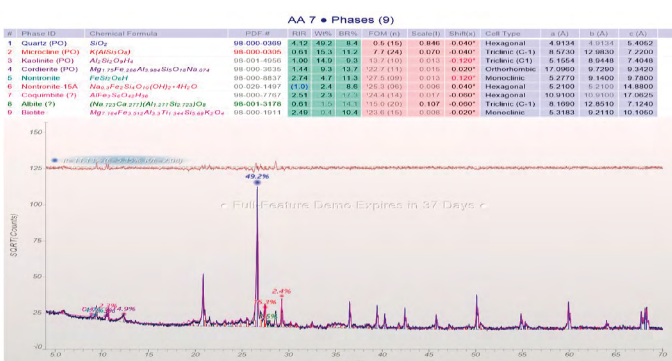

Figure 17. X-ray diffraction result of soil-fine fraction in the moderate EC$_a$ region of cacao plot (Sample AA7)

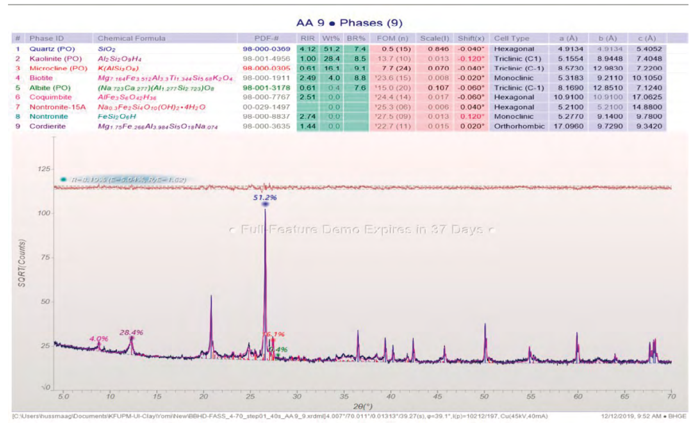

Figure 18. X-ray diffraction result of soil-fine fraction in the moderate EC$_a$ region of cacao plot (Sample AA9)

