

**CONTRIBUTION OF ORGANIC MATTER TO THE CATION
EXCHANGE CAPACITY OF SOME SOILS IN NIGERIA**

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ABSTRACT

The relative contributions of clay and organic matter to the cation exchange capacity of soils have been of great interest to many researchers. Organic matter, as a critical component of the soil, plays significant roles which far exceed its quantitative distribution in the soil. It is regarded as the major contributor of CEC in weathered soils because of its several functional groups such as R-COO⁻, R-C=O, R-COH and R-SH that deprotonate and leave net negative charge on the humus. The objective of this study was to assess the contribution of SOM to CEC of soils in Nigeria. Data on CEC, OM, pH and clay were collected from 191 soil samples based on literature reports across the country. Data was analyzed using SIGMAPLOT STATISTICAL SOFTWARE. There was no significant relationship between CEC and pH measured in either H₂O or dilute CaCl₂ solution. CEC correlated significantly with clay and explained 55% of the variation in CEC of the soils. The organic carbon (OC) has the highest correlation with CEC and explained 72% of the variation of the CEC. The predictive empirical model for estimating CEC from OC is $CEC = 5.81 + 5.23 (OC)$, $r^2 = 0.72$. A unit change in OC increases CEC by 5.23 mmol kg⁻¹ in contrast to the small increase in CEC by mere 0.4 mmol kg⁻¹ per unit change in clay content. On a unit change basis, OC contribution to CEC was thirteen times greater than clay. Therefore land management practices that increase and maintain the organic matter contents must be adapted to sustain the fertility of soils in Nigeria.

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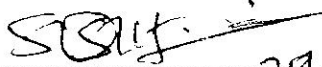
CERTIFICATION

The project "CONTRIBUTION OF ORGANIC MATTER TO THE CATION EXCHANGE CAPACITY OF SOME NIGERIAN SOILS" by Akinteye Damaris Opeyemi meets the regulation governing the award of B.Agric in Federal University Oye-Ekiti, and it is approved for its contribution to scientific knowledge and literary presentation.

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Supervisor

Date:


----- 28/03/19

Prof S.O Shittu

Head of Department

Date: 28/03/19.

DEDICATION

I dedicate this work to God almighty, most gracious and merciful, who is the Author and Finisher of my faith, my source of strength and help.

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CHAPTER ONE

1.0 INTRODUCTION

Colloids in soils are charged particles that can attract both positively and negatively charged ions to form bonds whose strengths depend on the number of charges on the ion. Anions move freely in the soil solution and are readily available to plants and easily leached. Sometimes anions form compounds with cations and become insoluble and temporarily unavailable to plants or for leaching. The colloidal constituents of soils are the clay fraction including part of the silt and the humus that carry net negative charges. The cations are clustered around the surfaces of the clay and humus particles and are usually readily displaced by other cations added to the soil or released into the soil solution which may be taken up by plant root.

Cation exchange capacity of a soil is due to the inorganic constituents such as clay minerals, hydrous oxides, primary and secondary minerals and organic matter. Cation exchange capacity (CEC) is a measure of how many cations are retained on the soil particle surfaces. (Brady *et al.*, 2008). It is a very important soil property that influences soil structure stability, nutrient availability, soil pH and the soil reaction to fertilizers and other ameliorants. It is defined as the amount of positive charge that can be exchanged per mass of soil, usually measured in cmol/kg. Cation exchange capacity arises from various negative charges on the soil particle surfaces, especially those of clay minerals and soil organic matter. Phyllosilicate clays consist of layered sheets of aluminium and silicon oxides. The replacement of aluminium or silicon atoms by other elements with lower charge (e.g. Al^{3+} replaced by Mg^{2+}) can give the clay structure a net negative charge. This charge does not involve deprotonation and is therefore pH-independent, and called permanent charge. In addition, the edges of these sheets expose many acidic hydroxyl groups that are deprotonated to leave negative charges at the pH levels in many soils. Cations retained electro statically are easily exchangeable with cations in the soil solution, thus, the CEC of a soil represents the total amount of exchangeable cation the soil can adsorb. The soils with a higher CEC have greater capacity to maintain adequate quantities of Ca^{2+} , Mg^{2+} and K^+ than a soil with a low CEC. The CECs are strongly affected by nature and quantity of clay minerals and organic matter present in the soil. Highly weathered soils containing hydroxyl Al or soils with predominantly 1:1 minerals

have low CEC. Also, the soils with high clay and organic matter contents have high CEC compared to low organic matter soils like sandy soils.

Soils have CEC primarily because clay particles and organic matter present in the soil tend to be negatively charged. A soil with a higher CEC may not necessarily be more fertile because its CEC can also be occupied by acid cations such as hydrogen (H^+) and aluminum (Al^{3+}). However, when combined with other measures of soil fertility, CEC is a good indicator of soil quality and productivity. Soil CEC is normally expressed in one of two numerically equivalent sets of units: meq/100 g (milliequivalents of charge per 100 g of dry soil) or cmole kg⁻¹ (centimoles of charge per kilogram of dry soil).

Organic matter is a critical component of the soil. Its role in soil is highly significant and generally exceeds its quantitative distribution. In the soils of the tropical region, the organic matter is regarded as the major contributor of CEC (Jones and Wild, 1973.).

Krull *et al.*, (2000) discussed the importance of SOM and pointed out CEC as one of the chemical importance of SOM but failed to reveal the fact that CEC may be a limiting factor for having a fertile soil.

Also little is known about the extent of contribution of organic matter to the CEC of soils in Nigeria. Most studies show a linear correlation between SOC and CEC but no model has been developed to be able to predict and quantify the extent of contribution. Although (Oades *et al.*, 1989) described the relationship between CEC_v (i.e pH dependent variable charge CEC) and organic carbon with an equation, but this did not account for the relationship between soil organic matter and total CEC of soils (i.e both pH dependent variable charge and permanent charge CEC.).

Much information concerning the cation-exchange properties of clay minerals has been obtained by many workers. However, relatively little attention has been given to the quantitative relationship between CEC and soil organic matter. Measurements of soil CEC show significant dependence on OM in several soils.

CEC is used as a measure of soil nutrient retention capacity, and the capacity to protect groundwater from metal contamination (Brady and Weil, 1999). According to (Bergaya and Vayer, 1997) CEC buffers fluctuations in nutrient availability in soil solution and soil pH. Plants obtain part of their nutrients from cation exchange sites by a process called contact exchange. Cation exchange capacity is also a key to understanding soil fertility. (Rowell,

1994). Nutrients that are held by charges on a soil are termed 'exchangeable' as they become readily available to plants (Rowell, 1994). The higher the CEC of a soil, the more nutrients it is likely to hold and the higher will be its fertility level (Fullen and Catt, 2004). Exchangeable ions are not easily leached away from roots and are rapidly available for plants.

1.1 OBJECTIVES

The main objective of the study is to determine the contribution of OM to CEC of some soils in Nigeria.

SPECIFIC OBJECTIVES

The specific objectives are to:

- Determine the quantitative relationship between organic matter content of soil and CEC.
- Develop a predictive model for estimating CEC from organic matter content of soils.

CHAPTER TWO

2.0 LITRERATURE REVIEW

2.1 The Importance of Organic Matter in Soil Fertility

Organic matter can be defined as the grouping of organic carbon containing compounds which are originated from living thing and deposited on or within the soil structural components (Brady and Weil 1999).SOM includes remains of plant and animal residues deposited on the earth surface or the application of organically synthesized materials by man (Brady and Weil 1999). The importance of organic matter in the soil is the unique feature distinguishing soil from the parent rock.

Organic substances play a direct part in the formation of fertile soils as they are the sources of plant nutrients which are liberated in available forms during mineralization. Organic substances also play indirect part in the supplies of nutrients and water for plants and are readily provided in building soil of good structure. High organic matter levels in soils are vital to productivity and sustainability of plants. (Wilhem, 2001).

Organic matter in a soil is also linked to soil formation as the action of organic matter plays significant role on parent rock weathering. The soil contains many living organisms such as bacteria, fungi, algae, actinomycetes, earthworms, nematodes, and arthropods all contributing to the biological and microbiological activities responsible for the oxidation of plant material, roots, dead organisms and other organic residues that accumulate in soils. As organic material decomposes, soil organic matter is formed. Ten to fifteen percent of this organic material is readily decomposable, while the remainder takes much longer.

2.2 Overview of principal functions of Soil Organic Matter

The functions of SOM can be broadly classified into three groups: biological, physical and chemical functions. (Baldock and Skjemstad, 1999). These groups are not static entities but with dynamic interactions occurring among the three major components.

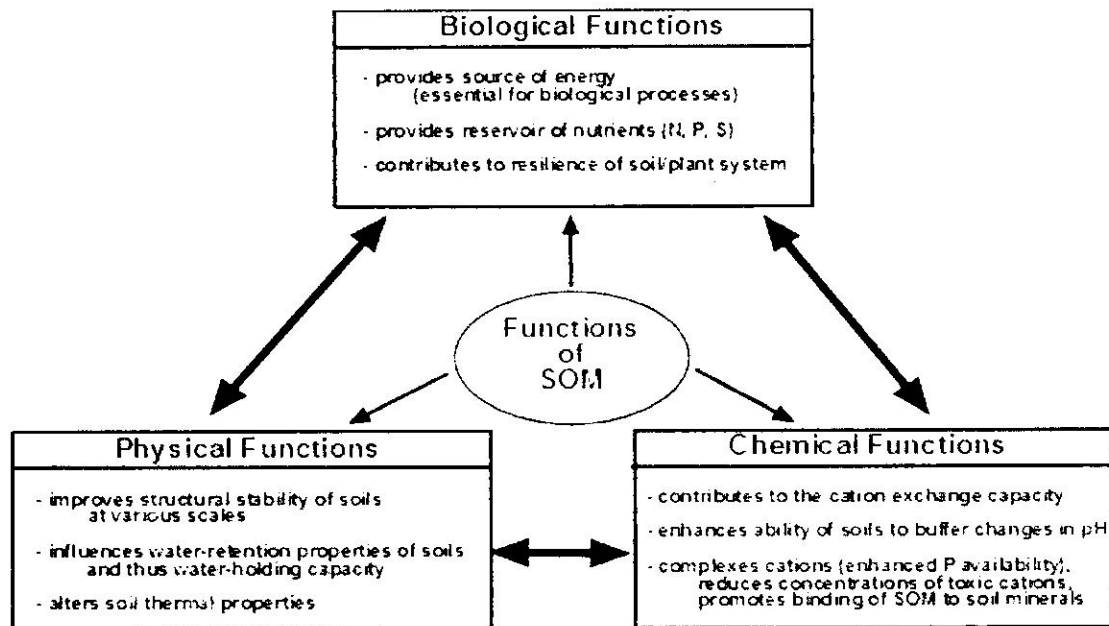


Figure 1: Functions of SOM and the dynamic interactions occurring among the different functions. (Source: Baldock and Skjemstad, 1999).

2.2.1 Soil structure and aggregate stability

Organic matter is an important factor in the formation of a good soil structure. The structure of a soil is of great importance in determining its fertility. Among the functions of organic matter is that it improves soil structure and aggregate stability, including other physical properties, (Oades *et al.*, 1984), and (Carter and Stewart, 1996). The addition of SOM reduces bulk density (Db) and increases water holding capacity, but also effectively increases soil aggregate stability. According to (Angers and Carter 1996) there is a significant relationship between water-stable aggregates (WSA) and SOC content, particularly labile carbon. They reported that a minimum of 2% SOC was necessary to maintain structural stability and observed that if SOC content was between 1.2-1.5%, stability declined rapidly. (Boix-Fayos

et al., 2003) reported a threshold of 3-3.5% SOC to achieve increases in aggregate stability. According to (Howad, 1990), a threshold value for most soils is at 2% SOC equivalent to 3.4% SOM, below which most soils are prone to structural instability and crop yields reduction. There is really no defined threshold value for organic matter level (Loveland and Web, 2003) However, (Doran and Safley, 1997) argued for different threshold values for different soils. (Channey and Swift, 1984) found a linear increase in the aggregate stability and aggregate size with an increasing level of SOM or SOC.

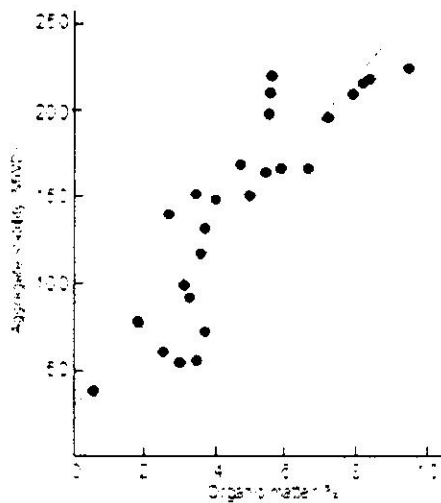


Figure 2: Relationship between aggregate stability and organic matter content (drawn from Channey and Swift, 1984).

Kay and Angers (1999) and observed similar relationships between SOC content and aggregate stability. (Carter, 1992) found that maximum structural stability was obtained at 4.5% SOC. (Hayenes and Swift, 1990), reported that the type of organic matter is more critical to structural stability than the net amount of the organic matter. However, there is no consensus as to the type of organic matter required for soil structure and aggregate stability probably because of the different types of organic matter. (Elliott, 1997) suggested that particulate organic matter (POM) was probably more important in soil structural stability because of its short turnover time than other organic matter fractions.

