PHOSPHORUS SORPTION AS INFLUENCED BY pH IN KULFO SERIES OF NIGERIAN INSTITUTE FOR OIL PLAM RESEARCH (NIFOR), BENIN CITY, EDO STATE.

BY

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FACULTY OF AGRICULTURE,

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A PROJECT REPORT SUBMITTED TO THE

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CERTIFICATION

This is to certify that this project was carried out by Opemipo Blessing ADIGUN in the Department of Soil Science and Land Management, Faculty of Agriculture, University of Benin City.

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DEDICATION

This report is dedicated to Almighty God who through his love and grace made the completion of this program.

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ABSTRACTS

Phosphorus (P) is one of the essential macronutrients needed for plant growth but its use efficiency is reduced due to adsorption sometimes caused by influence of pH. The study aimed at determining the chemical and physical properties of the sampled soil as well as P sorption capacity at different pH in kulfo soil series of Nigeria Institute for Oil Palm Research (NIFOR), Benin city, Edo state. The study was conducted on twelve (12) samples collected from four (4) soil depths (0-30, 30-60, 60-90, and 90-120 cm) in four (4) replicates from the Kulfo soil series. Physical and chemical properties were determined following standard procedures while the P sorption capacity were determined by equilibrating 5 g soil for 24 hours in 25 ml of P retention solution containing 1000 mg P/L as KH_2PO_4. The P in the soil P retention suspension was read using the Nitric vanadomolybdate yellow method. The amounts of P adsorbed were calculated by plotting a graph of absorbency against % p retention (100, 80, 60, 40, 20 and 0%) of the standard serial solution. Afterward, P retention of the samples were determined from the regression equation of the curve. The data obtained were subjected to statistical analysis using Genstat statistical package. The means were separated at 5% level of probability using Duncan multiple range test. The physical properties indicated that the soil's textural class was predominantly sandy loam for all depths, except at 0-30 cm, where it was Loamy Sand. The chemical properties of the soils revealed that they were acidic, with a mean pH value of 4.71. Other soil properties such as K, Ca, Mg and Na were within the normal range of crop production. The % p sorption varied with soil depths at all pH level, the % P retention at pH (3.0, 4.6, 7.0 and 8.6) had a mean value of (23.5, 19.0, 13.85 and 14.15) respectively. The influence of pH on P sorption calls for a compressive P management approach for the soil, designing the best P management practice to reduce P sorption in soil.

CHAPTER 1

1.0 INTRODUCTION

Phosphorus (P) is one of the essential macronutrient elements required for plant growth and development. Long term applications of organic and inorganic fertilizer have resulted in increase in the P status of soil. However the amount of plant available P in the soil is usually inadequate to meet the plant growth requirements. This unavailability of P in plant makes it the most limiting nutrient in the soil (sirnivasan *et al*., 2012), and this deficiency reduces plant growth, development and yield. During phosphate fertilizers application to the soil, it get dissolved in the soil liquid phase, substantial amount of the applied phosphate are adsorbed on the soil colloids thereby reducing the use efficiency of the applied phosphate fertilizers by plants (Tucher *et al*., 2018). This phenomenon is called P sorption or fixation.

P sorption is the removal of liable P from the soil solution on or into the solid phase of the soil (Umumarongie-Ilori *et al*., 2012). The P sorption process is influenced by soil properties especially the pH level and other environmental factors (Asomaning, 2020). At acidic levels (ie below 6.5), Fe and Al oxyhydroxides dominates the soil solution and adsorb P through an inner-sphere complexation (Rayment and Lyons, 2011). On the other hand, At alkaline pH levels of soils, Ca & Mg oxides will greatly adsorb through the formation of insoluble Ca & Mg phosphate (Jiang *et al*., 2023). Thus, the extent of P adsorption and availability greatly varies from different soils owing to their diferences in pH, other soil properties and management practices ((Muindi *et al*., 2015; Moazed *et al*., 2010). Moreso, understanding the P-sorption characteristics of soils are important for designing appropriate management strategies as well as predicting the needed amount of P fertilizer requirements to be applied (Tucher *et al*., 2018). As plants remove P from the soil solution, P is replenished by the active pool, and the rate of replenishment depends on the soil pH.

Most soils in the tropics, with Nigeria inclusive, have been reported to be generally acidic and thus limiting the supply of P due to Al & Fe reaction with phosphate ions ($H_2P0_4^-$)to form a hydroxyl phosphate that is insoluble and unavailable for plants uptake. (Mbene and Tamungangi *et al*., 2017).

Moreover, Several work has been published on P sorption has influences by pH (Gustafsson *et al*., 2012; Penn and Camberato, 2019; Muindi *et al*., 2015, Haile *et al*., 2020), however there is paucity of research on phosphorus adsorption as influenced by pH at soil series level. Hence, understanding the sorption of P at soil series level is very essential in developing appropriate P management strategies for sustainable Agricultural production and environment protection.

1.1 OBJECTIVES OF THE STUDY

The broad objective of the study was to determine the phosphorus sorption as influenced by pH in kulfo soil series of NIFOR. While the specific objectives were to:

1. examine the status of some physical and chemical properties of the soil.

2. determine P sorption capacity at different pH levels.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 PHOSPHORUS

Phosphorus (P) is an essential primary nutrient required by plants in large quantities. Typically, the soil contains a total phosphorus content ranging from 0.02 % to 0.15 %. Plants take up P from soil solution either through the process of root interception, mass flow or diffusion (kreszies *et al.,* 2018). However, these processes are affected due to a major part of soil phoshorus not available in forms useful to plants making it a limiting nutrient in crop production (Okalebo *et al*., 2002).

Plants can absorb P in three different forms: phosphate ion (PO_4^{3-}), secondary dibasic phosphate ion (HPO_4^{2-}), and primary monobasic phosphate ion (H_2PO^{4-}). A lack of phosphorus lowers crop yields because it is necessary for the synthesis of cell membranes, plant genetic material, and mechanisms in plant cells that store and transfer energy for chemical reactions. (Prassad and Chakraborty, 2019). Hence, the initial growth stages of plants are predominantly dependent on P due to its role in cell division and development.

2.2 FORMS OF PHOSPHORUS IN SOILS.

Soil is an important medium made up of various vital resources that influences agricultural production. Plants, just as other living organisms require soil P for their growth, development and reproduction (Njoyim *et al*., 2016). Phosphorus is one of the most important nutrients for biological growth and biogeochemical cycle which has a significant impact on soil (Wang *et al.* 2017 and Condron and Newman, 2011). Many factors such as the soil parent material, the extent of weathering and erosion, crop removal, climatic conditions, and fertilization practices etc. exert influence on soil's phosphorus content. In soils, phosphorus (P) exists in two primary forms: inorganic and organic, together making up the total soil phosphorus content. Approximately 30 to 65 percent of total soil phosphorus is in organic forms, while the remaining 35 to 70 percent is in inorganic forms (Rishi and Debolina, 2019).