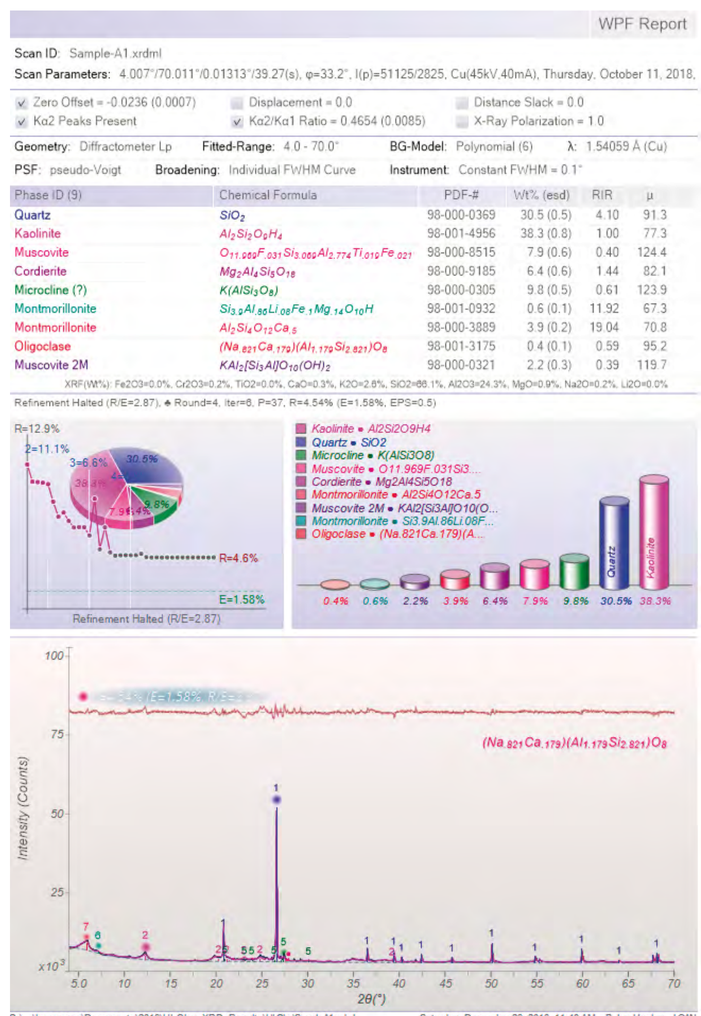

Figure 19. X-ray diffraction result of soil-fine fraction in the high EC$_a$ region of cacao plot (Sample A1)

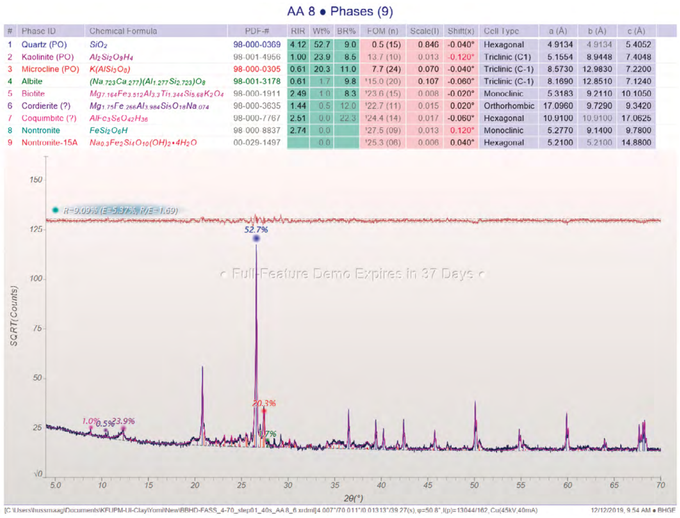

Figure 20. X-ray diffraction result of soil-fine fraction in the high EC_a region of cacao plot (Sample AA8)