2.2.2 Water-Holding Capacity

An important indicator of soil physical fertility is the capacity of soil to store and supply water and air for plant growth. The ability of soil to retain water is termed water holding capacity (WHC). In particular, the amount of plant-available water in relation to air-filled

porosity at field capacity is often used to assess soil physical fertility (Peverill *et al.*, 1999). Total plant available water (PAW) is the amount of water held by a soil at its field capacity FC, at matric suction of -10 kPa. WHC of soils is controlled primarily by the number of pores and pore-size distribution of soils, and by the specific surface area of soils. In turn, this means that with an increase in SOC content, there is increased aggregation and decreased Db. Thereby increasing the total pore space as well as the number of micropores. (Haynes and Naidu, 1998). These relationships highlight the interconnectivity between soil structure, Db and WHC. The effect of organic carbon on the WHC of soil is generally assumed to be positive but the types of carbon responsible for this effect and synergistic behaviour with other soil properties is not well understood.

According to (de Jong, 1983) and (Hynes *et al.*, 1998) soil water content increases with increasing SOC.

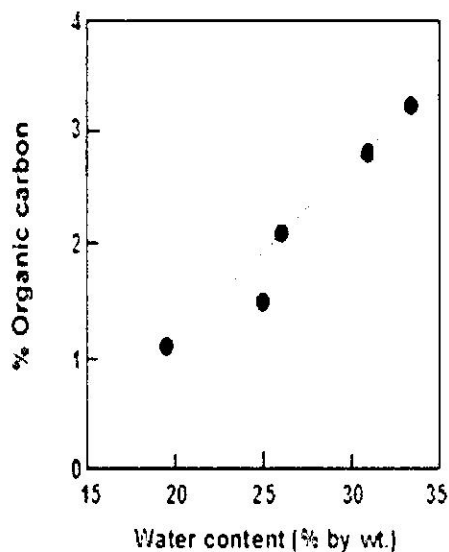


Figure 3: Increase with %C in water retention at 10 kPa suction of silty aggregates (redrawn from Emerson and McGary, 2003).

Similarly, (Loveland and Webb, 2003) reported that SOC contributed <13% to the variance in soil water content, Danalatos *et al.*, (1994) did not find any effects of SOM on water retention. Furthermore, experiments at different matric potentials are likely to influence the effect of SOC as McBride and MacIntosh, (1984) reported that SOC affected water retention at -1500 kPa only if the SOC content was >5%.

Soil organic matter promotes drought tolerance of the crop. A soil with an adequate level of organic matter will be less erodible, have increased water and nutrient retention, and also be easier to work and plow. Other advantages include resistance to soil crusting and compaction, greater fertility, better root growth of crops, and improved crop yields. Improvement and maintenance of the soil requires the addition of organic residues.

2.2.3 Buffer Capacity and pH

The buffering capacity of a soil is the soil's ability to resist changes from fluctuations of pH and plant nutrients. According to the information given by Bloom, (1999), buffering capacities of SOM can easily approach 200 cmolc kg. Aitken *et al.*, (1990) also estimated that SOC may have a BC >300 times compared with that of kaolinite. Soil organic matter acts as a buffer over a wide range of pH values: this is because of the availability of different functional groups (e.g. carboxylic, phenolic, acidic, alcoholic, amine, amide etc).

Soil buffering is considered to be an important aspect of soil health, as it assures reasonable stability in soil pH and reduces the amount of chemicals lime or sulphur needed to change the soil pH, of acid and saline soil respectively. The BC of a soil is defined as its resistance to changes in pH when an acid or base is added. Buffering at intermediate pH values (5-7.5) is mainly governed by exchange reactions where clays and functional groups of SOM act as sinks for H⁺ and OH⁻ Brady, (1990).

Starr *et al.*, (1996) and Curtin *et al.*, (1996) documented a good correlation between buffering capacity and soil organic matter, despite the acidifying measures of fertilizer application and stocking rates, the rate of change in pH was relatively slow due to high buffering capacity of the soil which was in turn as a result of high soil organic carbon content (i.e 4.6% organic carbon in surface soil with 0-10cm dept). Again Magdoff *et al.*, (1987) show from their analysis that at low soil organic matter level change in SOM resulted in large change in the soil buffering capacity, but at large SOM level the change in buffering capacity is small.

2.2.4 SOM as a Source of Nutrients

SOM is an important source of nutrients for plants in general and crops in particular.

Wolf and Snyder, (2003) reported that most nutrients in SOM are derived from the mineralisation of SOM and become available for plant uptake during decomposition therefore

the proportion of SOM considered as the most important in providing nutrients to plants is the particulate organic matter fraction.

The SOM provides the largest pool of macronutrients as >95% of N and S and 20-75% of P was found in SOM Duxbury *et al.*,(1989) and Baldock *et al.*,(1999). About 40-50% of organic N is identifiable and quantifiable as amino acids and amino sugars and the remaining portion consists of unidentifiable structures. The principal form of organic S added to soil is amino acid S (methionine, cysteine, cystine), which accounts for up to 30% of the total organic S pool.

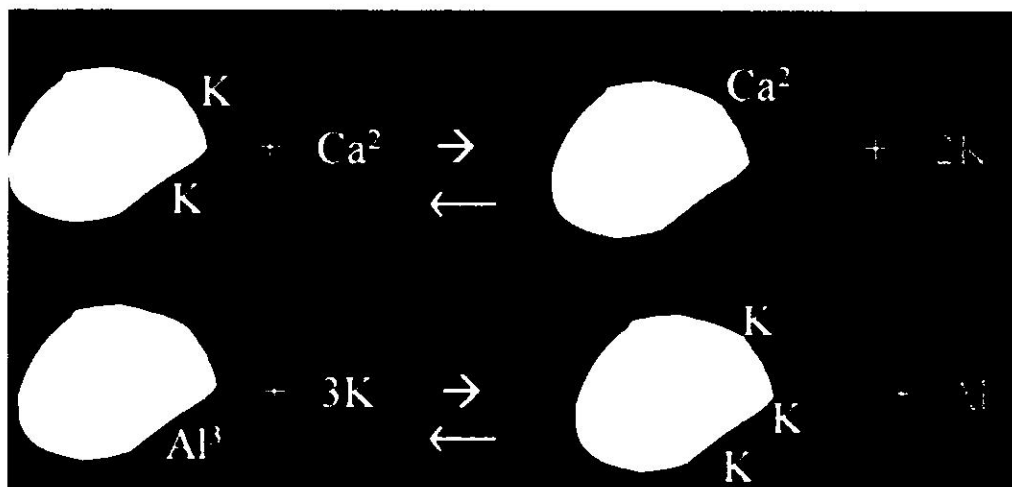
2.3 Cation Exchange Capacity of soils

Cations are positively charged ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+), sodium (Na^+), hydrogen (H^+), aluminum (Al^{3+}), iron (Fe^{2+}), manganese (Mn^{2+}), zinc (Zn^{2+}) and copper (Cu^{2+}). These cations are held by the negatively charged clay and organic matter particles in the soil through electrostatic forces (negative soil particles attract the positive cations). Cation exchange capacity (CEC) as the measure of the total capacity of a soil to hold exchangeable cations Peverill *et al.*, (1999); CEC indicates the negative charge present per unit mass of soil. A high CEC contributes to the capacity of soils to retain plant nutrient cations. The cations on the CEC of the soil particles are easily exchangeable with other cations and as a result, they are plant available. Hence, the CEC of a soil represents the total amount of exchangeable cations that the soil can absorb. Ketterings, (2007).

CEC is expressed as centimol of charge per kilogram of soil (cmole/kg), that is numerically equivalent to the previous conventional unit of mequiv./100g Krull *et al.*, (2000).

High CEC of soils indicates more clay or organic matter present Ketterings, (2007). Also high CEC (clay) soils have a greater water holding capacity than low CEC (sandy) soils. Low CEC soils are more likely to develop potassium and magnesium (and other cation) deficiencies. High CEC soils are less susceptible to leaching and losses of cations. While for soils with low CEC e.g sandy soils, a large one-time addition of cations like potassium can lead to large leaching and losses as the soil isn't able to hold on to the excess K. The lower the CEC, the faster the soil pH will decrease with time. Therefore, sandy soils need less lime than clay soils to increase the pH to desired levels.

The interchange between a cation in a soil solution and one on a soil colloid must be charge balanced.



Illustrated by (Blaskó, 2011)

The percentage base saturation (BS%) is the proportion of CEC satisfied by basic cations, basic cations including Ca, Mg, K, and Na. As the BS% increases, the pH increases. High base saturation is preferred but not essential for tree fruit production. The availability of nutrient cations such as Ca, Mg and K to plants increases with increasing BS%. Base saturation is usually close to 100%. base saturation below 100% indicates that part of the CEC is occupied by hydrogen and/or aluminum ions (Blaskó, 2011).

Several different methods exist to measure CEC but the choice of method depends on the factors influencing CEC of most soils. These factors include pH, ionic strength, degree of variable and permanent charge, colloids and the type of clay.

	Method	Reference
Non-calcareous soils, permanent charge	Exchange with $1M NH_4Cl_2$ pH7	Rayment and Higginson (1992)
	Exchange with $1M NH_4COOCH_3$ pH7	Blakemore et al. (1987)
Calcareous soils.	Exchange with $1M NH_4Cl_2$ pH8.5	Rayment and Higginson (1992)
	Exchange with $1M (OH-C_2H_4)(CH_3)_3NCl$	Tucker (1985)
Vaible Charge soils	Compulsive exchange with	

	BaCl ₂ /NH ₄ Cl	Gillman and Sumpher (1986);
	Exchange with 0.01M silver thiourea.	Rayment and Higginson (1992) Blakemore et al. (1987)
Exchange acidity	Exchange with 0.001M KCl	Rayment and Higginson (1992) Oorts et al. (2003)
detemination	Exchange with BaCl ₂ in tiethanol amine at pH 8.2 and acid titation of excess triethanolamine.	Rayment and Higginson (1992) Blakemore et al. (1987)
Removal of Soluble salts	Pre-teatment with a solvent.	Rayment and Higginson (1992) Tucker (1985); Rayment and Higginson (1992)

Table 3.1: **Summary of common methods used for measuring cation exchange capacity** (modified from Peverill et al., 1999).

2.4 Origin of charge in the soil.

Soils have permanent and variable charge. Elements with an electrical charge are called an ion. Ions with positive charges are called cations and are written in the ionic form. Examples are potassium (K⁺), sodium (Na⁺), hydrogen (H⁺), calcium (Ca⁺), and magnesium (Mg⁺⁺). Ions with a negative charge are called anions. Examples are chlorine (Cl⁻), nitrate (NO₃⁻), sulfate (SO₄⁻), phosphate (H₂PO₄⁻). Electric charges in solid particle surface in soils usually develop from two principal ways, both of which are the primary sources of negative and positive charge (Sposito, 2008). This includes isomorphous substitution and charges developed from the protonation/deprotonation reaction which are pH-dependent and are also referred to as variable charges (Bolland 1980). Ionization of hydroxyl groups on the surface of other soil colloids and organic matter can result in what is describes as pH dependent charges-mainly due to the dependent on the pH of the soil environment. The main source of

charge on clay minerals is isomorphous substitution which confers permanent charge on the surface of most layer silicates.

2.4.1 ISOMORPHOUS SUBSTITUTION:- Brady and Weil (2008) discussed isomorphous substitution as surface charges emanating from the substitution of one cation for another in the octahedral and/ or tetrahedral sheets, substitution for cations like Si, Al & Mg in the phyllosilicate clays. Most of the charges associated with 2:1 type clays have this type of charge, and as a result clay will function like ion in solution. The substitution of one cation for another in the structure of a mineral, in isomorphous substitution is usually without changing the basic structure of that mineral. If the substituting ion is of different valence (charge), the result is either the introduction of a deficit or a surplus charge at that site. For example, substitution of Al^{+3} for Si^{+4} in a tetrahedral site, or Fe^{+2} for Al^{+3} in an octahedral site, results in a local charge deficit of +ve charge that is: the mineral attains a negative charge. The net charge associated with a clay crystal is the sum of the positive and negative charges, negative charges predominate in most silicate clays since those substituting ions leading -ve charges far outweigh those producing +ve charges. (Brady, 2008)

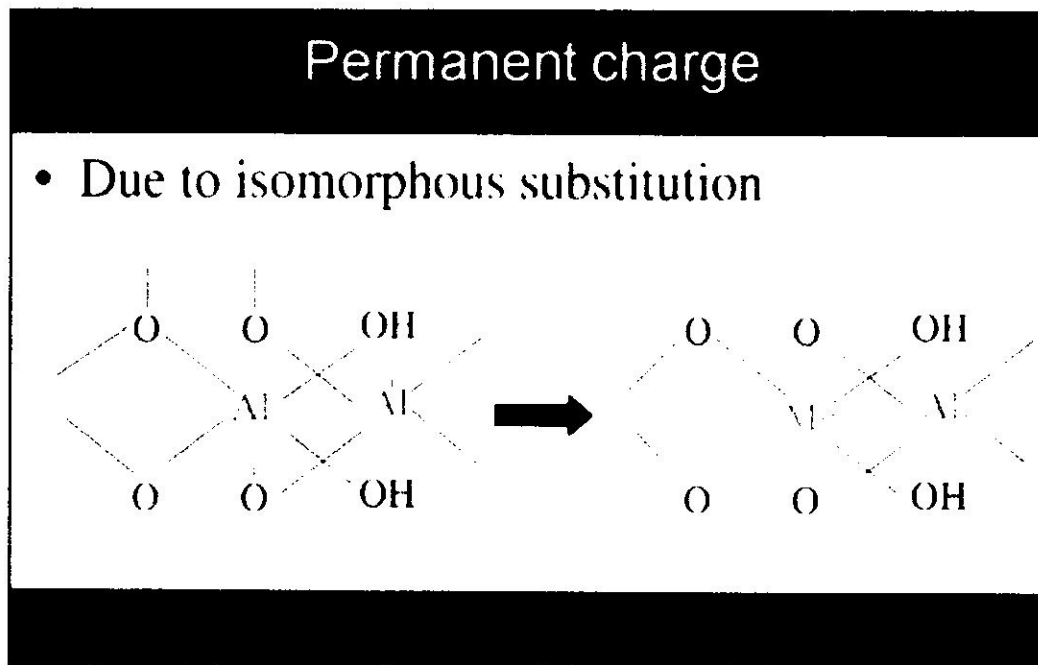
Positive charges on isomorphous substitution: When substituting cation has a higher charge than the ion for which it substitutes it is always a source of positive charge (Brady, 2008), such positive charges are characteristics of trioctahedral hydroxide sheet in the interlayer of clay minerals such as chlorites, and this charge is balanced by negative charge in the tetrahedral sheet. Substitutions in both the tetrahedral and octahedral sheets can occur in several 2:1 type silicate clays, including chlorites and smectites. In a tetrahedral sheet, there are three magnesium ions surrounded by oxygen and hydroxyl groups, this sheet have no charge. However, if an Al^{3+} ion substitutes for one of the Mg^{2+} ions, a positive charge results.