2.2.1 Organic Phosphorus

Soil organic phosphorus is an important component of soil fertility which is essential for plant growth and development. The levels of soil organic phosphorus vary depending on the soil type, land use, and management practices. The major sources of soil organic phosphorus is through decomposition of organic matter such as crop residues, animal manure, and plant roots (Olibone *et al.,* 2010). The most naturally occurring forms of soil organic phosphorus have been characterized as esters of ortho-phosphoric acids and various monoesters and diesters. This organic phosphorus (esters) have been identified in five classes of compounds which includes Inositol phosphates, Phospholipids, Nucleic acid, Nucleotides and Sugar phosphates. The first three are dominant groups (Hasan and Raghad, 2018). Inositol Phosphates ($C_6H_6(OH)_6$) or phosphate mono-esters of a sugar-like compound are the most abundant of the known organic P compounds, accounting for up to 50% of the total organic P in the soil. (Sheraz *et al.*, 2012). They tend to be quite stable in acid and alkaline condition, and they interact with higher molecular weight humic compounds. Nucleic acids from RNA and DNA; and phospholipids which are partially derived from microbial and plant cell membranes both combines to contribute a mere 1-2% of the total organic phosphorus content in most soils (Brady and Weil, 2017; Dodd and Sharpley*, 2*015).

2.2.2 Inorganic Phosphorus

Inorganic phosphorus in soil is majorly categorized into three principal groups of compounds: calcium-bound inorganic phosphorus (Ca-P), iron-bound inorganic phosphorus (Fe-P), and aluminum-bound inorganic phosphorus (Al-P) (Brady and Weil, 2017). In acidic soils, iron and aluminum-bound forms of inorganic P are dominant while calcium bound compounds dominate in most alkaline soils. Majority of the phosphorus in each group exhibits very low solubility, making it unavailable for plant uptake due to sorption (Brady and Weil, 2017).

2.3 PHOSPHORUS FERTILIZATION

The three primary nutrients (nitrogen, phosphorus and potassium) constitute the basic components of most inorganic NPK fertilizers, but whereas nitrogen and potassium are often readily available to plants, P is frequently not so readily available to plants (Teing *et al*., 2013). A minimal amount of plant-accessible phosphorus is found in the dissolved form within the soil solution. Thus to make up for this, additional phosphorus can be supplied to plants through the application of either organic or inorganic fertilizers (Hopkins, 2015). Fertilization practices such as the addition of organic manure, crop residues, rock phosphate, water-soluble P fertilizers and incorporation of phosphorus solubilizing organism are highly recommended to increase P solubility and availability in highly weathered soil.

2.4 PHOSPHORUS TRANSFORMATION

Phosphorus, in its many organic and inorganic forms, exhibit specific behaviors in soil ecosystems (Turner *et al*., 2007). Phosphorus undergoes a continuous cycle, moving between various soil reservoirs through processes such mineralization, immobilization, adsorption, precipitation, desorption, weathering, and dissolution (Prassad and Chakraborty, 2019). Below are some explanations of these processes;

2.4.1 Phosphorus Mineralization

P mineralization is the conversion of organic phosphorus molecules into inorganic phosphorus forms that can be taken up by plants. The change is crucial for the cycle of phosphorus in the ecosystem, as plants absorb inorganic forms of phosphorus. The enzymatic decomposition of organic materials is predominantly performed by soil microbes (Samal *et al.*, 2020). Mineralization of certain organic forms of soil phosphorus has been seen, however the degree of this transition is likely to differ depending on soil conditions, such as soil pH.

2.4.2 Phosphorus Precipitation

This is a process in which phosphorus reacts with other substances in the soil to generate a solid material. Precipitated P refers specifically to compounds that are chemically uniform particles produced from ions in a solution. Fe and Al are the predominant soil components in acidic soils that are responsible for the chemical precipitation of P. The combination of Fe and P in equal amounts results in the lowest solubility at pH levels between 2 and 3, while the combination of Al and P in equal amounts results in the lowest solubility at pH 4 (Plante, 2007). The Fe and Al silicates and sesquioxides are the main sources that provide Fe^{2+} and Al^{3+} ions, which then result in the creation of chemically precipitated Fe and Al phosphates in acidic soils (Gregor, 2005). In alkaline soils, P is precipitated by Ca & Mg oxides to form insoluble Ca & Mg phosphate (Jiang *et al.*, 2023).

2.4.3 Phosphorus Dissolution

Phosphate mineral dissolution takes place when a solid mineral, which was created during precipitation, dissolves and releases phosphorus. Over time, phosphorus can dissolve to replenish the phosphate content in the soil solution. This process enhances the availability of phosphorus in the soil. (Barrow *et al*., 2023).

2.4.4 Phosphorus Fixation

P is immobile within the soil system, existing in a fixed position between the liquid and solid phases. The phosphate ions penetrate the liquid-solid interface to form new compounds with the hydrated minerals. The phosphate ions are strongly bonded by the minerals and non-diffusible structural components to form units of colloid-bound P (Dabrowski, 2001). The phosphate ions that are maintained in the diffusible ion atmosphere as compensation for ions with opposite charges are referred to as solid bound P. Phosphorus fixation reactions can be categorized into chemical and physical fixation. Chemical fixation involves the reaction of phosphate ions primarily with Fe, Al, and Ca on the surface of clay, resulting in the formation of Fe, Al, and Ca hydroxyl phosphates (Dabrowski, 2001). Physical fixation refers to the process of P being adsorbed onto the surface of clay minerals without any chemical reactions taking place.

2.5 PHOSPHORUS SOLUBILIZATION MECHANISM

Phosphate solubilization occurs by diverse microbiological activities, such as the generation of organic acids and protons. The ability of bacteria to produce metabolites, such as organic acids, determines the process. There are several different ways that microbes can break down insoluble organic and inorganic soil phosphates and microbes such as bacteria and fungi are responsible for a significant portion of the global cycling of these phosphates (Babalola and Glick, 2012;

Sirnivasan *et al*., 2012; Sharma *et al*., 2013). Phosphorus solubilization is accomplished by several saprophytic bacteria and fungi that operate on soil phosphates with low solubility, primarily through methods involving chelation (Whitelaw, 2000). Plant solubilizing bacteria (PSB) release organic and inorganic acids that solubilize inorganic phosphorus (P). These acids contain hydroxyl and carboxyl groups that chelate cations such as aluminum (Al), iron (Fe), and calcium (Ca), hence reducing the pH in alkaline soils (Stevenson, 2005).