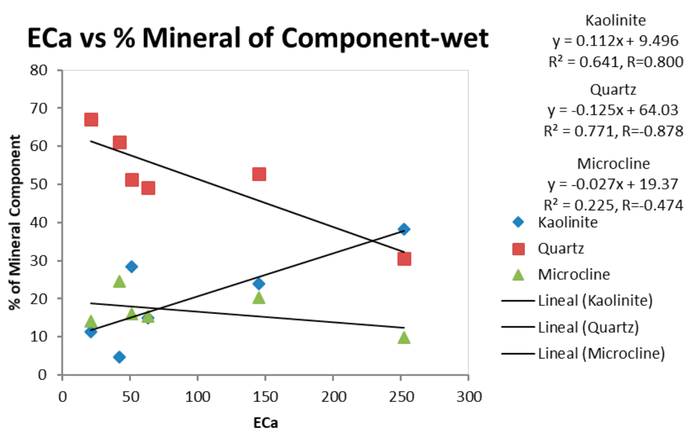

Figure 21. Relationship between ECa and mineral components during wet season

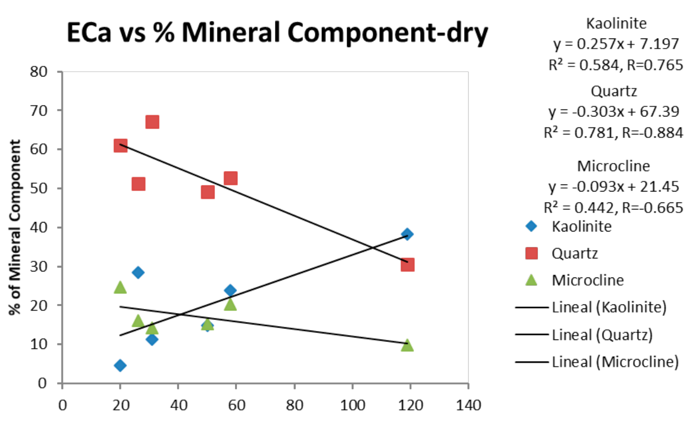

Figure 22. Relationship between ECa and mineral components during dry season

The relationship between apparent electrical conductivity and the dominant minerals (Figs. 21 and 22) showed that there is strong positive interaction with the kaolinite (0.765-0.800) whereas negative interactions with the quartz (0.878-0.884) and microcline (0.474-0.665) during wet and dry seasons. This suggests that the EC_a is being influenced by the kaolinite; high ECa values denote a large quantity of kaolinite and better nutrient retention. Thus, it is possible to infer that soil derived from biotite granite gneiss with EC_a of 100 µS/cm and above is adequate for effective growth of cacao plant.

Conclusion

The petrographic analysis unveiled the mineral constituents present in the rock, including the clay mineral that would form upon weathering, such as kaolinite. This observation aligns with the outcomes derived from the XRD analysis. The composition of minerals within the rock significantly influences the subsequent soil formation resulting from the disintegration of the crystalline rock. This connection can be utilized for evaluating soil productivity.

The EC_a map (Figs. 10 and 11) has proven instrumental in characterizing field conditions during both wet and dry seasons. EC_a serves as an indirect method for assessing soil nutrients and water content. Notably, the soils were determined to be non-saline. Regions marked by high EC_a values exhibit elevated levels of dissolved solutes, a notable concentration of clay, enhanced water retention, and valuable insights into soil permeability variation.

The EC_a map facilitates the grouping of areas characterized by similar soil properties, which is valuable for guiding further soil sampling and examination efforts. The mapping of soil EC_a provides valuable information about changes in soil conditions and highlights areas warranting heightened attention.

Soil pH significantly impacts the availability of essential nutrients for plant uptake. Notably, regions with high EC_a values show elevated concentrations of Ca, Mg, K, Na, and CEC values. Additionally, available P distribution is relatively uniform across the three regions. Regions with high EC_a values indicate a higher level of base saturation and non-sodic soil conditions. This favors nutrient retention, effective aeration, and drainage. On the other hand, low and moderate EC_a regions tend to be sodic, leading to nutrient leaching and heightened erosion susceptibility.

A notable agreement exists between the clay type determined via CEC analysis and the clay mineralogy revealed by XRD analysis (kaolinite). Soil enrichment is intricately linked to its mineral composition. Dominant minerals such as kaolinite, microcline, and quartz significantly influence soil characteristics. Regions with substantial quantities of kaolinite clay and lower quartz and microcline content exhibit a pronounced ability to retain soil moisture and nutrients. Consequently, these conditions lead to healthy plant growth and notably enhanced pod production, as observed in the high EC_a regions.

The essence of geospatial analysis of EC_a is to streamline and demarcate area(s) with utmost attention. This would reduce the cost of soil sampling and analyzing the entire farm for geochemical evaluation, thus enabling effective management of agricultural soil.

References

Adewole, M. B., & Adeoye, G. O. (2014). Assessment of soil properties and crop yield under agroforestry in the traditional farming system. *African Journal of Agricultural Research,* 9(27), 2119-2123.

Al-Ani, T., & Sarapää, O. (2008). *Clay and clay mineralogy: physical–chemical properties and industrial uses*. Geological Survey of Finland, Report M19/3232/2008/41.

Allred, B. J., Groom, D., Ehsani, M. R., & Daniels, J. J. (2008). Resistivity method. In: Allred, B. J., Daniels, J. J., & Ehsani, M. R. (Eds.). *Handbook of agricultural geophysics*. CRC Press, Taylor and Francis Group, 85-108.