Most of the permanent charge in soils resides:

- On surfaces of layer-silicates mainly the 2:1 layer silicates (illite, vermiculite, smectite).
- The 2:2 clays (chlorite).
- The 1:1 clays (kaolinite) -> contain only a small amount of permanent charge on their planar surfaces.

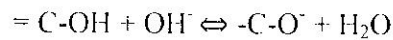
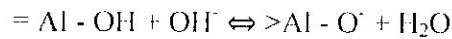
Negative charge by isomorphous substitutions: Negative charge is found in minerals where there has been an isomorphous substitution of a lower charged ion for a higher charged ion.

The substitution of Mg^{2+} for Al^{3+} leaves an unsatisfied $-ve$ charge, and is an important source of $-ve$ charge on smectite, vermiculite and chlorite clays. An example is the substitution of Al^{3+} for Si^{4+} in the tetrahedral sheet, leaving one unsatisfied $-ve$ charge from the tetrahedral oxygen atoms.

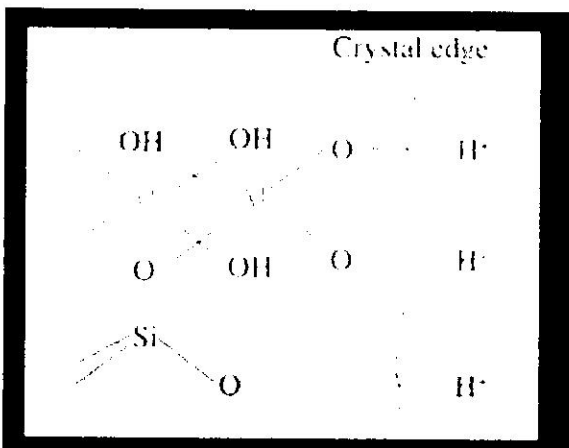
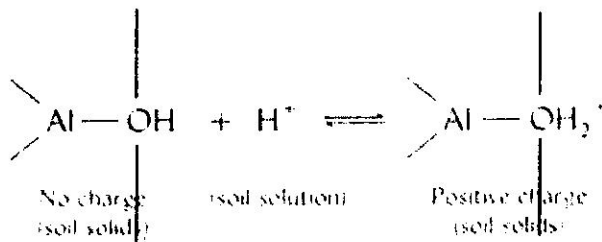


2.4.2 PH DEPENDENT CHARGE: -. These are also referred to as variable charge. “Variable charge” are pH dependent charges associated primarily with hydroxyl (OH) on the surface of organic and inorganic soil constituents with reactive surface groups whose charge varies with pH, and ionic concentration and composition of the soil solution (Van. Qafoku, Noble, & Xu, 2017). pH dependent charge increases with increasing pH arising on the surface of soil colloids by the releasing or accepting of H^+ which can provide either negative or positive charges. Variable charge is developed on the surface groups as a result of adsorption or desorption of solid-like ions that are constituents of the solid phase. i.e., H^+ , and the adsorption or desorption of solid-unlike ions that are not constituents of the solid phase. (Kim, 2014) The magnitude of variable charge varies with pH and type of colloid; it is an important type of charge for 1:1 layer, iron and aluminium oxide clays and organic colloids.

pH dependent negative charges: Negative charge on soil particle surface increases if the pH increases because more OH^- ions are available to force the reactions to the right (Brady & Weil, 2008). If pH is lowered, OH^- ion concentrations are reduced, the reaction goes back to the left and $-ve$ charge is reduced. The removal of positively charged complex aluminium hydroxyl ion also increases $-ve$ charges as pH increases. When pH is raised, the $\text{Al}(\text{OH})_2^+$ ions react with the OH^- in the soil solution to form insoluble $\text{Al}(\text{OH})_3$, thereby freeing the negatively charged sites.



pH dependent positive charges: Positive charge on humus some silicate clays and Fe, Al oxide develops by protonation which is the attachment of H^+ ions to the surface OH group



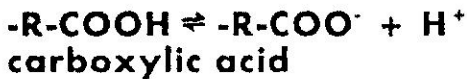
Positive charge development from crystal edges.

The appearance of OH groups on the edge of crystal edges can also give rise to positive charge as protons do not only dissociate from exposed OH groups but they can also absorb or gain protons by a process called protonation of exposed OH group (Kim, 2014).

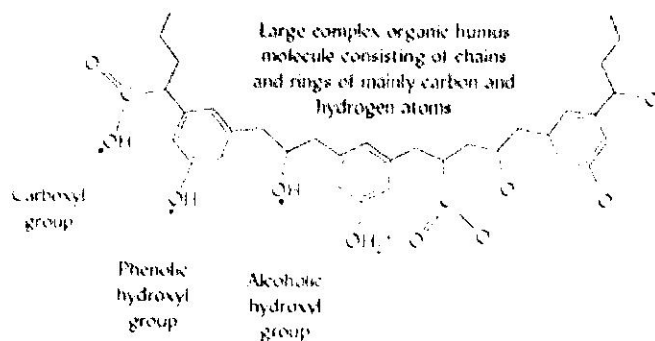
2.4.3 Sources of Charge in Soil Organic Matter

Charge development in soil organic matter is predominantly negative, as it is provided by the functional groups mainly carboxylic and phenolic groups. According to (Duxbury *et al.*, 1989) positive charge can occur through the protonation of amino group but positive charge development is considered relatively small in SOM. The source of negative charge in organic matter is different from that of clay minerals; the dissociation (separation into smaller units) of organic acids causes a net negative charge in soil organic matter, and again this negative charge is balanced by cations in the soil. Because organic acid dissociation depends on the soil pH, the CEC associated with soil organic matter is called pH-dependent CEC. This means that the actual CEC of the soil will depend on the pH of the soil. Given the same amount and type of organic matter, a neutral soil (pH ~7) will have a higher CEC than a soil with e.g. pH 5, or in other words, the CEC of a soil with pH-dependent charge will increase with an increase in pH.

At low pH, soil charge becomes more positive and at high pH negative charge increases, therefore the pH of soil organic matter is usually high. Humic substances have a negative surface charge because of the deprotonation of the OH group. Organic matter makes significant contributions to cation exchange, due to its large number of charged functional groups. Charge develops in organic matter by processes called PROTONATION AND DEPROTONATION. Protonation leads to positive charge in organic matter, and occurs under acidic conditions. Deprotonation leads to negative charge development.



DEPROTONATION



Tan and Dowling (1984) pointed out that permanent (CEC_p) and a pH-dependent variable charge (CEC_v), majorly illustrates the contribution of SOM and minerals to soil CEC. Most soils carry both types of charges as CEC tends to increase with increasing pH, and CEC measured at pH 8.2 is considered as total CEC. CEC_p is considered to be derived from the clay fraction and other mineralogical components (e.g. amorphous oxides) while CEC_v is regarded to be derived from soil humus and accordingly, the presence of organic matter generally causes the CEC in variable-charge clay soils to be greater. However, some components of SOM are known to be of greater importance in contributing to CEC_v than others. According to Oades *et al.*, (1989) an increase in CEC_v is due to the functional groups of SOM. A decline of CEC with soil depth is a consequence of the decline in SOM. The relationship between CEC_v and organic carbon followed the equation, Oades *et al.*, (1989)

$$\text{CEC}_v = 1.32 + 1.09 \text{ SOC} \quad (r^2 = 0.76)$$

From the equation 1% increase in SOC leads to 1 unit (cmole kg⁻¹) of increase in CEC in variable charge soils.

2.4.4 POINT OF ZERO NET CHARGE IN SOIL.

The point-of-zero charge in soil is defined as the pH value where the number of protonated and deprotonated sites is equal, and higher levels of SOM result in a lowering of the zero point (Krull *et al.*, 2000). The point of zero net charge according to (Sposito, 2008) is the pH value at which the net adsorbed ion charge is equal to zero.

The effect of SOM on the point-of-zero charge (pH₀) of the soil variable-charge component is considered the most important aspect in increasing CEC_v. Therefore, the greater the difference between soil pH and pH₀, the greater the net surface charge will be on variable charge components, and if pH₀-pH is < 0 the net charge is negative.

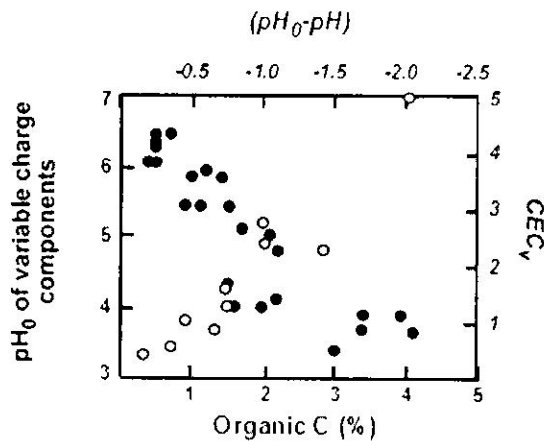


Figure 4: Relationship between pH₀ and SOC content (filled circles) and increase in CEC of variable charge components (CEC_v) with increasing negativity (pH₀-pH) (open circles) in Oxisols under virgin rainforest from northern Queensland (modified from McBride, 1994).

Organic matter itself generally has a low pH₀, which is due to the presence of carboxyl groups (Oades *et al.*, 1989). The high molecular weight (HMW) fraction contributes less to CEC compared with the low molecular weight (LMW) fraction (c. 500 cmole kg⁻¹) (Wolf and Snyder, 2003). (Oades *et al.*, 1989) maintaining SOC at highest possible SOC contents increases the variable charge component of the soil total CEC. The SOM decreases pH₀ by 1 pH unit for each 1% increase in organic C; this would equate to 17 t ha⁻¹ of SOM in the 0-10 cm (assuming SOM = 1.7 x organic carbon).

2.5 Factors affecting the cation exchange capacity of soils

Cation exchange capacity of soils is affected by many factors which include: soil texture, nature of clay minerals, soil reaction, soil type, soil pH, and soil organic matter content.

2.5.1 Soil pH

The amount of negative charge from deprotonation of clay hydroxyl groups or organic matter depends on the pH of the surrounding solution. Increasing the pH (i.e. decreasing the concentration of H⁺ cations) increases the variable charge, and therefore also increases the cation exchange capacity. CEC measurement depends on pH, and therefore is often made with a buffer solution at a particular pH value. If this pH differs from the natural pH of the soil, the measurement will not reflect the true CEC under normal conditions. Such CEC measurements are called 'potential CEC'. Alternatively, measurement at the native soil pH is

termed 'effective CEC', which more closely reflects the real value, but can make direct comparison between soils more difficult. As the pH is raised, the hydrogen held by the organic colloids and silicate clays (kaolinite) becomes ionized and replaceable. The net result is an increase in the negative charge on the colloids and in turn an increase in cation exchange capacity. Clay soils with high cation exchange capacity can retain large amounts of cations and reduce the loss of cations by leaching. Sandy soils, with low cation exchange capacity retain smaller quantities of cations and therefore cations are removed from soil by leaching.

Influence of pH on CEC of smectite and SOM

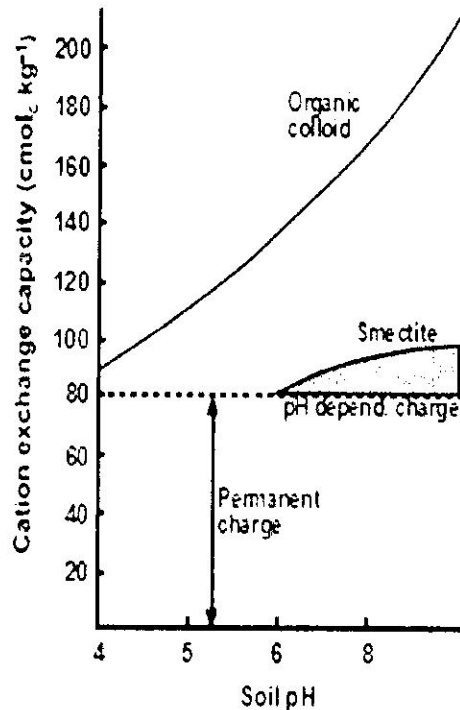


Figure 5: (source: Brady 1990).