The degree of P-solubilization is also influenced by the presence of accessory minerals in the rock phosphate. Once the pH of the growth media increases, the solubilized phosphate may undergo a reaction with the calcium (Ca) and magnesium (Mg) that are present in the rock phosphate (Lemanowicz and Krzyżaniak, 2015). The presence of free carbonates in rock phosphates further diminishes the degree of solubilization, as a significant portion of organic acids is used to neutralize the free carbonates. Organic phosphate solubilization, also known as mineralization of organic phosphorus, takes place in soil through the decomposition of plant and animal remnants that contain significant quantities of organic phosphorus molecules.

2.6 SORPTION/FIXATION IN SOILS

Sorption and fixation within soils pertain to the process of binding ions and molecules to soil particles. Fixation involves nutrients becoming bound in the soil, reducing their immediate availability to crops. This occurs when nutrients react with the soil or ions in the soil solution, forming compounds or tightly holding onto nutrients. These 'fixed' nutrients may become available to plants later, although this could take time (Daniel, 2021). This attachment can occur through physical adsorption, where the chemical or nutrient adheres to the surface of the soil particles through weak van der Waals forces or electrostatic interactions. It can also be through chemical adsorption, where a chemical reaction occurs between the soil particle and the chemical nutrient (Mbene *et al*., 2017).

Chemical sorption onto soil particle surfaces is a critical process governing the availability of chemicals for uptake by organisms and their potential loss from soils into groundwater and surface waters. The mechanisms of chemical sorption encompass inner- and outer-sphere adsorption and precipitation onto mineral surfaces. Several factors that influence sorption behavior include the properties of soil mineral and organic matter surfaces, as well as the mechanisms of chemisorption (Daniel, 2021).

2.7 PHOSPHORUS SORPTION

The term P sorption encompasses adsorption and retention. In both cases P is fixed to the soil matrix. P Adsorption is the net accumulation of P at the interface between the soil's solid and water-soluble phases. It is determined by the availability of native soil P and the amount of P applied to soils as fertilizers (Pierzyski *et al*., 2005). The unavailability of P have been reported to be largely due to sorption process in soils. Despite relatively high total phosphorus levels in soil, which can range from 200 to 6,000 pounds per acre, approximately 80 percent of this phosphorus remains fixed and unavailable for plant uptake (Prassad and Chakraborty, 2019). When soluble P compounds are applied to the soil, it undergoes a series of reactions which removes it from soil solution and renders it unavailable for plants uptake. Additionally, P compounds often react rapidly with other soil minerals by precipitation reactions and adsorption onto the soil's solid particle surfaces. Adsorption reaction is one of the principal processes involved in the retention of P on soil surfaces (Pierzyski *et al*., 2005).

In tropical soils, phosphorus adsorption is a major process that controls its availability to crop plants. Soils with high phosphorus adsorption capacity are often unable to supply adequate phosphorus to the growing crops thereby affecting their yields. From the review, soil acidity and alkalinity, soil temperature and the electrical potential of clay surface are the main factors influencing phosphorus adsorption. Also, precipitation was discovered to be the main mechanism of P adsorption in tropical soils. The soil's buffering potential for P, which is dependent on the proportion of total P in the soil solution also defines the soil's ability to sorb P (Njoyim *et al*., 2016). When soluble phosphorus is applied through chemical fertilizers application in acid soils, it gradually reacts with Fe and Al compounds present in the soil and consequently, gets transformed into relatively insoluble compounds (variscite and strengite), which are hardly available to plants (Asomaning, 2020). With time, solubility of these compounds decreases, resulting in P-fixation. Phosphate applied as water-soluble P source does not remain in the soil for a long period and quickly starts getting converted into sparingly soluble or insoluble compounds. The transformation of applied P greatly depends on physical and chemical behavior of soils.

2.8 PHOSPHORUS DESORPTION IN SOILS

Desorption is the release of adsorbed P from its bound state into the soil solution phase. Depending on the capacity of the soil to replenish the soil solution P, the P removed from the soil solution by plant root needs to be replaced. The P removed from the soil solution can be replaced through desorption of adsorbed P, microbial mineralization process of soil organic matter or added organic inputs, and application of fertilizer to the soil (Bolland *et al*., 2001). Adding organic matter to tropical soils can be an efficient strategy to optimize P fertilization by reducing P sorption and enhancing sorbed P reversibility in soils (Guedes *et al*., 2016). Moreover, desorption of initially bound phosphate from soil components is important both for nutrient availability to plant and for predictions of P leaching (Hartikainen *et al*., 2010).

2.9 SOIL PHOSPHORUS SORPTION AT THE SERIES LEVEL

Soil series are the lowest categorical level of soil taxonomy (Brevik and Hartmink, 2013). They encompass all soil types that originate from the same parent materials and share the same geological history (Simonson, 1997). Each soil series is distinct from any other soil series based on a unique combination of definite soil features. Consequently, each soil series varies significantly in its capacity to retain phosphorus.

2.10 FACTORS INFLUENCING PHOSPHORUS SORPTION IN SOILS.

The availability of nutrients in tropical soils is primarily influenced by the sorption and desorption processes, which are determined by the varying surface charge properties of soil components [Wang and Li, 2010]. It is important to take into account the concentration of P in the soil solution (intensity factor) and the soil's ability to replenish P in the solution (Bolland *et al*., 2001). The primary determinants of maximal soil phosphorus adsorption capacity are soil pH, the physical and chemical properties of the adsorbent, soil organic matter content, temperature, surface acidity, and electrical potential of clay surfaces

2.10.1 Soil pH

Soil pH is the measure of the acidity and the alkalinity of the soil. It significantly influences the availability of phosphate in the soil. Soil pH can impact the occurrence of metal ions that react with orthophosphate, as well as the capacity of iron and aluminum oxides to retain phosphorus ions (Plante, 2007). The pH range of 6.5 to 7.3 is considered the most favorable pH level for the availability of phosphorus in soils (Penn and Camberato, 2019). The presence of highly exchangeable Al and Fe ions in acidic soils poses a challenge because it can render orthophosphate unavailable in the soil solution. This occurs when phosphate ions react with Fe and Al oxides to form amorphous Fe-P and Al-P compounds, which are insoluble in water (Asmare *et al.,* 2015; Li *et al.,* 2015). Acidic soils have two ways in which phosphorus (P) becomes unavailable. This occurs through the precipitation of P by aluminum (Al) or iron (Fe), as well as the sorption of P by oxides and hydroxides of Al or Fe, such as gibbsite, haematite, and goethite (Chien *et al*., 2012; Wang *et al*., 2012).

When alkaline and calcareous soils are present, soluble P combines with cations and CaCO3 to create calcium phosphates with limited solubility (Deveau *et al*., 2010). This process reduces the availability of phosphorus in the soil.