Arévalo-Gardini, E., Canto, M., Alegre, J., Loli, O., Julca, A., & Baligar, V. (2015). Changes in soil physical and chemical properties in long term improved natural and traditional agroforestry management systems of cacao genotypes in peruvian amazon. *PLoS ONE,* 10(7): e0132147. DOI:10.1371/journal.pone.0132147

Balwant, P., Bramhanwade, K., Jyothi, V., Dhyani, S., Verma, P., Godio, A., & Chiampo, F. (2021). Application of electrical resistivity tool to monitor soil contamination by herbicide. *Current Science,* 120(10), 1636-1639. DOI: 10.18520/cs/v120/i10/1636-1639

Botta, C. (2015). *Understanding your soil test step by step*. Yea River Catchment Landcare Group, 1-49.

Costa, M. M., Queiroz, D. M., Pinto, F. A. C., Reis, E. F. D., & Santos, N. T. (2014). Moisture content effect in relationship between apparent electrical conductivity and soil attributes. *Acta Scientiarum Agronomy,* 36(4), 395-401. DOI: 10.4025/actasciagron.v36i4.18342

Demir, S., Alaboz, P., Dengiz, O., Senol, H., Yilmaz, K., & Baskan, O. (2022). Physicochemical and mineralogical changes of lithic xerorthent soils on volcanic rocks under semi-arid ecological conditions. *Earth Sciences Research Journal,* 26(4), 291-301. https://doi.org/10.15446/esrj.v26n4.96571

Dontsova, K., & Norton, L. D. (2001). Effects of exchangeable Ca:Mg ratio on soil clay flocculation, infiltration and erosion. In: D. E. Stott, R. H. Mohtar, & G. C. Steinhardt (Eds.). *Sustaining the Global Farm*. Selected papers from the 10th International Soil Conservation Organisation Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory, 580-585.

Edwards, L. S. (1977). A modified pseudosection for resistivity and induced polarization. *Geophysics,* 42, 1020-1036. https://doi.org/10.1190/1.1440762

Egesi, N. (2019). Petrography and structural features of migmatites, granites and granite gneisses at osokom and its environs Bansara area Southeastern Nigeria. *The Pacific Journal of Science and Technology*, 20(1), 356-364.

Fagbemigun, S. T., Oyebamiji, R. A., Faloyo, I. J., Arowoogun, I. K., Amosun, O. J., & Sanuade, O. A. (2021). Integration of electrical resistivity and soil analysis for Agricultural soil characterization—a case study. *Arabian Journal of Geosciences,* 14:377. https://doi.org/10.1007/s12517-021-06772-6

Fagbenro, A. W., & Woma, T. Y. (2013). Quantitative use of surface resistivity data for aquifer hydraulic parameter estimation. A review. *International Journal of Engineering Research & Technology (IJERT)*, 2(11), 342-348. DOI: 10.17577/IJERTV2IS110098

FAO, & ITPS. (2015). *Status of the world's soil resources (SWSR)-main report*. Food and Agriculture Organisation of the United Nations and Intergovernmental Technical Panel on soils, Rome, Italy, 607pp

Food and Agriculture Organisation (FAO). (2008). Guide to laboratory establishment for plant nutrient analysis. *FAO Fertilizer and Plant Nutrition Bulletin*, 19, 1-204.

Ganiyu S. A., Olurin, O. T., Oladunjoye, M. A., & Badmus, B. S. (2019). Investigation of soil moisture content over a cultivated farmland in Abeokuta Nigeria using electrical resistivity methods and soil analysis. *Journal of King Saud University–Science,* 32, 811–821. https://doi.org/10.1016/j.jksus.2019.02.016

Garcia, N., & Damask, A. (1991). *Physics for computer science students: with emphasis on atomic and semiconductor physics.* New York, Springer-Verlag.