Below pH 6 the charge for clay minerals is relatively constant (permanent CEC charge): above pH 6, contribution of the variable charge from clay minerals is evident (ionisation of H⁺ from hydroxy groups). By comparison, almost all of the charges on the organic colloid are considered to be pH dependent, i.e. variable charge

2.5.2 Clay mineralogy

The cation exchange capacity and specific area of the clay minerals are in the order: smectite>fine, mica>kaolinite. Hence, the cation exchange capacity of a soil dominated by smectite type of clay minerals is much higher than kaolinite type dominated soils. CEC depends on the nature of clay minerals present, since each mineral has its own capacity to exchange and hold cations e.g. the CEC of a soil dominated by vermiculite is much higher than the CEC of another soil dominated by kaolinite, as vermiculite is high activity clay unlike kaolinite which is low activity clay.

2.5.3 Soil texture

The negatively charged clay colloids attract positively charged cations and hold them. Therefore, the cation exchange capacity of soils increases with increase in percentage of clay content. Soil texture influences the CEC of soils in a way that it increases when soil's percentage of clay increases i.e. the finer the soil texture, the higher the CEC.

2.5.4 Soil Organic Matter

High organic matter content increases cation exchange capacity. (Brady and Weil, 2004) reported that the cation exchange capacity of clay minerals range from 10 to 150[cmol (p+) kg⁻¹] and that of organic matter ranges from 200 to 400[cmol (p+) kg⁻¹]. Soil organic matter plays a critical role in soil processes and is a key element of integrated soil fertility management (ISFM). Organic matter is widely considered to be the single most important indicator of soil fertility and productivity (Rowell, 1994). It consists primarily of decayed or decaying plant and animal residues and is a very important soil component. Benefits of Organic matter in soil according to (Ashman and Puri, 2002) include: increasing the soil's cation exchange capacity and acting as food for soil organisms from bacteria to worms and is an important component in the nutrient and carbon cycles.

Organic matter, like clay, has a high surface area and is negatively charged with a high CEC, making it an excellent supplier of nutrients to plants. In addition, as organic matter decomposes, it releases nutrients such as N, P and S that are bound in the organic matter's structure, essentially imitating a slow release fertilizer (Myers, 1995). Organic matter can

also hold large amounts of water, which helps nutrients move from soil to plant roots (Mikkuta, 2004).

2.6 Contribution of soil organic matter to cation exchange capacity

The cation-exchange capacity (CEC) of soils is mainly due to clay minerals and soil organic matter. It has been demonstrated that the contribution of organic matter to total CEC of soil is usually substantial and is often considerably greater than that of the clay minerals (Baldock & Nelson, 1999).

Clay and organic matter are the main sources of CEC (Peinemann *et al.*, 2002). The more clay and organic matter (humus) a soil contains, the higher its CEC and the greater the potential fertility of that soil. CEC varies according to the type of clay. It is highest in montmorillonite clay, lowest in heavily weathered kaolinite clay and slightly higher in the less weathered illite clay (Peinemann *et al.*, 2002). Sand particles have no capacity to exchange cations because it has no electrical charge (Brady and Weil, 1999).

Accordingly, there is generally a good correlation between SOC and CEC. (McGrath *et al.*, 1988) noted that the CEC of a sandy loam soil increases from 75 to 158 cmole/kg-1 as SOC increases from 0.46 to 1.39%.

Furthermore, the importance of SOM to CEC increases as soils weather and change from 2:1 aluminosilicates (CEC = 15-30 cmole kg⁻¹ soil) to kaolinite and amorphous oxides of Fe and Al (CEC = <5 cmole kg⁻¹ soil). In fact, most of the CEC in kaolinitic soils is associated with SOM and as reported by (Duxbury *et al.*, 1989) it is important to maintain high SOM level especially in tropical and sandy soils. Based on statistical analyses, (Parfitt *et al.*, 1995) estimated CECs for a variety of components, which illustrates the dependence of CEC on SOM in highly weathered soils: 221 cmole/kg⁻¹ for OC, 70-110 cmole/kg⁻¹ for smectite, 50 cmole/kg⁻¹ for allophane, 25 cmole/kg-1 for chlorite, illite and vermiculite and 10 cmole/kg⁻¹ for kaolinite.

2.6.1 Cation exchange capacity of soil organic matter

Organic matter can have 4 to 50 times higher CEC per given weight than clay. By comparison, the amount of CEC from SOM components is commonly around 150-250 cmole/kg⁻¹ (Wolf and Snyder, 2003). However, the CEC of organic matter itself is much higher as reported by (Duxbury *et al.*, 1989), who found that average values for total acidity

of extracted humic substances were between 700-1000 cmole kg⁻¹ organic matter (Bloom 1999) obtained a mean CEC value for SOM of 2000 cmole kg⁻¹ (n=60, pH 8). The reason that such high values are usually not expressed in soils is due to the partial blocking of negatively charged sites by Al and Fe (particularly in Oxisols). However, the significant contribution of SOM to CEC is not in doubt.

A commonly used technique to assess the effect of organic matter on CEC is by the destruction of SOC by H₂O₂ oxidation. While it was considered possible that oxalates were produced during the oxidation procedure, only negligible amounts of oxalates were detected. The CEC (at pH 7) after H₂O₂ oxidation decreased in all samples and the difference in CEC before and after removal of organic matter was well correlated with organic matter.

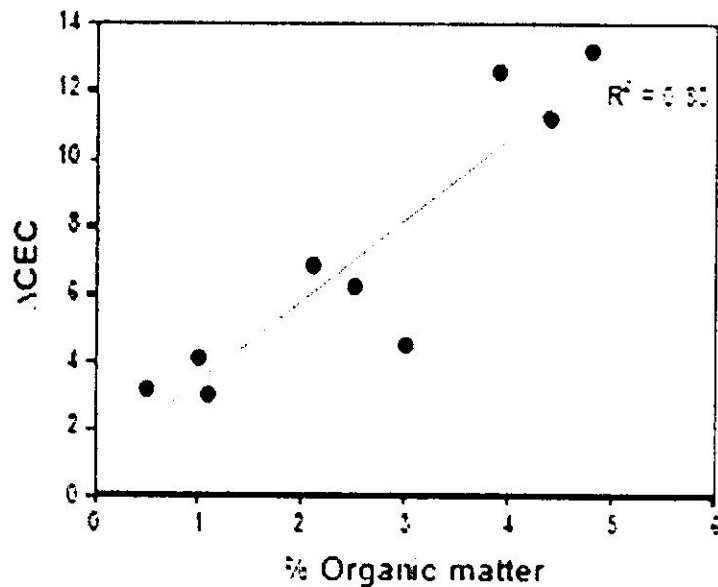


Figure 6: Relationship between ΔCEC and SOM (data from Clark and Nichols (1968)).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 DATA COLLECTION

Published data on cation exchange capacity (CEC), organic matter (OM), pH and clay were collected. Data on OC, CEC/ECEC, clay and pH were obtained from almost 200 publications on soils in Nigerian. The data collected were for soil samples taken at a depth of 0-20cm because organic matter contents at soil depth beyond these are quite insignificant in weathered soils. Sites and locations of the samples were from southern and northern part of Nigeria.

3.2 METHODS OF SOIL ANALYSIS

3.2.1 Soil pH

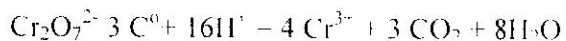
The soil pH was determined in 0.01M CaCl₂ and in H₂O with a pH glass electrode.

3.2.2 Organic Carbon

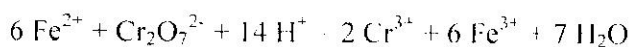
The soil organic carbon determination was based on the Walkley-Black chromic acid wet oxidation method. Organic carbon in the soil is oxidized by the dichromate ion (1 N K₂Cr₂O₇ solution). The reaction is assisted by the heat generated when two volumes of H₂SO₄ are mixed with one volume of the dichromate. The excess dichromate ion is back titrated with ferrous sulphate. The titre is inversely related to the amount of carbon present in the soil sample.

The selection of data was somewhat difficult because of the differences in methodology of OC determination and the soil calculations. Whereas Some of the published papers were full of wrong OM estimates, others were fair enough to be selected for final statistical analysis of the relationship between OC and CEC.

Dichromate ion reacts with carbon as follows:



Ferrous ion reacts with dichromate as follows:



3.2.3 Cation Exchange Capacity (CEC)

The cation exchange capacities of the soils were determined by the ammonium acetate method. The principle of measurement of CEC of soils by this method according to (Agbenin, 1995) involves four (4) basic steps

- 1 Saturation of the exchange site with a buffered solution of the NH_4^+ cation
- 2 Washing out of excess NH_4^+ salt with an alcohol
- 3 Displacing the NH_4^+ from the exchange site with a concentrated solution of another cation.
- 4 Determination of the amount of the NH_4^+ cation by the Kjeldahl distillation method.

Although the choice of cation may be governed by:

1. Ease of determination of the chosen cation.
2. The relative freedom of cation from fixation, hydrolysis and dispersion during washing

3.2.4 Particle size analysis.

Particle size analysis of the soils was done by the hydrometer method based on Stoke's law governing the rate of sedimentation of particles with varying sizes. Soil samples are treated with sodium hexametaphosphate to disperse the sand, clay and silt particles in soil aggregate. Vigorous stirring in an electric stirrer is done for further separation of clustered particles.

STATISTICAL ANALYSIS

The relationship between SOC and CEC was analysed by regression analysis to develop an empirical model for predicting the CEC from soil organic matter content. The regression analyses were performed in SIGMAPLOT statistical software (www.sigmaplot.com).

4.0. RESULT AND DISCUSSION

4.1. Selected Soil Properties

The pH of the soils used for this study ranged from 4.0-8.6, with a mean of 6.0 in water, and 3.4 to 7.8 with a mean of 5.5 in 0.01 M CaCl₂. On the basis of the pH in 0.01 M CaCl₂, the soils were strongly acidic to slightly alkaline (Table 1); Measurement of pH in water and dilute salt solution is required to fully define the character of soils. For instance, the greater pH of a soil in water than in a dilute salt solution is an indication of soils with a net negative charge (Goro and Uehara, 1985).

The clay concentration in the soils varied greatly, ranging from 147 to 665 g kg⁻¹ with a mean concentration of 124 g kg⁻¹ (Table 1). The soil texture was predominantly sandy except for few samples with extremely high clay content that exceeded 600 g kg⁻¹. It seems, a few of the soils were subsurface samples obtained from illuvial horizons. Generally, most arable soils in West Africa have clay contents ranging from 100 to 300 g kg⁻¹, rarely exceeding 350 g kg⁻¹ in the surface layer (Jones and Wild, 1975).

The concentration of organic carbon (OC) was quite low; varying between 0.24 and 29 g kg⁻¹ with a mean concentration of 4.8 g kg⁻¹ (Table 1). The relatively low concentration of OC in the soils is a consequence of the high rates of decomposition which exceed the rates of accretion of organic residues to the soils. High temperature and moisture availability accelerate microbial decomposition of organic residues and mineralization of organic matter in the soil. The concentrations of OC in the soils are consistent with the levels reported for many other soils in Nigeria and other West African countries (Jones and Wild, 1975; Kowal and Kassam, 1978).

The CEC concentrations were scanty ranging from 10 to 316 mmol kg⁻¹ or 1 to 32 emol kg⁻¹ (Table 1). Although, the CEC of a soil is the interplay of a number of factors, especially the clay concentration and type, some other factors also come into play. Such as pH and OC.

Soil property	No of samples	Range	Mean	Standard deviation
pH(H ₂ O)	177	4.0-8.6	6.0	±0.99
pH(CaCl ₂)	44	3.4-7.8	5.50	± 1.2
Clay (g/kg)	171	14.7-665	124.4	± 93.8
OC (g/kg)	191	0.24-28.7	4.76	± 5.42
CEC (mmol/kg)	191	10-316	32.4	± 33.8

Table 4.1 : Range of pH and the concentration of organic carbon (OC), Clay and CEC of the soils used for this study.

The low CEC concentrations of the soil probably reflect the low clay concentration and the nature of the soil clays. The soils dominated by low-activity clays (LAC), such as kaolinite, halloysite and oxides of Fe and Al, tend to have low CEC. It would seem therefore the soils used for the study are dominated by low-activity clays, in addition to the relatively low concentration of clays except for those samples from illuvial horizons. However, Jones and Wild (1957) indicated that 80 % of CEC of West African savanna soils is contributed by organic matter rather than the clay concentration because of the preponderance of LAC in the soils. For instance, the variation in the CEC of 11 soil samples from Samaru, Northern Nigeria, was predicted up to 94 % from its OC concentration as can be seen in Figure 1, suggesting that OC is a good predictor of CEC.