The pH of the soil solution determines the level of separation or combination of adsorbents, which is influenced by the specific value of pKa (Ajibola, *et a*l., 2017). The presence of a compound in its molecular, cationic, or anionic form can significantly impact the extent and strength of its adsorption and retention. This is because the energy of adsorption can vary greatly between the dissociated and associated forms (Ajibola *et al*., 2017). The adsorption capacity of organic molecules with significantly variable chemical properties is determined by three factors: the pH of the clay structure, the water solubility, and the continuous dissociation of the adsorbent (Burgos, 2002). The adsorption of acidic compounds was influenced by the pH of the suspension, but the adsorption of a simple compound was influenced by the air's acidity. The pH dependency of adsorption does not affect both adsorbents uniformly. It implies that the adsorption is not caused by coulombic forces, but rather by van der Waals forces. Therefore, the extent to which soils absorb phosphorus is influenced by their pH levels. The pH of the soil in coastal wetlands can have a significant impact on the process of P sorption or desorption (Reddy and DeLaune, 2008).

2.10.2 The Physical and Chemical Properties of the Adsorbent

Adsorption reactions frequently entail interactions occurring on the surfaces of the adsorbents. Iron and aluminum oxides are both capable of adsorbing phosphate, although aluminum oxides exhibit greater effectiveness in comparison to iron oxides (Asomaning, 2020). The reason for this could be attributed to the reduced crystallinity of the aluminum oxides, resulting in a higher specific surface area compared to iron oxides (Bolan *et al.*, 1985). Regarding synthetic oxides, the quantity of phosphate adsorbed per square meter appears to be greater for aluminum oxides compared to iron oxides, while the correlation is not very strong (Asomaning, 2020). The primary factor contributing to the variations in adsorption capacity is the disparity in crystallinity. The formation of soil is influenced by the reactivity of the oxides Al and Fe. The Al and Fe oxides with the lowest particle size, characterized by poor crystallinity, have the highest reactivity due to their larger specific surface area (Asomaning, 2020). The presence of Fe and Al ions can greatly decrease the levels of chlorophyll and total P. This is due to the attachment of phosphate onto the active site of Fe and Al.

2.10.3 Soil Organic Matter

Phosphorus is a vital element for the growth of plants, and its presence in soil is affected by several factors, including soil organic matter (SOM). Organic matter can enhance the sorption of phosphorus by facilitating the creation of stable complexes between phosphorus and soil particles, resulting in a decrease in phosphorus availability to plants. Phosphorus (P) in soil can be attached to soil organic matter (SOM), and the extent to which P is attracted to SOM is controlled by the types of P present and different biogeochemical and environmental conditions (such as soil moisture, SOM, and clay levels) (Zhang *et al*., 2014). Several studies have discovered that SOM can directly increase the P concentration in soil. Additionally, SOM has been identified as a significant component that influences the adsorption and desorption of P in soil through multiple mechanisms (Wang and Liang, 2014).

Humic acid is a significant constituent of organic matter that occurs naturally (Lin *et al*., 2017). It is specifically referred to as the percentage of organic matter that has undergone humification. Humic acid is the primary provider of adsorption sites in soil organic matter (SOM) and consists of different functional groups, including carboxyl groups (COOH), alcoholic hydroxyl groups (OH), and phenolic hydroxyl groups (Hua *et al*., 2008; Lin *et al*., 2017). Humic acid forms complex bonds with various metal oxides such as aluminium, iron oxide, silicon dioxide, and titanium dioxide. This interaction affects the adsorption of phosphate and the availability of phosphorus in soil, either directly or indirectly (Yan *et al*., 2016; Wang *et al*., 2015). By introducing exogenous humic acid, the organic matter content can be increased without having to wait for the slow process of organic matter humification. This method effectively eliminates the influence of vaporized mineral compositions and variations in other parameters on experimental results. When organic matter breaks down, it produces organic acids and other substances that can change the pH of the soil and impact the way phosphorus is absorbed. Moreover, the presence of organic matter might impact the process of soil particle aggregation and stabilization, hence influencing the kinetics of phosphorus sorption.

2.10.4 Temperature

The sorption of P in soils can be greatly affected by temperature. Typically, higher temperatures lead to acceleration in the rate of chemical processes. This can impact the adsorption and desorption mechanisms of phosphorus in soil, hence modifying or influencing its accessibility to plants and its capacity to migrate into water bodies. At elevated temperatures, the movement of phosphorus (P) in soil may be boosted as a result of increased desorption, which might potentially result in higher levels of P being lost by runoff or leaching. In addition, changes in temperature can affect the physical characteristics of soil, including its porosity and ability to retain water, which in turn affect the dynamics of phosphorus sorption. Typically, an increase in temperature leads to decreased sorption. However, there are instances where higher temperatures actually cause greater adsorption, as shown in certain scenarios (Horsfall and Spiff, 2005).

2.10.5 Surface Acidity

The difference between the activity of protons in the bulk suspension (as defined by pH) and the activity of protons at or near the colloidal surface (the acidity in the interfacial area) has been well-established for some time (Agmon *et al*., 2016). Surface acidity in soil systems refers to the acidity present on or above the colloidal surface. It indicates the system's capacity to act as both a Bronsted and Lewis acid. This word, coined as a hybrid, encompasses both the overall quantity of acid sites and their corresponding level of acidity (Yang *et al*., 2007). The surface acidity of the soil or colloidal system is a crucial characteristic that determines the extent and manner in which basic organic phosphorus molecules are adsorbed and desorbed, as well as whether acid-catalyzed chemical breakdown takes place (Agmon *et al*., 2016). Research provides abundant evidence that simple chemical compounds can be protonated by clays containing hydrogen and aluminum as the main exchangeable cations, as well as by intermediate, alkaline, and alkaline metal cations (Ajibola, *et al*., 2017

2.10.6 Electrical Potential of Clay Surface

The electrical field generated from the load-balancing cations is believed to be responsible for the varied surface anomalies found in clays, zeolites and other aluminum silicates. The size of aluminum-silicate surface fields arises from the conversion of adsorbed molecules into soil colloids. Various chemical reactions caused by this include breakdown of amines, decomposition of $CO(NH_3)_6^{3+}$ into N_2, $CO(OH)_2$, NH_3 and NH_4^+, protonation of amines etc. (chen *et al*., 2017). P fixation is strongly and positively associated with clay content of soil. This is due to increased specific surface area of clay combined with higher anion exchange site.

2.11 ESTIMATING SORPTION IN SOILS

Estimating phosphorus sorption in soils plays a crucial role in determining phosphorus availability to plants and optimizing fertilizer utilization. Various methods exist for estimating phosphorus sorption in soils, with one key approach being:

2.11.1 Phosphorus Sorption Isotherms/Models

Phosphorous adsorption isotherms are the equilibrium quantitative relationships between the quantities of adsorbed and dissolved phosphate at constant temperatures (Limousin *et al*., 2007). The purpose of investigating phosphate sorption isotherms is to gain a more comprehensive understanding of the mechanism that governs the interaction between phosphate ions and sesquioxides (oxides and hydroxides) in soils. In general, adsorption is defined by fitting the adsorption data into the adsorption isotherms and obtaining a mathematical explanation using one or more adsorption equations (Njoyim *et al*., 2016). The process of adsorption is primarily described through isotherms, which are functions that establish a connection between the concentration of the adsorbate and the pressure of the adsorbent in the case of a liquid or gas.