Gholizadeh, A., Soom, M. A. M., Anuar, A. R., & Aimrun, W. (2012). Relationship between apparent electrical conductivity and soil physical properties in a Malaysian paddy field. *Archives of Agronomy and Soil Science*, 58(2), 155-168. http://dx.doi.org/10.1080/03650340.2010.509132

Gransee, A., & Führs, H. (2013). Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. *Plant Soil,* 368, 5–21. DOI: 10.1007/s11104-012-1567-y

Gregory, K. J., Simmons, I. G., Brazel, A. J., Day, J. W., Keller, E. A., Sylvester, A. G., & Yãnez-Arancibia, A. (2009). *Environmental sciences: A student's companion*. SAGE publication ltd, London. https://doi.org/10.4135/9781446216187

Grisso, R. B., Alley, M., Wysor, W. G., Holshouser, D., & Thomason, W. (2009). *Precision farming tools: soil electrical conductivity communications and marketing*. College of Agriculture and Life Sciences, Virginia Polytechnic Institute and State University.

Hawkins, E., Fulton, J., & Port, K. (2017). *Using soil electrical conductivity (EC) to delineate field variation*. College of Food, Agricultural and Environmental Sciences, Ohio State University. https://ohioline.osu.edu/factsheet/fabe-565.

He, Y., DeSutter, T. M., & Clay, D. E. (2013). Dispersion of Pure Clay Minerals as Influenced by Calcium/Magnesium Ratios, Sodium Adsorption Ratio, and Electrical Conductivity. *Soil Science Society of America Journal,* 77, 2014–2019.

Heil, K., & Schmidhalter, U. (2017). The application of EM38: determination of soil parameters, selection of soil sampling points and use in agriculture and archaeology. *Sensors,* 17, 2540. DOI:10.3390/s17112540

Hillel, D. (2004). *Introduction to environmental soil physics*. Elsevier Academic Press, USA. 145 pp

Horneck, D. A., Sullivan, D. M., Owen, J. S., & Hart, J. M. (2011). *Soil test interpretation guide*. Oregon State University Extension Service, EC 1478, USA. 12p. https://catalog.extension.oregonstate.edu/ec1478.

Ibrahim, A., Toyin, A., & Sanni, Z. J. (2015). Geological characteristics and petrographic analysis of rocks of Ado-Awaiye and its environs, Southwestern Nigeria. *International Journal of Applied Science and Mathematical Theory*, 28-47.

Jaja, N. (2016). *Understanding the texture of your soil for agricultural productivity*. Virginia State University, Virginia Cooperative Extension, publication CSES-162P.

Kayode, O. T., Aizebeokhai, A. P., & Odukoya, A. M. (2022). Geophysical and contamination assessment of soil spatial variability for sustainable precision agriculture in Omu-Aran farm, Northcentral Nigeria. *Heliyon*, 8, e08976

Khadka, D., Lamichhane, S., Bhantana, P., Ansari, A. R., Joshi, S., & Baruwal, P. (2018). Soil fertility assessment and mapping of Chungbang Farm, Pakhribas, Dhankuta, Nepal. *Advances in Plants and Agricultural Research,* 8(3), 219‒227. DOI: 10.15406/apar.2018.08.00317

Kibria, G., & Hossain, S. (2019). Electrical resistivity of compacted clay minerals. *Environmental Geotechnics*, 6(1), 18–25. https://doi.org/10.1680/jenge.16.00005

Kim, K., Yoo, J., Kim, S., Lee, H. S., Ahn, K., & Kim, I. S. (2007). Relationship between the electric conductivity and phosphorus concentration variations in an enhanced biological nutrient removal process. *Water Science and Technology,* 55(1-2), 203-208.

Korsaeth, A. (2005). Soil apparent electrical conductivity (ECa) as a means of monitoring changes in soil inorganic N on heterogeneous morainic soils in SE Norway during two growing seasons. *Nutrient Cycling in Agroecosystems,* 72: 213–227. DOI 10.1007/s10705-005-1668-6

Manoucheri, H. R., Rao, K. H. & Forssberg, K. S. E. (2002). Triboelectric charge, electrophysical properties and electrical beneficiation potential of chemically treated feldspar, quartz and wollastonite. *Magnetic and Electrical Separation,* 11(1-2), 9-32.