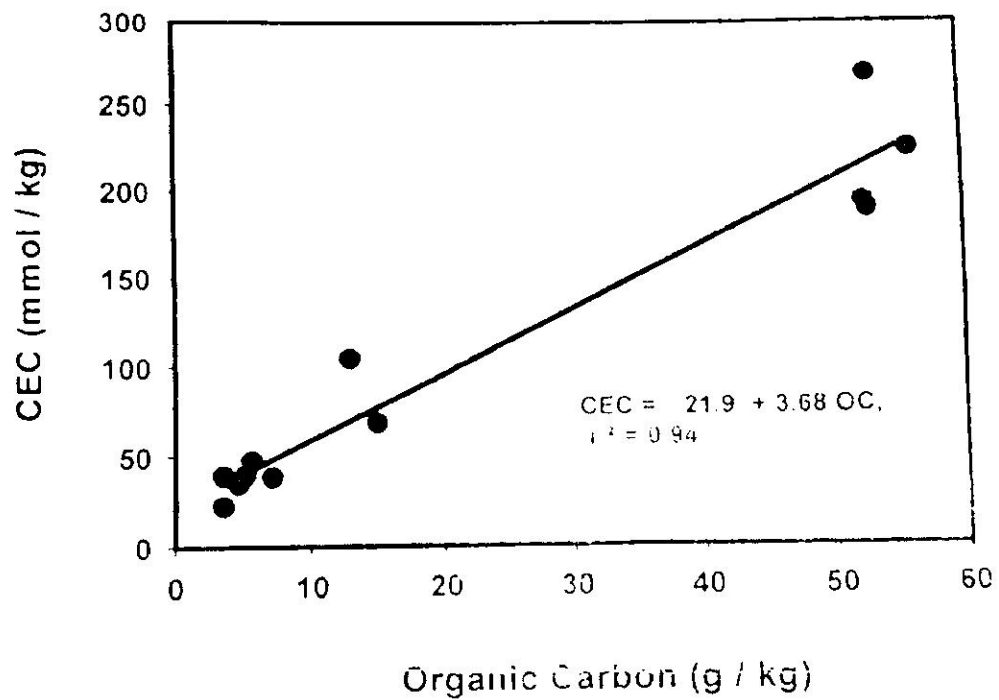


Figure 1. The relationship between concentration of organic carbon (OC) and cation exchange capacity (CEC) of some Haplustalls from Samaru, northern Nigeria (n = 11 samples)

4.2 Determinants of CEC of soils: A Quantitative Assessment

The study attempts to quantify the contribution of different soil factors to the CEC and develop an empirical model for estimating the CEC of Nigerian soils. The focus is on the contribution of OC to soil CEC. As a major soil parameter, the determination of CEC is quite expensive, laborious and time consuming. An empirical model that relates CEC to an easily measurable soil property will be worthwhile. Three soil properties that affect CEC significantly in soils are pH, clay and OC concentrations.

4.2.1 Relationship between pH and CEC

There is usually a significant relationship between pH and CEC in weathered tropical soils dominated by low activity clay because of the pH dependent charge that responds to potential determining ions, usually H^+ and OH^- ions. For the soils used in this study, the effect of pH on CEC is not significant (Fig. 2&3). The pH poorly predicted the cation exchange capacity of the soils.

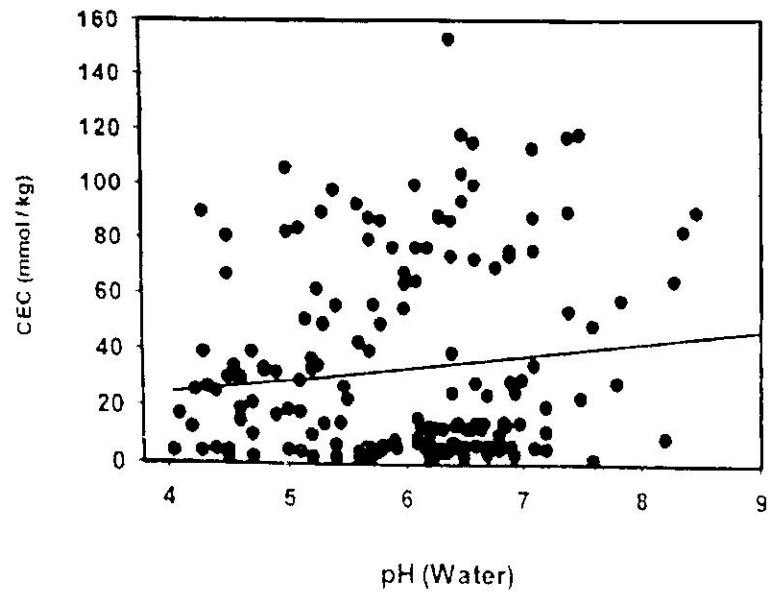


Figure 5. The relationship between pH in water and cation exchange capacity (CEC) of some Nigerian soils. The regression model is given by $CEC = 6.62 + 4.50 (pH_{(H_2O)})$ $r^2 = 0.017$ ($n = 182$ samples)

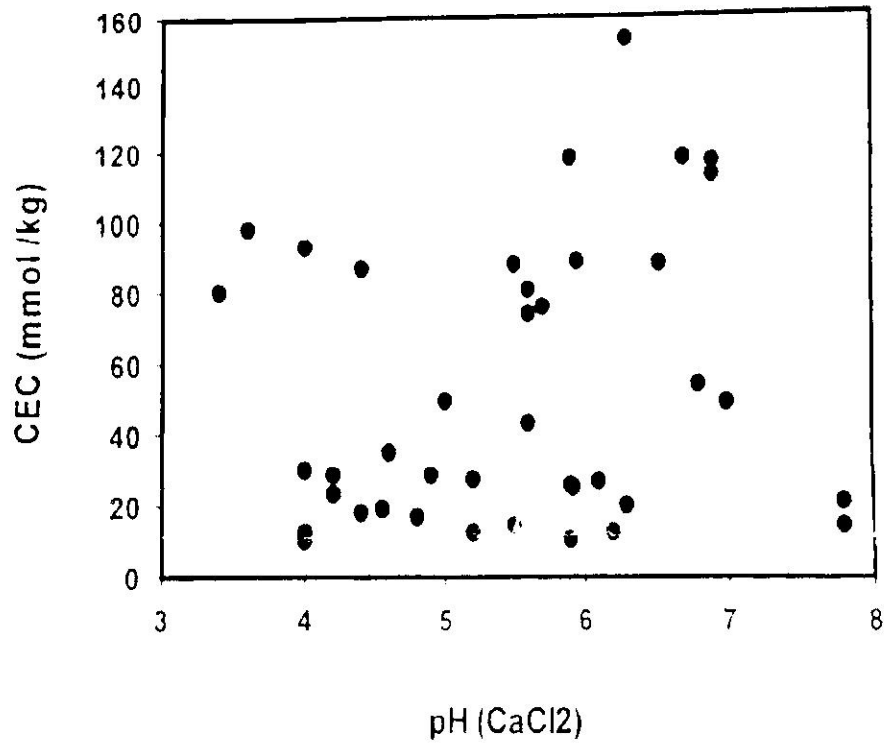


Figure 4. The relationship between the pH 0.01 M CaCl₂ solution and cation exchange capacity (CEC) of some Nigerian soils (n = 49 samples)

4.2.2 Relationship between clay concentrations and CEC

The clay concentration in a soil affects CEC profoundly. The higher the clay content, the higher the CEC of the soil. Apart from the clay concentration, the type of clay is of great importance. The 2:1 clay has greater CEC than 1:1 clay. For most weathered soils of the tropics such as these soils, the dominant clay is the low-activity clay that has little CEC as exhibited by the soils, the clay concentrations in the soils predict CEC up to 55% (Fig. 4).

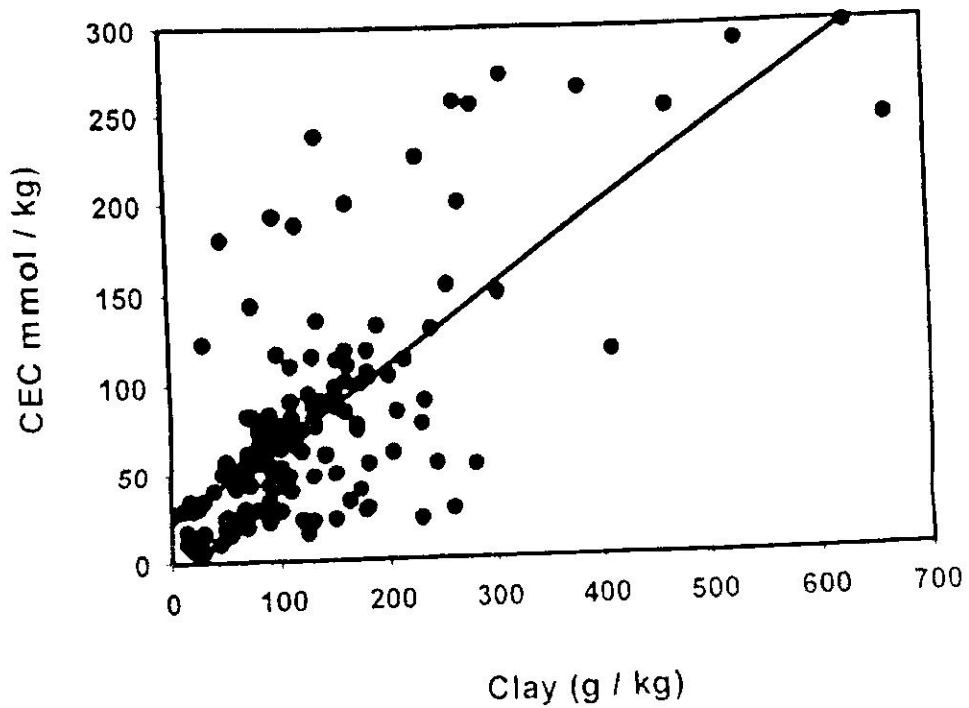


Figure 3. The relationship between the concentration of clay and cation exchange capacity (CEC) of some Nigerian soils. The regression model is given by $CEC = 22.3 + 0.44 (OC) - 0.55 (n = 171 \text{ samples})$

4.2.3 The relationship between OC and CEC

The soil organic carbon (OC) is a critical reactive component of the soil. Its role in the CEC of weathered soils has been alluded to in several studies, including the West African savanna soils: explain up to 80% of the variation in CEC. In the present study involving nearly 191 soil samples from various agroecological zones of Nigeria, the soil CEC was predicted up to 72% by OC. Jones and Wild (1973) showed that OC contributes nearly 80% of the CEC in west Africa savannah soils. For instance, analysis of CEC and OC relationship in 11 soils from Samaru of Nigeria shows a significance dependence of CEC on OC in the soil (Fig. 1) with OC accounting for about 94% of the variation in CEC.

One of the important properties of SOM, apart from its nitrogen content, is its high CEC that is associated with several chemically active groups. The CEC of humus is many times greater than clay. The many active functional groups that could protonate and deprotonate confers high CEC to humus or soil organic matter during. The process of humus formation, called humification, alters lignin in such a way that decreases the non-cation exchanging groups, such as methoxyl (-OCH₃), and increases the cation exchanging carboxyl groups. While charge development in SOM is predominantly negative, provided by functional groups, particularly carboxylic and phenolic acid groups, positive charge can occur through the protonation of amino groups but this is considered to be relatively small (Duxbury et al., 1989). The contribution of SOM to CEC can vary between 25-90% (Stevenson, 1994), depending on soil type, but most studies observed a contribution between 30-60% Tsutsuki, 1993; Loveland and Webb, (2003), 40-50%, respectively Thompson et al., 1989; Haynes and Naidu, (1998). Accordingly, there is generally a good correlation between SOC and CEC McGrath et al. (1988) noted that the CEC of a sandy soil increased from 75 to 158 cmol_ckg⁻¹ as SOC increased from 0.46 to 1.39%. Eshetu et al. (2004) also noted that there was a strong linear correlation.

Clay has high CEC because of their large surface area but the surface area of humus generally exceeds that of silicate clays and there is a dissociation of H⁺ from functional groups like carboxyl group (-COOH), phenolic group (-OH) etc, all this makes the exchange capacity of organic matter greater than that of clays. Humic acids in organic matter also attack soil minerals and accelerate their decomposition to release essential nutrients as exchangeable cations.

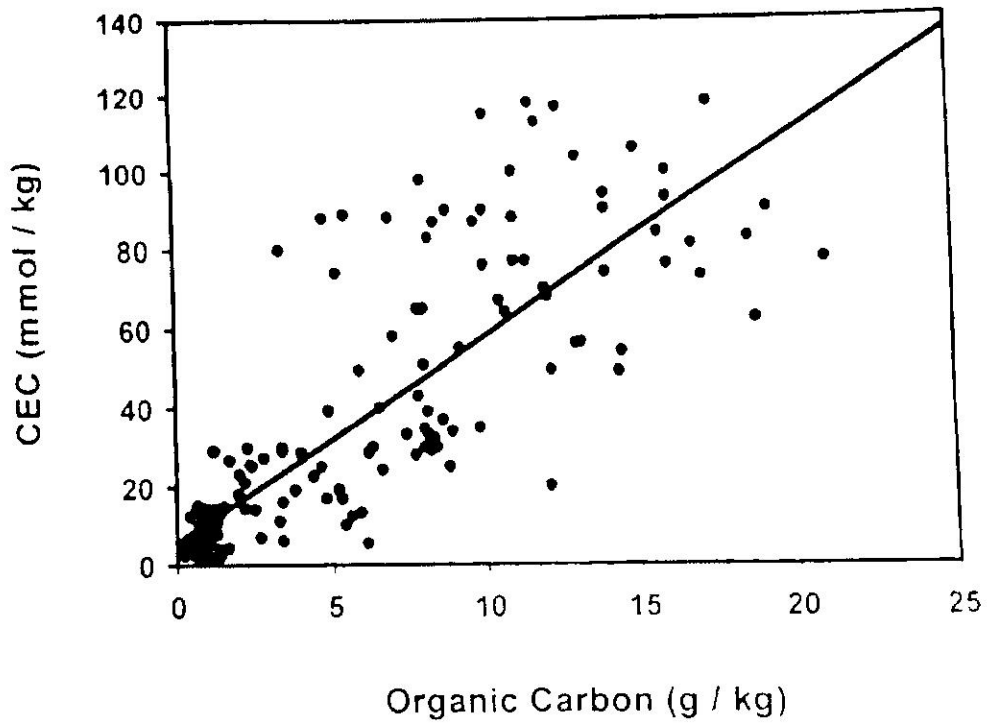


Figure 2. The relationship between concentration of organic carbon (OC) and cation exchange capacity (CEC) of some Nigerian soils. The regression model is given by $CEC = 5.81 + 5.23 (OC)$ $r^2 = 0.72$ ($n = 191$ samples).