Langmuir, Freundlich, Dubinin-Radushkevich, and Temkin are among the isotherm models that describe the process of adsorption/desorption (Jamal *et al*., 2018).

2.11.2 Langmuir sorption Isotherm/Model

Adsorbents and adsorbent structures are defined by the Langmuir Isotherm, which stipulates that the extent of adsorbent coverage is restricted to a single molecular surface (Chen *et al*., 2017). Soil chemists generally employ the Langmuir adsorption equation to monitor P adsorption and determine the crop's P requirements. When the equilibrium concentration is divided by the sum of adsorption per unit adsorbent, a straight line should be obtained when the adsorbent balance concentration is plotted against the Langmuir adsorption equation (Hussain *et al*., 2003). The Langmuir equation's advantage is that it enables the determination of the maximal adsorption and relative binding energy for P sorption (Hussain *et al*., 2003). The Langmuir isotherm equation is expressed is expressed in linear form as;

$$q_e = \frac{b\ Q(\max)}{1+bCe}$$

Where;

qe is the quantity of adsorbate adsorbed per unit weight of adsorbent at equilibrium (mg g^{-1}).

Ce is the concentration of adsorbate in solution at equilibrium following adsorption, expressed in mg l-1.

Q(max) is the maximal adsorption capacity (mg g^{-1}).

b is the Langmuir adsorption equilibrium constant (mg l^{-1}) is represented by b.

2.11.1.2 Freundlich Isotherm/Model

One of the adsorption isotherms that is frequently employed to characterize the adsorption of organics from aqueous streams onto activated carbon is the Freundlich Isotherm equation (Surchi, 2011). The Freundlich equation is generally regarded as strictly empirical; however, it was extensively employed to elucidate the adsorption of phosphate into soil (Aslam *et al*., 2000). The Freundlich isotherm is denoted as;

$X=aCn$.

Where;

X represents the quantity of adsorbate (P) that is sorbed per unit weight of soil (mg P/kg soil).

C is the concentration of P in the equilibrium solution (mg/l).

a is the constant that is associated with the sorption capacity.

n is the energy of phosphate sorption.

2.11.1.3 Temkin Adsorption Isotherm/Model

Temkin initially postulated the isotherm, which is another empirical equation. The adsorption heat of all molecules in the layer will decrease linearly with coverage as a result of interactions between the adsorbent and adsorbate (Tan *et al*., 2008). The equation for the Temkin isotherm is as follows:

$X = a + b \log C$.

Where;

X represents the quantity of P that is absorbed.

a and b are the temkin parameters.

C is the equilibrium concentration of P.

2.11.1.4 TOTH Adsorption Isotherm

The TOTH adsorption isotherm equation achieves an adsorption maximum at high ion concentrations, but it adheres to Henry's law at low ion concentrations (Kinniburgh, 1985).

The equation for the TOTH adsorption isotherm is as follows:

$$x= \frac{X_m InK_c}{[1+(K_c)^{\beta}]^{1/\beta}}$$

Where;

β is the heterogeneity parameter

K is the affinity parameter that is associated with the bonding energy.

Xm is the maximal adsorption per unit mass.

X is the quantity of P that has been sorbed in kilograms.

C is the equilibrium concentration of phosphorus in the solution (mg l^{-1}).

The langmuir equation is the result of this equation. Isotherm of adsorption when $\beta = 1$ Kinniburgh (1985).

2.11.1.5 Dubinnin- Radushkevich (D-R) Adsorption Isotherm/Model

Dubinin-Radushkevich (D-R) adsorption isotherm is a highly beneficial empirical theory that enables the estimation of the quantity of gas adsorbed in a microporous sorbent. The theory was founded on a pore filling paradigm (Keller and Staudt, 2005). The model has frequently been able to accurately suit the intermediate concentration data and high solute activities. The equation of the (D-R) model is as follows:

$$\log X = -\beta[\log(KC)]^2 + \log X_m$$

Where; X = the quantity of P sorbed (mg kg^{-1}).

Xm is the maximal adsorption per unit mass.

β is a constant that is associated with the adsorption energy.

K is the affinity parameter that is associated with the bonding energy.

C is the equilibrium concentration of phosphorus in the solution (mg L^{-1}).

2.11.2 Batch Equilibrium Test

Batch equilibrium tests, which are also referred to as static systems, are among the most frequently employed methods for estimating P sorption in soil (Wang *et al*., 2016; Feng *et al*., 2021). The adsorbed concentration can be easily determined by comparing the initial and equilibrium concentrations of the absorbate.

2.11.3 Sequential Extraction Procedure

The Sequential Extraction Procedure entails the sequential extraction of soil samples with solutions of progressively increasing strength to ascertain the distribution of phosphorus among various soil fractions. The extraction procedure can provide information on the quantities of phosphorus that are weakly, moderately, and firmly adsorbed to soil minerals, thereby indicating the amount of available and unavailable P in the soil (Chen *et al*., 2015).

2.11.4 Soil Testing

Soil phosphorus sorption can also be determined by soil assays that measure soil phosphorus levels, such as the Bray (Bray and Kurtz, 1945), Mehlich (Mehlich, 1984), or Olsen test (Oslen *et al*., 1954). The overall sorption capacity of the soil can be correlated with the quantity of read ily available phosphorus in the soil, as determined by these experiments (Miller and Arai, 2017).

2.12 APPLICATION OF SORPTION TO AGRICULTURE AND ENVIRONMENT

The objective of sustainable crop production is to preserve a high cereal yield without compromising the capacity of ecosystems to satisfy the needs of both present and future generations (Tilman *et al*., 2002). In agriculture, phosphorus is the second most growth-limiting macronutrient after nitrogen. Therefore, its correct administration in the soil is crucial for the production of sustainable crops. In soils that are deficient in P due to their inherent low P concentration, the only method to improve the soil's available P status to a target value that can sustain a high crop yield in the long term is to apply a relatively higher amount of mineral P fertilizers (Balemi and Negisho, 2012). Nevertheless, the available soil phosphorus concentration can be maintained at a level that can sustain a high crop yield through maintenance fertilization, which simply replaces the P withdrawn from the field along with the harvested crops, once the target value is achieved.