Mary, B., Peruzzo, L., Boaga, J., Cenni, N., Schmutz, M., Wu Y., Hubbard, S. S. & Giorgio, C. G. (2020). Time-lapse monitoring of root water uptake using electrical resistivity tomography and mise-à-la-masse: a vineyard infiltration experiment. Soil, 6, 95–114, https://doi.org/10.5194/soil-6-95-2020

Mertzanides Y., Tsakmakis I., Evangelos Kargiotis E. & Sylaios G. (2020). Electrical resistivity tomography for spatiotemporal variations of soil moisture in a precision irrigation experiment. International Agrophysics., 2020, 34, 309-319 doi: 10.31545/intagr/123943

McCauley, A., Jones, C. & Jacobsen, J. (2005). Basic soil properties. Soil and water management module 1 Montana State University, Extension Service Continuing Education Series, pg1-12. www.montana.edu/publications/ (last accessed November 2017).

Medeiros, W. N., Valente, D. S. M., Queiroz, D. M., Pinto, F. A. C. & Assis, I. R. (2018). Apparent soil electrical conductivity in two different soil types. *Revista Ciência Agronômica,* 49(1), 43-52. doi: 10.5935/1806-6690.20180005

Mohammed, M., El Mahmoudi, A. & Almolhem, Y. (2022). Applications of ElectromagneticInduction and Electrical Resistivity Tomography for Digital Monitoring and Assessment of the Soil: A Case Study of Al-Ahsa Oasis, Saudi Arabia. Applied Science, 12, 2067. https://doi.org/10.3390/app12042067.

Molin, J. P. & Faulin, G. D. C. (2013). Spatial and temporal variability of soil electrical conductivity related to soil moisture. *Scientia Agricola* 70(1), 1-5.

Moral, F. J. & Rebollo, F. J. (2017). Characterization of soil fertility using the Rasch model. *Journal of soil science and plant nutrition,* 17(2), 486-498.

Mzuku, M., Khosla, R., Reich, R., Inman, D., Smith, F. & MacDonald, L. (2005). Spatial variability of measured soil properties across site-specific management zones. *Soil Science Society of American Journal,* 69, 1572-1579.

Nigeria Geological Survey Agency (N. G. S. A.), (2009). The Geological Map of Nigeria. A publication of Nigeria Geological Survey Agency, Abuja, Nigeria.

Olaojo, A. A. & Oladunjoye, M. A. (2022). Field-scale apparent electrical conductivity mapping of soil properties in precision agriculture. *Brazilian Journal of Geophysics*, 40(3), 1-31 DOI: http://dx.doi.org/10.22564/brjg.v40i3.2171.

Olaojo, A. A. & Oladunjoye, M. A. (2023). Resolution of spatial variability of apparent electrical conductivity in agricultural soil assessment. *Arabian Journal of Geosciences*, (2023) 16:537, https://doi.org/10.1007/s12517-023-11650-4.

Olson-Rutz, K. & Jones, C. (2018). Soil nutrient management for forages: Phosphorus, potassium, sulphur and micronutrient. Montana State University Extension Service, EB0217. www.landresources.montana.edu/pdf/pub/foragePKSMEBO217. (last accessed October 2019).

Okunlola, O. A. & Owoyemi, K. A. (2015). Compositional characteristics of geophagic clays in parts of southern Nigeria. *Earth Science Research,* 4(2), 1-15.

Parsons, T. L. & Zwanzig, H. V. (2003). Mineral modes of gneiss along the Thompson Nickel Belt–Kisseynew domain boundary, Manitoba (parts of NTS 63J, 63O, 63P, 64A and 64B); in Report of Activities 2003, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, 132–136 pp.

Peralta, N. R. & Costa, J. L. (2013). Delineation of management zones with soil apparent electrical conductivity to improve nutrient management. *Computers and Electronics in Agriculture*, 99, 218–226.

Proffitt, T. (2014). Assessing soil quality and interpreting soil test results. www.winewa.asn.au. (last accessed September 2019).