CHAPTER 5

5.0. SUMMARY/CONCLUSION

Organic matter is a critical component of the soil that plays a significant role which exceeds its quantitative distribution. It is regarded as the major contributor of CEC. The soil OM has several functional groups, such as carboxylic, phenolic, ketonic, alcoholic, amino and sulphhydryl groups, that contribute to negative charge development of the soil through deprotonation. The contributions of clay and OM to the CEC of soils have been of great interest to many soil scientists; hence, attempts have been made to make predictions of CEC from clay and OC concentrations in soils. It is important to note that developing a predictive equation is a bit of a huge task. Moreover, predictive equations for soil CEC are, at best, applicable to limited agro-ecological zones. Most researchers fail to remember that the value of each factor believed to increase or decrease the CEC can be complicated by some climatic factors.

Different attempts have been made by most soil scientists though, yet there is no one predictive model for estimating CEC from OC that has global relevance. The predictive model from this study requires further validation for soils from other regions before it can be reliably recommended for CEC estimation. However, consistent with the reports of other workers on this subject, the soil OC explains about 72% of the variations in CEC of the experimental soils. The predictive model equation is $CEC = 5.81 + 5.23 (OC)$, $r^2 = 0.72$. This predictive model for CEC estimation from OC can serve as a departure point for further studies, involving a much larger number of samples than the number of samples used in the present study.

Although pH and clay content of soils are major factors affecting CEC, their contributions to charge development were marginal in the experimental soils. It is not clear why pH and clay concentration did not make any significant contributions to CEC through the pH-dependent charge of soil colloids. However, the clay concentration explains the CEC up to 55 %. One major limitation of the data collected for this study is the variation in analytical methods used for the determination of CEC and the clay concentration, including even the pH of the soils. Future studies must endeavour to collect data of pH, and the clay and OC concentrations determined by standard analytical methods.

REFERENCES

- Agbenin, J.O. 1995. Laboratory Manual for Soil and Plant Analysis. Department of soil science, Faculty of Agriculture, Ahmadu Bello University, Zaria.
- Angers, D. A. and Carter, M. R. 1996. Aggregation and organic matter storage in cool, humid agricultural soils. In 'Structure and organic matter storage in agricultural soils. (CRC Press: Boca Raton.) 193-211.
- Ashman, M and Puri G, 2002. Essential Soil Science: A Clear and Concise Introduction to Soil Science
- Baldock, J. A. and Nelson, P. N. 1999. Soil Organic Matter. In 'Handbook of Soil Science. USA: CRC Press: Boca Raton. USA. Ed M. 25-84.
- Baldock, J. A., Oades, J. M., Waters, A. G., Peng, X., Vassallo, A. M., and Wilson, M. A. 1992. Aspects of the chemical structure of soil organic materials as revealed by solid-state ¹³C NMR spectroscopy. Biogeochem. 16: 1-42.
- Baldock, J. A. and Skjemstad, J. O. 1999. Soil organic carbon/soil organic matter. In 'Soil Analysis: an Interpretation Manual. (CSIRO Publishing: Collingwood.) 159-170.
- Baldock, J. A. and Skjemstad, J. O, 2000. Role of the soil matrix and minerals in protecting natural organic materials against biological attack. Org. Geochem. 31: 697-710.
- Brady and Weil. 1999. The nature and properties of soils, 12th edition. prentice hall publisher, LONDON.
- Brady, N. C. 1990. 'The nature and properties of soils. MacMillan Publishing Company: New York.

Brady, N.C., and Weil, R. 2004. Elements of the nature and properties of soil. 2nd edition. Pearson Prentice Hall, New Jersey.

Brady, N. C., and Weil, R. 2008. The nature and properties of soil 14th edition. Pearson Prentice Hall, New Jersey.

Begaya and Vayer, 1997. CEC of clays: Measurement by adsorption of a copper ethylenediamine complex. *Appl Clay Sci.* 12: 275-280.

Bloom, P. R. 1999. Soil pH and pH buffering. In 'Handbook of Soil Science. CRC Press, Boca Raton, Florida (Ed M. E. Sumner.) 333 - 352.

Carter, M. R. 1992. Influence of reduced tillage systems on organic matter, microbial biomass, macroaggregate distribution and structural stability of the surface soil in a humid climate. *Soil Till. Res.* 23: 361-372.

Carter, M. R. and Stewart, B. A. 1996. 'Structure and organic matter storage in agricultural soils.' CRC Press: Boca Raton.

Chaney, K. and Swift, R. S. 1984. The influence of organic matter on aggregate stability in some British soils. *J. Soil Sci.* 35: 223-230.

Curtin, D., Campbell, C. A., and Messer, D, 1996. Prediction of titratable acidity and soil sensitivity to pH change. *J. Environ Qual.* 25: 280-284.

De Jong, R. 1983. Soil water desorption curves estimated from limited data. *Can. J. Soil Sci.* 63: 697-703.

Doran, J. W. and Safley, M, 1997. Defining and assessing soil health and sustainable productivity. In 'Biological Indicators of Soil Health. (Eds C. E. Pankhurst, B. M. Doube, and V. V. S. R. Gupta.) CAB International: New York, 1-28.

- Duxbury, J. M., Smith, M. S., and Doran, J. W., 1989. Soil organic matter as a source and a sink of plant nutrients. In 'Dynamics of soil organic matter in tropical ecosystems. (Eds D. C. Coleman, J. M. Oades, and G. Uehara.). University of Hawaii Press: Honolulu, 33-67.
- Elliott, E. T., 1997. Rationale for developing bioindicators of soil health. In 'Biological Indicators of Soil Health. CAB International: New York, 49-78.
- Goro, Uehara, 1985. The mineralogy, chemistry and physics of tropical soils. 4:139-380
- Haynes, R. J. and Naidu, R., 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nut. Cycl. Agron.* 51: 123-137.
- Haynes, R. J. and Swift, R. S., 1990. Stability of soil aggregates in relation to organic constituents and soil water content. *Journal of Soil Science* 41: 73-83.
- Haynes R.J., & Labile J., 2005 organic matter fractions as central components of the quality of agricultural soils: an overview. *Adv. Agron.* 85: 221–268.
- Howard, P. J. A. and Howard, D. M., 1990. Use of organic carbon and loss-on-ignition to estimate soil organic matter in different soil types and horizons. *Bio. Fertil. Soils*, 9: 306-310.
- Jones, M., and Wild, A., 1973. The organic matter content of the savanna soils of west africa. *J. Soil Sci.* 24, 42-53.
- Jones, M., & Wild, A., 1975. Soils of west African savanna. England: Commonwealth Agricultural Bureaus, Wallingford, England.
- Kay, B. D. and Angers, D. A., 1999. Soil Structure. In 'Handbook of Soil Science. (Ed M. E. Sumner.) CRC Press: Boca Raton, USA, 229 -276.

Ketterings, Q., Reidand, S., & Renuka, R. 2007. Cation Exchange Capacity (CEC). Agronomy Fact Sheet: Series 22 .

Kim, Tan, H. 2014. principles of soil chemistry (Fourth edition ed.). CRC press Taylor and Francis group.

Kowal, J.M., and Kassam, A. 1978. Agricultural ecology of savanna. Commonwealth Agricultural Bureaus, Harpenden, England.

Krull, E. S., Skjemstad, J. O., & Baldock, A. J. 2000. Functions of Soil Organic Matter and the Effect on Soil Properties.

Loveland, P. and Webb, J. 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. *Soil Till. Res.* 70: 1-18.

Magdoff, F. R. and Bartlett, R. J. (1985). Soil pH buffering revisited. *Soil Sci Soc. Am. J.* 49:145-148.

McGrath, S. P., Sanders, J. R., and Shalaby, M. H. 1988. The effects of soil organic matter levels on soil solution concentrations and extractibilities of manganese, zinc and copper. *Geoderma*, 42: 177-188.

M.D.A Bolland, A.Mposner, & Quirk, J. 1980. pH-Independent and pH-dependent surface charges on kaolinites soils.

McDowell, M., Bruland, G., Deenik, J., & Grunwald, S. (2012). Effects of subsetting by carbon content, soil order, and spectral classification on prediction of soil total carbon with diffuse reflectance spectroscopy. *Appl. Environ. Soil Sci*, 22: 1-14.

Nelson, P. N., Baldock, A., Clarke, P., Oades, J. M., and Churchman, G. J. (1999). Dispersed clay and organic matter in soil: their nature and associations. *Aust J. Soil Res.* 37: 289-316.

Oades, J. M. (1984). Soil organic matter and waterstable aggregates in soils. *Plant Soil* 76, 319-337.

Parfitt, R. L., Giltrap, D. J., and Whitton, J. S. (1995). Contribution of organic matter and clay minerals to the cation exchange capacity of soils. *Comm. Soil Sci Plant Anal*, 26: 1343-1355.

Peverill, K. I., Sparrow, L. A., and Reuter, D. J. 1999. 'Soil Analysis. An Interpretation Manual.' CSIRO Publishing: Collingwood.

Rowell, D.L. 1994. *Soil science: Methods & applications*. John Wiley & Sons Inc. New York. 350.

Starr, M., Westman, C. J., and Ala-Reini, J. 1996. The acid buffer capacity of some Finnish forest soils: Results of acid addition laboratory experiments. *Water, Air Soil Pollut* 89, 147-157.

Tan, K. H. and Dowling, P. S. 1984. Effect of organic matter on CEC due to permanent and variable.

Tisdall, J. M. and Oades, J. M. 1982. Organic matter and waterstable aggregates in soils. *J. Soil Sci.* 33: 141-163

Van, R. E., Qafoku, N., Noble, A., & Xu, R. 2017. Variable charge soils : mineralogy and chemistry. In R. Lal (Ed.). Taylor and Francis, CRC Press

Wilhelm, N. 2001. Importance of organic matter (biomass). GRDC Research updates - southern region, 1- 3.

Wolf, B. and Snyder, G. H. 2003. 'Sustainable Soils: The place of organic matter in sustaining soils and their productivity.' (Food Products Press of The Haworth Press : New York.)

Oades, J. M., Gillman, G. P., and Uehara, G. 1989. Interactions of soil organic matter and variable-charge clays. In 'Dynamics of soil organic matter in tropical ecosystems. Eds D. C. University of Hawaii Press: Honolulu.69-95.

Sposito, G. 2008. The chemistry of soils: 2nd edition. New York: Oxford University Press, New York.

APPENDIX

Appendix 1: relationship between CEC and Ph_{water}

LOCATION/ SITE	SOIL		
	DEPTH	pH/ IN H2O	CEC Cmol/kg
KAKURI	0-15	4.2	123
KAKAU	0-15	4.9	268
TRIKANIYA	0-15	6.2	104
ROMI	0-15	5.4	68
GYALLESU	0-15	7.4	15.4
KAMACA	0-15	7.6	14.9
KABBUNI BRIDGE	0-15	7.5	11.8
CONTROL	0-15	6.4	7.4
BASHAMA ROAD	0-15	7.4	11.7
UNGUWAR MUAZU	0-15	7.2	20
SHETIMA ROAD	0-15	7.1	11.3
CONTROL	0-15	6.5	11.8
KARI 1	0-15	5.8	87
KARI 2	0-15	5.7	80
K.WAMBAI 1	0-15	5.4	98
K.WAMBAI 2	0-15	5.7	88
ALKARI	0-15	4.7	21
KOLORI	0-15	6.1	16
FCE GOMBE 1	0-15	5.1	18
FCE GOMBE 2	0-15	4.6	19
MAZA	0-15	7.1	76
DAKUL 1	0-15	5.6	43
DAKUL 2	0-15	5.6	93
ASHAKA 1	0-15	7.1	316
ASHAKA 2	0-15	7	298
OBOKUN	0-15	4.5	81
OFFA	0-15	6.4	53
IDOFIAN	0-15	6.4	83

ZARIA	0-15	5.8	71
MOKWA	0-15	4.6	65
JOS	0-15	4.7	10.1
MINNA	0-15	6.8	5.05
MOKWA	0-15	6.7	6.32
APOMU	0-15	5.2	2.35
IHIAGWE (OWERRI)	0-15	4.28	4.14
EGWE (OGUTA)	0-15	4.05	4.03
AMAURO (OKIGWE)	0-15	4.01	6.47
MBATO (OKIGWE)	0-15	4.35	5.37
KANO	0-15	6.9	8.7
BOBO	0-15	6.4	10.4
SIKASSO	0-15	6.5	10.6
SAMARU SOIL 1	0-15	5	3.32
SAMARU SOIL 2	0-15	5.2	2.98
SAMARU SOIL 3	0-15	4.6	2.26
SAMARU SOIL 4	0-15	5.5	3.92
AMAVO	0-15	4.3	3
OSSIOMA	0-15	4.3	2.8
AMASA	0-15	4.3	2.92
UMOBASI	0-15	4.5	3.32
<hr/>			
BADEGGI NATIONAL CEREAL			
INSTITUTE	0-15	5.4	6.01
BADEGGI	0-15	5.4	6.03
SAMARU	0-10	6.2	6.8
SAMARU	0-20	6	5.7
FAKO	0-10	5.66	2.4
FAKO	0-15	5.7	4.1
TSAKWANYA	0-15	6.35	6.8
TSAKWANYA	0-17	6.41	6
LAKA	0-18	6.41	11.6
JERE KADUNA	0-15	4.2	2.35
JERE KADUNA	0-13	4.7	3.24