The P contained in crop residues that are left in the field can be recycled by incorporating the residues into the soil, while a portion of the P in crop residues that are fed to livestock can be returned to the soil in the form of manure and bone meal (Balemi and Negisho, 2012). Plants and microorganisms can exude phosphatases and phytases, which can facilitate the mineralization of these organic P sources. Nevertheless, the P that was removed, in addition to cereal grains, other edible vegetable parts, and livestock products such as milk, meat, and cow dung meant for human sustenance, must be replaced by the application of mineral P fertilizer (Tilman et al., 2002). Consequently, the quantity of mineral P fertilizer necessary for maintenance fertilization decreases when the P that is extracted from the soil by harvested crops can be reintroduced as crop residues and manures. In summary, the sustainable production of crops can be facilitated by the consistent application of maintenance P fertilizers, the incorporation of crop residues, and the application of organic manures, which can reduce nutrient extraction (Balemi and Negisho, 2012). The continuous administration of P fertilizer to satisfy the growth and development requirements of plants can result in a substantial reserve of residual P in soils. However, this reserve is not readily accessible to plants (Rowe *et al*., 2016).

2.13 Enhancing the Solubility of Phosphorus in Tropical Soil

Phosphorus is the second most growth-limiting macronutrient, following nitrogen. A substantial contribution to sustainable crop production is made by the proper management of phosphorus in the soil. P availability, P use efficiency, and fertilizer P recovery are substantially influenced by a variety of factors, such as soil pH, texture, the type of clay minerals, calcium carbonate, organic matter, and the Mg/Ca ratio of irrigation water. Nevertheless, the primary constraints on the availability or solubility of P in tropical soils are the low soil pH and low soil organic matter contents (Rasul, 2011). Hydroxyl–ion activities are reduced by low soil pH, which leads to an increase in the formation of iron and aluminum phosphate. This results in low concentrations of soluble P and/or reduced solubility of organic and inorganic P forms in highly weathered soils. Fertilization practices that enhance the solubility and availability of phosphorus in highly weathered soil, including the incorporation of phosphorus solubilizing organisms that increase soil pH and organic matter content, the addition of organic manure, crop residues, rock phosphate, and water-soluble P fertilizers, are highly recommended (Negassa and Leinweber, 2009). The negative charges on the soil surfaces with variable charges are increased by the organic matter formed from the application of organic manure, which in turn increases the available P in the soil (Njoyim *et al*., 2016). Additionally, organic matter contains negatively charged functional groups, including carboxyl and phenol, that interact with Al^{3+} and Fe^{3+} to reverse the process of P complexation with Al^{3+} and Fe^{3+}, thereby increasing the availability of P in the soil (Njoyim *et al*., 2016). In highly weathered soil, the organic acids that are released as a result of the manure's addition compete more effectively for adsorption sites and reduce P sorption. Rock phosphate (RP) is a natural P mineral rock that is employed as an industrial chemical, animal feed supplement, and phosphatic fertilizer (Reddy *et al*., 2002). RP is distinguished by its delayed release of P; consequently, the solubilization of RP is improved by the application of RP in conjunction with microbes that solubilize P. P solubilizing microorganisms can induce the release of P from RP by producing organic acids during their metabolic activities (Swamy *et al*., 2010; Geonadi, *et al*., 2000). In highly weathered soil, phosphates from applied P fertilizers can be fixed by free oxides and hydroxides of aluminum and iron, rendering them unavailable to plants, as a result of the predominance of Al^{3+} and Fe^{3+} (Weeks and Hettiarachchi, 2019). Inorganic P fertilizers can be solubilized by the incorporation of P solubilizing microorganisms (such as bacterial and fungi) into the soil (Puente *et al*., 2004). According to Balemi and Negisho (2012), crop residues have been associated with an increase in the availability of phosphorus in tropical soil. Crop residues that are left in the field can be recycled if they are incorporated into the soil. However, if they are fed to livestock, the P in them can only be returned to the soil through manure or bone meal. The quantity of phosphorus discharged into the soil from crop residues is contingent upon the concentration of phosphorus in the crop residues. Nevertheless, the crop residue that is discharged into the soil from P can be mineralized or immobilized. Microbial P immobilization occurs when the total P content of the crop residue is insufficient to meet the microorganisms' P requirements (Randhawa *et al*., 2005; Richardson, 2007). The action of soil microorganisms results in the net mineralization of organic P and the decomposition of organic matter (Ayaga *et al*., 2006).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 DESCRIPTION OF THE STUDY SITES

The study was carried out on soil collected from Nigeria Institute for Oil Palm Research (NIFOR) which lies between latitude 06^o 36' 59.7" N and longitude 05^o 37' 15.8" E in Ovia North-East local government area of Edo state, about 24km from the state capital Benin City. It is located in the rainforest ecological zone, with an altitude 149.40m, mean annual temperature of 31^{o}C and a bimodal rainfall regime. NIFOR soils are developed on coastal plain sand and classified into four soil series (local classification) which are Ahiara, Kulfo, Alagba and Orlu soil series. The site was planted to cassava (*Manihot esculenta*) as at the time of sampling.

3.1.1 Soil Sampling

Representative soil samples were collected with an auger from Kulfo soil series from four depths (0-30, 30-60, 60-90 and 90-120 cm) in three replications, making a total of twelve (12) samples from field nine (9) classified as kulfo series. The coordinates of the points where the soil samples were collected lie between latitude 06° 34' 11.7" N, 06° 34' 09.5" N, 06° 34' 07.0" N and longitude 005° 36' 58.4" E, 005° 36' 58.2" E, 005° 36' 58.0" E. The twelve soil samples were labeled in a polythene bag and taken to the laboratory for analysis.

3.2 LABORATORY ANALYSIS

Soil samples were air-dried, grounded and sieved through a 2 mm sieve and analyzed for selected physical and chemical properties using standard procedures.

3.2.1 Particle size determination

This was determined using the Hydrometer method of Bouyocuos (1951) as modified by Day (1965). 51g of the soil sample was weighed into a soil shaking bottle. 100 ml of calgon was added and the mixture was stirred using a stirring rod, dispersed using a dispersing machine for 5 minutes and transferred into a 1000 ml measuring cylinder, made up to mark with distilled water and the soil particles were set in motion using a plunger. The first hydrometer (H_1) and temperature (T_1) readings were taken after 40 seconds while the second hydrometer (H_2) and temperature (T_2) readings were taken after 2 hours using the standard soil hydrometer with Bouyoucos scale in g/L and thermometer respectively. The first reading was used to calculate the percentage of clay and silt in the soil while the second reading was used to calculate the percentage of clay in the soil, according to the formula below:

$$\%\,(\text{Clay} + \text{Silt}) = \frac{H_1 \pm 0.3\,(T_1 - 20°C) \times 100}{w}$$

$$\%\text{Clay} = \frac{H_2 \pm 0.3\,(T_2 - 20°C) \times 100}{w}$$

%Sand = 100% - % (Clay + Silt)

Where;

H_1 = first hydrometer reading

T_1 = first temperature reading

H_2 = second hydrometer reading

T_2 = second temperature reading

w = weight of soil sample used

3.2.2 Textural Classification

Textural classification was determined using the textural triangle (soil survey staff, 2003).