Revil, A. & Glover, P. W. J. (1998). Nature of surface electrical conductivity in natural sands, sandstones, and clays. *Geophysical Research Letters,* 25(5), 691-694

Ribeiro, M. A. Q., de Almeida, A. F., Mielke, M. S., Gomes, F. P., Pires, M. V. and Baligar, V. C. (2013). Aluminum effects on growth, photosynthesis, and mineral nutrition of cacao genotypes. *Journal of Plant Nutrition* 36(8), 1161-1179.

Rodríguez-Pérez, J. R., Plant R. E., Lambert, J. & Smart, D. R. (2011). Using apparent soil electrical conductivity (ECa) to characterize vineyard soils of high clay content. *Precision Agric,* 12, 775–794. DOI 10.1007/s11119-011-9220-ys

Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A. & Richard, G. (2005). Electrical resistivity survey in soil science: a review. *Soil & Tillage Research,* 83, 173–193.

Scherer, T. F., Franzen, D. & Cihacek, L. (2013). Soil, Water and Plant Characteristics Important to Irrigation. https://www.ag.ndsu.edu/publications/crops/soil-water-and-plant *characteristics-important-to-irrigation/ae1675.pdf* AE1675 *(Revised).* (last accessed October 2017).

Siqueira, G. M., Dafonte, J. D., Armesto, M. V. & e Silva, E. F. F. (2014). Using multivariate geostatistics to access patterns of spatial dependence of apparent soil electrical conductivity and selected soil properties. *The Scientific World Journal*, 2014. dx.doi.org/10.1155/2014/712403, (last accessed September 2017).

Sonon, L. S., Kissel, D. E., & Saha, U. (2014). Cation exchange capacity and base saturation. University of Georgia *UGA-Extension Circular 1040. https://extension.uga.edu/publications/detail.html?number=C1040&title=Cation%20Exchange%20Capacity%20and%20Base%20Saturation.* (last accessed August 2019).

Terzaghi, K. & Peck, R. B. (1967). Soil Mechanics in Engineering Practice. New York: J. Wiley and Sons, Inc.

UNSW. (2007). Soil properties: Exchangeable cations. terraGIS. www.terragis.bees.unsw.edu.ac/terraGIS_soil/sp_exchangeable_cations.html. (last accessed October 2019).

USDA Natural Resources Conservation Service, (2011). Soil Quality Indicators. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/health/assessment/?cid=stelprdb1237387. (last accessed September 2017).

van Vliet, J. A., Slingerland, M. & Giller, K. E. (2015). Mineral nutrition of cocoa. A review. Wageningen University and Research Centre, Wageningen, 57pp.

Warrick, A. W. & Nielsen, R. R. (1980). Spatial variability of soil physical properties in the field. In: D. Hillel (Ed) Application of soil physics, Academic Press, New York, NY, USA.

Watanabe, Y., Kikuno, H., Asiedu, R., Masunaga, T. & Wakatsuki, T. (2015). Comparison of physicochemical properties of soils under contrasting land use systems in southwestern Nigeria. *JARQ* 49(4), 319–331.

White, A. F., Bullen, T. D., Schulz, M. S., Blum, A. E., Huntington, T. G. & Peters, N. E. (2001). Differential rate of feldspar weathering in granitic regoliths. *Geochimica et Cosmochimica Acta*, 65(1), 847-869.

White, P. J. & Broadley, M. R. (2003). Calcium in plants. *Annals of Botany*, 92, 487-511. Wilson, M. J. (2004). Weathering of the primary rock-forming minerals: processes, products and rates. *Clay Minerals*, 39, 233–266

Wodaje, A. & Abebaw, A. (2014). Analysis of selected physicochemical parameters of soils used for cultivation of garlic (*Allium sativum* L.). *Science, Technology and Arts Research Journal (International Journal of Wollega University, Ethiopia),* 34, 29-35.

Yusof, N. Q. A. M. Zabidi, H. (2016). Correlation of mineralogical and textural characteristics with engineering properties of granitic rock from Hulu Langat, Selangor. *Procedia Chemistry*, 19, 975–980.