JERE KADUNA	0-14	4.5	1.66
JERE KADUNA	0-8	6.2	2.79
AGO ATSAVIYA (HFV)	0-15	7.3	257
AGO ATSAVIYA (IFF)	0-15	5.9	238
OSARA OKENE (SGV)	0-15	6.6	200
OSAVA (SGF)	0-15	5.2	90
KAGORO (NGV)	0-15	5.3	84
KACHIA KAGORO (NGF)	0-15	5.1	110
TAMARINDES ZAMFARA (NZ)	0-15	6.2	7.6
ADANSONIA ZAMFARA (NZ)	0-15	6.2	5.4
PILOSTIGNE ZAMFARA (NZ)	0-15	6.3	6.5
COMBRETUM ZAMFARA (NZ)	0-15	6.6	5.8
CASSIA ZAMFARA (NZ)	0-15	6.5	5.3
BRACHIARIA ZAMFARA (NZ)	0-15	5.8	5.7
INTERPHASE ZAMFARA (NZ)	0-15	6.7	5.5
TAMARINDUS (CZ)	0-15	5.7	6.4
ADANSONIA (CZ)	0-15	6	7.3
PILOGTIGNA (CZ)	0-15	6.1	6.4
COMBRETUM (CZ)	0-15	5.8	5.6
CASSIA (CZ)	0-15	6.4	5.4
BRACHIARIA ZAMFARA (CZ)	0-15	6.4	5.6
INTERPHASE ZAMFARA (CZ)	0-15	6.8	6.6
TAMARINDUS (SZ)	0-15	5.4	7.3
ADANSONIA (SZ)	0-15	6.6	7.5
PILOGTIGNA (SZ)	0-15	6.4	7.7
COMBRETUM (SZ)	0-15	6.2	7.3
CASSIA (SZ)	0-15	6.8	7.5
BRACHIARIA ZAMFARA (SZ)	0-15	5.9	6.1
INTERSPACE ZAMFARA (SZ)	0-15	6.5	3.4
FARU	0-7	5.7	5.2
KWASHIBAWA	0-10	7.2	5.6
RUKU DAWA	0-15	7.1	6.8
SAMARU 1993	0-15	6.43	3.1

SAMARU 1994	0-15	6.93	2.9
SAMARU 1995	0-15	6.25	3.4
AGRIC RESEARCH ZARIA	0-15	6.7	2.3
AGRIC RESEARCH FARM ZARIA	0-16	5.7	10.1
ILLELA	0-15	5.2	1.8
SOKOTO	0-15	5.6	2.2
SANGIWA	0-15	5.7	1.5
JERE BOWL PEDON 1	0-11	7.6	24.34
JERE BOWL PEDON 2	0-13	6.7	29
JERE BOWL PEDON 3	0-10	6.9	13
JERE BOWL PEDON 5	0-10	6.2	11.3
JERE BOWL PEDON 6	0-15	7.2	10.3
AFAKA FOREST RESERVE	0-13	6.8	8.2
AFAKA FOREST RESERVE	0-12	5.9	7.7
AFAKA FOREST RESERVE	0-8	5.9	4.8
SAMARU RESEARCH FARM	0-15	4.4	6.1
KOKI	0-15	6.9	8.8
ZUNGERU	0-15	7.1	11.5
KWANKWACI	0-15	6.6	10
GADA	0-15	6.6	9
KASTINA ROAD	0-15	7.4	7.4
SITE 1	0-15	5.79	4.95
SITE 2	0-15	5.25	6.2
TISAFE	0-15	6.17	5.14
	0-15	5.92	5.48
	0-15	5.69	3.99
EMUADO	0-15	5.7	2.79
DABAGI (2008)	0-15	5.73	5.64
DABAGI (2009)	0-15	5.41	5.61
KANO	0-15	8.28	6.5
ZAMFARA	0-15	7.84	5.8
SOKOTO	0-15	8.47	9
KEBBI	0-15	8.36	8.3

AMBROSE (ALLI UNIVERSITY)	0-15	5.15	5.06
SAMARU	0-15	4.7	39.1
BODIJA MARKET	0-15	7.5	23.1
ILE OGBON	0-15	6.4	2.5
OLUKUNLE	0-15	6.3	1.5
KUMAPAYI	0-15	6.3	5.6
LAGOS CONTONMENT	0-15	5.9	1
AWOTAN APETE	0-15	8	64.6
ASKAR PAINT	0-15	7.8	28.4
NISER DUMPSITE	0-15	6.6	28.5
YARTAGIMBE	0-15	5.47	2.72
WASSANIYA	0-15	4.33	2.66
TIMAJIRI	0-15	6.94	2.52
DAJI	0-15	4.23	2.55
	0-15	6.25	12.36
	0-15	6.57	12.5
	0-15	6.13	12.52
	0-15	6.98	14.34
	0-15	6.86	13.56
	0-15	6.3	12.54
	0-15	6.43	13.4
	0-15	6.84	14.54
	0-15	6.26	12.5
	0-15	6.67	14.36
	0-15	6.56	12.56
	0-15	6.85	14.36
	0-15	6.52	12.34
	0-15	6.45	14.36
	0-15	6.65	12.36
	0-15	6.17	12.56
	0-15	6.32	12.32
	0-15	6.45	14.26
	0-15	6.78	14.2

	0-15	6.6	9
	0-15	8.2	19.3
	0-15	9.5	18.8
	0-15	5	3.32
	0-15	5.2	2.98
	0-15	4.6	2.26
	0-15	5.5	3.92
EKSU OILPALM PLANTATION	0-15	6.4	70
EKSU TEAK PLANTATION	0-15	6.5	94
EKSU WETLAND A	0-15	5.9	77
EKSU WETLAND B	0-15	6.1	77
EKSU WETLAND C	0-15	6.1	100
EKSU CASSAVA PLANTATION	0-15	6.6	75
EKSU MAIZE PLANTATION	0-15	6.1	65
EKSU VEGETABLE PLANTATION	0-15	6.9	76
	0-15	4.5	3.33
	0-15	4.55	3.02
	0-15	4.4	2.5
	0-15	4.9	3.2
	0-15	4.8	3.24
	0-15	4.8	3.34
	0-15	5.2	3.69
	0-15	5.25	3.46
IBADAN	0-15	5.44	14.37
OWENA	0-15	5.76	4.14
OVIA (CASSAVA PLANTATION)	0-15	5.1	4.29
OVIA (OIL PALM PLANTATION)	0-15	4.5	4.39
OVIA (BANANA PLANTATION)	0-15	5	4.75
OWERRI	0-15	5	8.2
MKPUKE (HIGHWAY)	0-15	4.6	2.8
EKPUKE (INDUSTRIAL AREA)	0-15	4.5	2.2
ASOKWA CONTROL	0-15	4.5	2.9

SAMARU (AGRIC RESEARCH)	0-15	5.1	8.9
IKORODU	0-15	6.1	1.4
OJO	0-15	5.3	6.7
AGERIGE	0-15	4.5	5.5
BENIN	0-15	5.99	4.18
ASABA CAMPUS	0-15	6.31	2.34
EMMANUEL ALAYANDE			
COLLEGE OYO	0-15	6.5	16.95
UNIVERSITY OF CALABAR	0-15	4.1	4.37
EKSU TEACHING AND			
RESEARCH FARM	0-15	5.6	2.27

Appendix 2: relationship between CEC and $\text{pH}_{\text{CaCl}_2}$

LOCATION/ SITE	SOIL DEPTH	pH IN CaCl_2 0.01m	CEC Cmol/kg
KAKURI	0-15	4	123
KAKAU	0-15	4.8	268
TRIKANIYA	0-15	5.9	104
ROMI	0-15	5.2	68
GYALLESU	0-15	5.2	15.4
KAMACA	0-15	6.8	14.9
KABBUNI BRIDGE	0-15	7	11.8
CONTROL	0-15	6.7	7.4
BASHAMA ROAD	0-15	5.6	11.7
UNGUWAR MUAZU	0-15	6.9	20
SHETTIMA ROAD	0-15	6.3	11.3
CONTROL	0-15	6.9	11.8
ZARIA	0-15	5.9	71
MOKWA	0-15	6.9	65
JOS	0-15	4.4	10.1
ABU FACULTY OF AGRIC	0-15	3.4	9
UNGUWA MUAZU	0-15	3.6	20
BASHAMA	0-15	3.6	11.7
SHETTIMA	0-15	5.5	11.3
BOMPAL	0-15	5.5	14.8
	0-15	12.1	15.2
	0-15	12.5	13.2
	0-15	11.8	6.8
	0-15	11.8	5.7
	0-15	11.5	2.35

SHARADA	0-15	6.2	3.24
CHALLAWA	0-15	7.8	1.66
SAMARU	0-10	5.7	2.79
SAMARU	0-15	5.6	257
JERE KADUNA	0-15	4	238
JERE KADUNA	0-13	4.6	200
JERE KADUNA	0-14	4	90
JERE KADUNA	0-8	5.6	84
AGO ATSAVIYA (HFV)	0-15	6.3	110
AGO ATSAVIYA (HFF)	0-15	4.5	3.1
OSARA OKENE (SGV)	0-15	5.3	2.9
OSAVA (SGF)	0-15	4.2	3.4
KAGORO (NGV)	0-15	4	2.3
KACHIA KAGORO (NGF)	0-15	4.2	10.1
SAMARU 1993	0-15	5.92	1.8
SAMARU 1994	0-15	6.53	2.2
SAMARU 1995	0-15	5.95	2.2
AGRIC RESEARCH ZARIA	0-15	5.7	1.5
AGRIC RESEARCH FARM ZARIA	0-16	4.7	24.34
ILLELA	0-15	4.9	29
SOKOTO	0-15	4.2	13
SANGIWA	0-15	5.2	11.3
JERE BOWL PEDON 1	0-11	6.1	10.3
JERE BOWL PEDON 2	0-13	0.25	6.1
JERE BOWL PEDON 3	0-10	5.9	39.1
JERE BOWL PEDON 5	0-10	5.2	
JERE BOWL PEDON 6	0-15	5.2	
SAMARU RESEARCH FARM	0-15	4	
SAMARU	0-15	4.4	
	0-15	5.5	9
	0-15	7.8	19.3
	0-15	8.6	18.8
SAMARU (AGRIC RESEARCH)	0-15	3.55	8.9

Appendix 3: relationship between CEC and CLAY

LOCATION SITE	SOIL DEPTH	CLAY g/kg-1	CEC Cmol/kg
KAKURI	0-15	31.3	123
KAKAU	0-15	14.7	268
TRIKANIYA	0-15	14.7	104

ROMI	0-15	16.7	68
GYALLESU	0-15	256	15.4
KAMACA	0-15	304	14.9
KABBUNI BRIDGE	0-15	180	11.8
CONTROL	0-15	120	7.4
BASHAMA ROAD	0-15	98	11.7
UNGUWAR MUAZU	0-15	268	20
SHETIMA ROAD	0-15	152	11.3
CONTROL	0-15	160	11.8
KARI 1	0-15	130	87
KARI 2	0-15	130	80
K.WAMBAI 1	0-15	150	98
K.WAMBAI 2	0-15	150	88
ALKARI	0-15	90	21
KOLORI	0-15	30	16
FCE GOMBE 1	0-15	50	18
FCE GOMBE 2	0-15	70	19
MAZA	0-15	90	76
DAKUL 1	0-15	90	43
DAKUL 2	0-15	150	93
ASHAKA 1	0-15	630	316
ASHAKA 2	0-15	630	298
OBOKUN	0-15	110	81
OFFA	0-15	70	53
IDOFIAN	0-15	90	83
ZARIA	0-15	115	71
MOKWA	0-15	735	65
MINNA	0-15	47	5.05
MOKWA	0-15	89	6.32
IHIAGWE (OWERRI)	0-15	60	4.14
EGWE (OGUTA)	0-15	40	4.03
AMAURO (OKIGWE)	0-15	80	6.47
MBATO (OKIGWE)	0-15	280	5.37
KANO	0-15	150	8.7
BOBO	0-15	200	10.4
SIKASSO	0-15	180	10.6
SAMARU SOIL 1	0-15	90	3.32
SAMARU SOIL 2	0-15	90	2.98
SAMARU SOIL 3	0-15	230	2.26
SAMARU SOIL 4	0-15	110	3.92
ABU FACULTY OF AGRIC	0-15	138	9

UNGUWA MUAZU	0-15	268	20
BASHAMA	0-15	98	11.7
SHETTIMA	0-15	152	11.3
BOMPAI	0-15	135	14.8
SHARADA	0-15	125	15.2
CHALLAWA	0-15	190	13.2
AMAVO	0-15	25	3
OSSIOMA	0-15	72	2.8
AMASA	0-15	68	2.92
UMOBASI	0-15	163	3.32
BADEGGI NATIONAL CEREAL INSTITUTE	0-15	140	6.01
BADEGGI	0-15	141	6.03
FAKO	0-10	50	2.4
FAKO	0-15	60	4.1
TSAKWANYA	0-15	20	6.8
TSAKWANYA	0-17	30	6
LAKA	0-18	410	11.6
AGO ATSAVIYA (HFV)	0-15	266	257
AGO ATSAVIYA (HFF)	0-15	138	238
OSARA OKENE (SGV)	0-15	164	200
OSAVA (SGF)	0-15	109	90
KAGORO (NGV)	0-15	159	84
KACHIA KAGORO (NGF)	0-15	162	110
TAMARINDUS ZAMFARA (NZ)	0-15	80	7.6
ADANSONIA ZAMFARA (NZ)	0-15	90	5.4
PILOSTIGNE ZAMFARA (NZ)	0-15	80	6.5
COMBRETUM ZAMFARA (NZ)	0-15	70	5.8
CASSIA ZAMFARA (NZ)	0-15	100	5.3
BRACHIARIA ZAMFARA (NZ)	0-15	50	5.7
INTERPHASE ZAMFARA (NZ)	0-15	50	5.5
TAMARINDUS (CZ)	0-15	90	6.4
ADANSONIA (CZ)	0-15	110	7.3
PILOGTIGNA (CZ)	0-15	100	6.4
COMBRETUM (CZ)	0-15	80	5.6
CASSIA (CZ)	0-15	70	5.4
BRACHIARIA ZAMFARA (CZ)	0-15	70	5.6
INTERPHASE ZAMFARA (CZ)	0-15	90	6.6
TAMARINDUS (SZ)	0-15	90	7.3
ADANSONIA (SZ)	0-15	80	7.5
PILOGTIGNA (SZ)	0-15	80	7.7