3.2.3 Soil pH

The soil pH was determined in 1:1 of soil and water suspension using a glass electrode pH meter after calibration with a buffer solution (Tan, 1996).

3.2.4 Soil Organic Carbon (OC)

The soil organic carbon (OC) content was determined by the wet oxidation method of walkley and Black (1934). 1g of soil was weighed into a conical flask. 10 ml of 0.167 M $K_2Cr_2O_7$ was added and the conical flask was swirled. 20 ml of concentrated H_2SO_4 was added and swirled for 1 minute and the mixture was allowed to cool for 30 minutes after which 100 ml distilled water was added and the conical flask was swirled and allowed to cool. 3 drops of ferroin complex indicator was added. The mixture was swirled and titrated against 0.5 N $FeSO_4.7H_2O$ to a brownish red end point (T). Blank was prepared and titrated (B) following this procedure without soil.

$$\% \text{ OC} = \frac{N(B-T)0.3F}{w}$$

Where;

N = nomality of acid used

B = blank titre value

T = sample titre value

F = correction factor

w = weight of soil

3.2.5 Total Nitrogen (N)

Total nitrogen was determined by the micro kjeldahl method (Bremner and Mulvaney, 1982).

3.2.6. Available Phosphorus (P)

Available P was extracted by the Bray-1 solution according to methods of Bray and Kurtz (1945). The P in the extract was developed by the Sulphuric acid molybdate blue method of Murphy and Riley (1962). Sulphuric molybdate and ascorbic acid stock solutions were prepared for the blue colour development procedure. A standard P solution was also prepared and used to prepare working solutions ranging from 0 to 8 ppm.

3.2.7 Exchangeable Bases

Exchangeable bases (K, Ca, Mg, Na) were extracted using 1 N ammonium acetate (1N NH_4OAc), buffered at pH 7. Na and K was read using the flame photometer while Ca and Mg were determined using the Atomic absorption spectrophotometer (AAS).

3.2.8 Cation Exchange Capacity (CEC)

The cation exchange capacity was determined by the direct summation methods where soils were treated with 1 M NH_4OAc at pH 7.0 and CEC was calculated by summation of Ca, Mg, Na and K (Udo *et al.,* 2009).

3.2.9 Exchangeable acidity (EA)

Exchangeable acidity was determined by extracting soils with 1 M KCl as reported by Juo (1979). 5 g of soil was weighed into a soil shaking bottle, 100 ml 1 M KCl was added, shaken for 1 hour and filtered using whatman No. 42 filter paper. 10 ml of the filtrate was measured into a conical flask, 5 drops of phenolphthalein were added and made up to 50 ml mark. The extractant was titrated against 0.01 M NaOH to a pink endpoint and the EA was calculated using the formula below;

$$\text{EA} = \frac{T \times M \times V_1 \times 100}{V_2 \times W}$$

Where,

T = titre value

M = molarity of acid used (0.01 M)

V_1 = volume of extractant (10 ml)

V_2 = final volume of extract used for titration (50 ml)

W = weight of soil

3.2.10 Effective Cation Exchange Capacity (ECEC)

The ECEC was calculated by the summation of Exchangeable bases and Exchangeable acidity.

3.2.11 Base Saturation

Percentage base saturation was determined by the equation given below:

$$\% \text{ Base Saturation} = \frac{\text{Total exchangeable basic cation} \times 100}{\text{ECEC}}$$

3.2.12 Determination of Phosphorus Sorption as Influence by pH

3.2.12.1 Preparation of P Retention Solution

P retention solution (1000 mg P L^{-1}) was prepared by weighing and dissolving 8.80g Potassium dihydrogen phosphate (KH_2PO_4) and 32.8 g of anhydrous sodium acetate in about 1 liter of water. 23 ml of glacial acetic acid was added as well. Afterward, it was transferred to a 2 liter volumetric flask and make to volume of 1950 ml with distilled water. Acetic acid (HOAC) or NaOH solution was used to adjust the pH to 3, 4.6, 7, 8.6, and 10.6 respectively and made up to volume with water.

3.2.12.2 Preparation of Standard serial dilution

Standard serial dilution was prepared by pipetting 0, 10, 20, 30, 40, and 50 ml of the P retention solution (1000 mg/L) into 50 ml volumetric flasks and make to volume with distilled water. The standards correspond to 100, 80, 60, 40, 20 and 0 % P retention respectively.

3.2.12.3 Preparation of Nitric Vanadomolybdate acid solution

0.9g ammonium vanadate was dissolved in 500 ml boiling water and cooled. 6 ml of concentrated HNO_3 (70 %) was added and diluted to 1 liter with distilled water. 16 g of ammonium molybdate was also dissolved in boiling water at 50°C, cooled and diluted to 1 liter with distilled water. 100 ml of concentrated HNO_3 (70 %) was diluted to 1 liter with distilled water. The diluted HNO_3 was transferred into a 3 liter bottle jar, the vanadate solution was added as well as the molybdate solution and mixed thoroughly.

3.2.12.4 Phosphorus Sorption Experiment

The sorption study was carried out on twelve (12) soil samples of various depths according to standard procedure recommended by Udo *et al*. (2009). Five (5) grams of air dried soil was weighed into series of fifty milliliters (50 ml) plastic bottles, 25 ml of P retention solutions consisting of different pH (3.0, 4.6, 7.0 and 8.6) was added. The suspension was shaked for 24 hours at 20°C using a mechanical shaker, filtered using Whatman No 42 filter paper and P in the filtrate was read using the Nitric vanadomolybdate yellow method.

3.2.12.5 Colorimetric determination of P in filtrate

1 ml of the standard serial solution and sample filtrate was taken into different 25 ml beakers independently. 19 ml of the Nitric vanadomolybdate acid solution was added to each of the 1ml sample filtrate and standard solution. It was allowed to stand for 30 minutes for maximum colour development and homogenization. It was then read using the 80 UV-Vis spectrophotometer (PG instrument Ltd) at 466 nm.

3.2.13 Determination of P Sorption Parameters

A graph of Absorbency (Abs) against % P retention was plotted and the P retention of the sample was calculated from the curve. Since the curve showed a decrease in ABS with a decrease in P concentration (increase in P absorption), the standard solution with the highest P concentration was plotted as the origin of the graph.

3.3 STATISTICAL ANALYSIS

Data collected was statistically analyzed using the Genstat statistical package (12th edition). Duncan multiple range test was used to separate means at 5% level of probability.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 PHYSICAL PROPERTIES OF THE SAMPLED SOILS.

4.1.1 Particle Size Distribution

The particle size distribution of the soil at various depths is shown in Table 1.