COMBRETUM (SZ)	0-15	80	7.3
CASSIA (SZ)	0-15	90	7.3
BRACHIARIA ZAMFARA (SZ)	0-15	70	6.1
INTERSPACE ZAMFARA (SZ)	0-15	30	3.4
FARU	0-7	60	5.2
KWASHIBAWA	0-10	70	5.6
RUKU DAWA	0-15	100	6.8
SAMARU 1993	0-15	16	3.1
SAMARU 1994	0-15	20	2.9
SAMARU 1995	0-15	18	3.4
AGRIC RESEARCH ZARIA	0-15	150	2.3
AGRIC RESEARCH FARM ZARIA	0-16	160	10.1
ILLELA	0-15	50	1.8
SOKOTO	0-15	90	2.2
SANGIWA	0-15	30	1.5
JERE BOWL PEDON 1	0-11	665	24.34
JERE BOWL PEDON 2	0-13	530	29
JERE BOWL PEDON 3	0-10	240	13
JERE BOWL PEDON 5	0-10	215	11.3
JERE BOWL PEDON 6	0-15	181	10.3
AFAKA FOREST RESERVE	0-13	74	8.2
AFAKA FOREST RESERVE	0-12	230	7.7
AFAKA FOREST RESERVE	0-8	130	4.8
SAMARU RESEARCH FARM	0-15	203	6.1
KOKI	0-15	150	8.8
ZUNGERU	0-15	130	11.5
KWANKWACI	0-15	110	10
GADA	0-15	110	9
KASTINA ROAD	0-15	170	7.4
SITE 1	0-15	93	4.95
SITE 2	0-15	118.8	6.2
IISAFE	0-15	96	5.14
	0-15	243.5	5.48
	0-15	173.5	3.99
EMUADO	0-15	100.5	2.79
DABAGI (2008)	0-15	25	5.64
DABAGI (2009)	0-15	25	5.61
KANO	0-15	114	6.5
ZAMFARA	0-15	108	5.8
SOKOTO	0-15	233	9
KEBBI	0-15	207	8.3

AMBROSE (ALLI UNIVERSITY)	0-15	49	5.06
SAMARU	0-15	190	39.1

Appendix 4: relationship between CEC and OM

LOCATION: SITE	SOIL DEPTH	OM g kg ⁻¹	CEC Cmol/kg
KAKURI	0-15	5.6	123
KAKAU	0-15	5.3	268
TRIKANIYA	0-15	1.3	104
ROMI	0-15	1.5	68
GYALLESU	0-15	14.5	15.4
KAMACA	0-15	14.4	14.9
KABBUNI BRIDGE	0-15	11.6	11.8
CONTROL	0-15	14	7.4
BASHAMA ROAD	0-15	12.5	11.7
UNGUWAR MUAZU	0-15	12.1	20.3
SHETIMA ROAD	0-15	11.8	11.3
CONTROL	0-15	17.4	11.8
KARI 1	0-15	8.4	87
KARI 2	0-15	3.4	80
K. WAMBAI 1	0-15	8	98
K. WAMBAI 2	0-15	4.8	88
ALKARI	0-15	2.2	21
KOLORI	0-15	3.4	16
FCE GOMBE 1	0-15	2	18
FCE GOMBE 2	0-15	3.8	19

MAZA	0-15	1.6	76
DAKUL 1	0-15	7.8	43
DAKUL 2	0-15	1.6	93
ASHAKA 1	0-15	1	316
ASHAKA 2	0-15	2.3	298
OBOKUN	0-15	16.8	81
OFFA	0-15	28.7	53
IDOFIAN	0-15	30.3	83
ZARIA	0-15	3.7	71
MOKWA	0-15	1.75	65
JOS	0-15	8.4	10.1
MINNA	0-15	2.39	5.05
MOKWA	0-15	3.3	6.32
APOMU	0-15	6	2.35
IIIAGWE (OWERRI)	0-15	8.13	4.14
EGWE (OGUTA)	0-15	1.32	4.03
AMAURO (OKIGWE)	0-15	22.4	6.47
MBATO (OKIGWE)	0-15	28.4	5.37
KANO	0-15	9.7	8.7
BOBO	0-15	13.1	10.4
SIKASSO	0-15	15	10.6
SAMARU SOIL 1	0-15	7.4	3.32
SAMARU SOIL 2	0-15	3.4	2.98
SAMARU SOIL 3	0-15	4.4	2.26
SAMARU SOIL 4	0-15	4.9	3.92
ABU FACULTY OF AGRIC	0-15	10	9
UNGUWA MUAZU	0-15	6.3	20
BASHAMA	0-15	6.9	11.7
SHETTIMA	0-15	6.9	11.3
BOMPAI	0-15	6.6	14.8
SHARADA	0-15	6.8	15.2
CHALLAWA	0-15	5.9	13.2
AMAVO	0-15	6.3	3
OSSIOMA	0-15	7.7	2.8
AMASA	0-15	8.2	2.92
UMOBASI	0-15	11.8	3.32
BADEGGI NATIONAL CEREAL INSTITUTE	0-15	3.2	6.01
BADEGGI	0-15	3.3	6.03
SAMARU	0-10	12.1	6.8
SAMARU	Oct-20	4.5	5.7

FAKO	0-10	2.7	2.4
FAKO	0-15	3.8	4.1
TSAKWANYA	0-15	2.7	6.8
TSAKWANYA	0-17	3.4	6
LAKA	0-18	1.8	11.6
JERE KADUNA	0-15	9.2	2.35
JERE KADUNA	0-13	13.6	3.24
JERE KADUNA	0-14	10	1.66
JERE KADUNA	0-8	17.6	2.79
AGO ATSAVIYA (HFV)	0-15	28.8	257
AGO ATSAVIYA (HFF)	0-15	40.5	238
OSARA OKENE (SGV)	0-15	28	200
OSAVA (SGF)	0-15	19.2	90
KAGORO (NGV)	0-15	15.7	84
KACHIA KAGORO (NGF)	0-15	33.2	110
TAMARINDES ZAMFARA (NZ)	0-15	13	7.6
ADANSONIA ZAMFARA (NZ)	0-15	6.1	5.4
PILOSTIGNE ZAMFARA (NZ)	0-15	8.9	6.5
COMBRETUM ZAMFARA (NZ)	0-15	6.1	5.8
CASSIA ZAMFARA (NZ)	0-15	5.8	5.3
BRACHIARIA ZAMFARA (NZ)	0-15	5.4	5.7
INTERPHASE ZAMFARA (NZ)	0-15	3.7	5.5
TAMARINDUS (CZ)	0-15	10.7	6.4
ADANSONIA (CZ)	0-15	7.2	7.3
PILOGTIGNA (CZ)	0-15	9.5	6.4
COMBRETUM (CZ)	0-15	6.7	5.6
CASSIA (CZ)	0-15	5.4	5.4
BRACHIARIA ZAMFARA (CZ)	0-15	5.9	5.6
INTERPHASE ZAMFARA (CZ)	0-15	3.7	6.6
TAMARINDUS (SZ)	0-15	17.1	7.3
ADANSONIA (SZ)	0-15	8.1	7.5
PILOGTIGNA (SZ)	0-15	11.4	7.7
COMBRETUM (SZ)	0-15	7	7.3
CASSIA (SZ)	0-15	7	7.3
BRACHIARIA ZAMFARA (SZ)	0-15	6.3	6.1
INTERSPACE ZAMFARA (SZ)	0-15	4.4	3.4
FARU	0-7	8	5.2
KWASHIBAWA	0-10	10	5.6
UKU DAWA	0-15	8	6.8
SAMARU 1993	0-15	0.46	3.1
SAMARU 1994	0-15	0.69	2.9

SAMARU 1995	0-15	0.56	3.4
AGRIC RESEARCH ZARIA	0-15	9.2	2.3
AGRIC RESEARCH FARM ZARIA	0-16	5.4	10.1
ILLELA	0-15	0.9	1.8
SOKOTO	0-15	1.4	2.2
SANGIWA	0-15	1.1	1.5
JERE BOWL PEDON 1	0-11	6.6	24.34
JERE BOWL PEDON 2	0-13	11.9	29
JERE BOWL PEDON 3	0-10	14.1	13
JERE BOWL PEDON 5	0-10	8.6	11.3
JERE BOWL PEDON 6	0-15	9.5	10.3
AFAKA FOREST RESERVE	0-13	8.4	8.2
AFAKA FOREST RESERVE	0-12	6.2	7.7
AFAKA FOREST RESERVE	0-8	4	4.8
SAMARU RESEARCH FARM	0-15	5.9	6.1
KOKI	0-15	11	8.8
ZUNGERU	0-15	10.1	11.5
KWANKWACI	0-15	11	10
GADA	0-15	14	9
KASTINA ROAD	0-15	5.2	7.4
SITE 1	0-15	12.2	4.95
SITE 2	0-15	18.8	6.2
TISAFE	0-15	5.5	5.14
	0-15	10.46	5.48
	0-15	6.53	3.99
EMUADO	0-15	11.2	2.79
DABAGI (2008)	0-15	1.32	5.64
DABAGI (2009)	0-15	1.3	5.61
KANO	0-15	7.8	6.5
ZAMFARA	0-15	7	5.8
SOKOTO	0-15	8.8	9
KEBBI	0-15	8.2	8.3
AMBROSE (ALLI UNIVERSITY)	0-15	8	5.06
SAMARU	0-15	8.1	39.1
BODIJA MARKET	0-15	20.3	23.1
ILE OGBON	0-15	4.65	2.5
OLUKUNLE	0-15	18	1.5
KUMAPAYI	0-15	5.81	5.6
LAGOS CONTONMENT	0-15	40.7	1
AWOTAN APETE	0-15	22	64.6
ASKAR PAINT	0-15	40.1	28.4

NISER DUMPSITE	0-15	61.6	28.5
YARTAGIMBE	0-15	2.82	* 2.72
WASSANIYA	0-15	1.72	2.66
TIMAJIRI	0-15	2.44	2.52
DAJI	0-15	2.37	2.55
	0-15	4.42	12.36
	0-15	4.83	12.5
	0-15	5.64	12.52
	0-15	6.16	14.34
	0-15	7.79	13.56
	0-15	7.91	12.54
	0-15	8.02	13.4
	0-15	8.43	14.54
	0-15	9.07	12.5
	0-15	9.71	14.36
	0-15	9.77	12.56
	0-15	9.07	14.36
	0-15	10.2	12.34
	0-15	12.26	14.36
	0-15	11	12.36
	0-15	12.3	12.56
	0-15	13.5	12.32
	0-15	13.6	14.26
	0-15	14.9	14.2
	0-15	10	9
	0-15	52.5	19.3
	0-15	52.8	18.8
	0-15	7.4	3.32
	0-15	3.4	2.98
	0-15	4.4	2.26
	0-15	4.9	3.92
EKSU OILPALM PLANTATION	0-15	12	70
EKSU TEAK PLANTATION	0-15	14	94
EKSU WETLAND A	0-15	21	77
EKSU WETLAND B	0-15	11	77
EKSU WETLAND C	0-15	16	100
EKSU CASSAVA PLANTATION	0-15	5	75
EKSU MAIZE PLANTATION	0-15	8	65
EKSU VEGETABLE PLANTATION	0-15	10	76
	0-15	7.9	3.33
	0-15	8.9	3.02
	0-15	8.8	2.5

	0-15	8.2	3.2
	0-15	8.3	3.24
	0-15	8.1	3.34
	0-15	8.6	3.69
	0-15	8	3.46
IBADAN	0-15	2.2	14.37
OWENA	0-15	0.57	4.14
OVIA (CASSAVA PLANTATION)	0-15	0.73	4.29
OVIA (OIL PALM PLANTATION)	0-15	0.76	4.39
OVIA (BANANA PLANTATION)	0-15	0.65	4.75
OWERRI	0-15	18.6	8.24
EZELU	0-15	15.3	14.8
MKPUKE (HIGHWAY)	0-15	9.7	2.8
EKPUKE (INDUSTRIAL AREA)	0-15	8	2.2
ASOKWA CONTROL	0-15	12.4	2.9
SAMARU (AGRIC RESEARCH)	0-15	7.1	8.
IKORODU	0-15	25.2	1.4
OJO	0-15	10.5	6.7
AGERIGE	0-15	9.18	5.5
BENIN	0-15	16.7	4.18
ASABA CAMPUS	0-15	9.1	2.34
EMMANUEL ALAYANDE COLLEGE OYO	0-15	4.8	16.95
UNIVERSITY OF CALABAR	0-15	11.6	4.37
EKSU TEACHING AND RESEACH FARM	0-15	0.95	2.27