The sand content was the dominant soil separate fraction and it decreased with increased soil depths, the silt content was inconsistent, while the clay content increased with increased soil depths. However, the sand, silt and clay ranged between (756.60 - 838.30 g kg^{-1}, 49.7 – 74.6 g kg^{-1} and 112.0 – 189.5 g kg^{-1}) with mean values of (780.00 g kg^{-1}, 59.9 g kg^{-1} and 160.0 g kg^{-1} respectively. It was observed that sand is the dominant soil fraction and tends to decreased with increased soil depths, the dominant sand fraction could be attributed to the nature of the parent rock while the clay content could be due to lessivation as reported by Brady and Weil (2007).

4.2 CHEMICAL PROPERTIES OF THE SAMPLED SOILS

The chemical properties of the soils are shown in Table 2.

The soil pH was strongly acidic across the soil depths, the pH ranged between 4.62 – 4.84 with mean value of 4.71; however, it is still within the suitable soil pH range for some crop cultivation as reported by FAO (2005). The low soil reaction could be due to the nature of the parent material overlying the soil which has been reported to be generally acidic (Awwal, 2021).

Table 1: Particle size distribution of the soil (g/kg)

Depth (cm)	Sand	Silt	Clay	Textural class
0-30	838.30	49.70	112.00^{b}	LS
30-60	767.60	74.60	157.80^{a}	SL
60-90	757.80	61.60	180.70^{a}	SL
90-120	756.60	53.90	189.50^{a}	SL
Mean	780.0	59.90	160.0	
CV	6.2	44.8	15.2	

Means with different letter within columns are significantly different from one another at $P \leq 0.05$ using Duncan Multiple Range Test. LS= loamy sand; SL= sandy loam.

Table 2: Chemical properties of kulfo soil series in NIFOR

Depth	pH	OC	N	Av. P	K	Ca	Mg	Na	EA	CEC	ECEC	BS
(cm)	(H_2O)	(g/kg)	(g/kg)	(mg/kg)	(cmol/kg)							(%)
0-30	4.84	8.36^{a}	0.42^{a}	0.40	0.34	0.81^{a}	0.25	0.09	0.42^{b}	1.49	1.91	77.79^{a}
30-60	4.70	6.89^{ab}	0.33^{ab}	0.39	0.35	0.45^{b}	0.26	0.08	0.72^{a}	1.14	1.86	61.18^{b}
60-90	4.62	5.49^{b}	0.28^{b}	0.37	0.24	0.59^{ab}	0.28	0.09	0.68^{a}	1.19	1.87	63.52^{b}
90-120	4.69	5.68^{b}	0.28^{b}	0.39	0.27	0.71^{ab}	0.28	0.08	0.67^{a}	1.34	2.01	66.84^{b}
Mean	4.71	6.61	0.33	0.39	0.30	0.64	0.27	0.09	0.62	1.29	1.91	67.33

Means with different letter within columns are significantly different from one another at $P \leq 0.05$ using Duncan Multiple Range Test.

OC= Organic Carbon, Av. P= Available Phosphorus, EA= Exchangeable acidity, CEC= Cation exchange capacity, ECEC= Effective cation exchange capacity, BS= Base saturation.

Organic carbon (OC) and Total Nitrogen (N) both exhibited a significant decrease as soil depth increased. OC ranged from 5.68 to 8.36 g kg^{-1}, with a mean value of 6.61 g kg^{-1}, while N ranged from 0.28 to 0.42 g kg^{-1}, with a mean of 0.33 g kg^{-1}. The higher levels of organic carbon near the soil surface are likely due to substantial litter fall from the surrounding vegetation (Egbuchua, 2012). Available Phosphorus (P) fell within the range of 0.37 and 0.40 mg kg^{-1}, with a mean value of 0.39 mg kg^{-1}. This mean P value was significantly lower than the critical range of 3-7 mg kg^{-1} reported by Chude *et al*., 2011. The lower P concentrations are likely linked to soil acidity, indicated by consistently low pH values < 5.0 across various soil depths. Harrison (2007) observed that at these pH levels, aluminum (Al) and iron (Fe) become highly soluble and react with phosphate ions ($H_2PO_4^-$) to form insoluble hydroxyl-phosphate, making it unavailable for plant uptake. Potassium (K), Calcium (Ca), Magnesium (Mg), Sodium (Na), Exchangeable acidity (EA), Cation exchange capacity (CEC), Effective cation exchange capacity (ECEC) and Base saturation (BS) did not increase significantly within creased soil depth sand there were no significant differences among them across the soil depths, except for Ca and BS. However the K, Ca, Mg, Na, CEC, ECEC and BS ranges from 0.24 - 0.35 cmol kg^{-1}, 0.45 and 0.81 cmol kg^{-1}, 0.25 - 0.28 cmol kg^{-1}, 0.08 - 0.09 cmol kg^{-1}, 1.14 - 1.49 cmol kg^{-1}, 1.86 - 2.01 cmol kg^{-1}, and 61.18 - 77.79 % with mean values of 0.30 cmol kg^{-1}, 0.64 cmol kg^{-1}, 0.27 cmol kg^{-1}, 0.09 cmol kg^{-1}, 1.29 cmol kg^{-1}, 1.91 cmol kg^{-1}, and 67.33 %, respectively.

4.3 PHOSPHORUS SORPTION AT DIFFERENT pH LEVELS.

The amount of P adsorbed at different soil pH across various soil depths are presented in the Figure 1.

At 0-30 soil depth, It was observed that the % P retention decreases from pH 3 (19.90) to pH 7 (9.63) and slightly increases at pH 8.6 (11.86). Similar trend was observed at 30-60 cm soil depth. However, at 60-90 cm and 90-120 cm depth, the % P retention decreases slightly from pH 7 (17.26 and 13.63) to pH 8.6 (16.54 and 13.46) respectively. The lowest % P sorption was observed at 0-30 cm soil depth. At pH 3, the highest % P retention was observed compared to the % p retention of the other pH level. It increased with increased soil depths with no significant difference. However, the % p retention of pH 3 ranges between 19.93 and 25.74 with a mean value of 23.5 which was the highest of P adsorbs compare to other pH value. The highest % P retention at pH 3 obtained in this study is in line with the findings of Penn and Camberato, (2019), and Haile *et al* (2020) who reported P adsorption to sharply increased as the soil pH decreased from the neutral pH level.

The striking finding of the study was that the % p retention was lowest at pH 7 which significantly increased with increased soil depth up to 60-90cm soil depth (17.26) and decreased slightly to 90-120 soil depth (13.63). However, the % P retention ranged from (9.63 – 17.26) with a mean value of 13.85. Considering the mean value across the various soil pH, it was observed that P retention was least at pH 7 (13.85) which could be attributed to the reduced effect of Fe & Al and Ca & Mg on P. This is in agreement with Lopez-Hernandez and Burnham (2006) who showed that P adsorption clearly increased at pH lower than pH 7.

However, this findings was contrary to the reports of Muindi *et al* (2015) who reported P adsorption to be highest at pH 4.86 and pH 4.68 than in pH 4.08, when they reported sorption in acid soils of western Kenya.

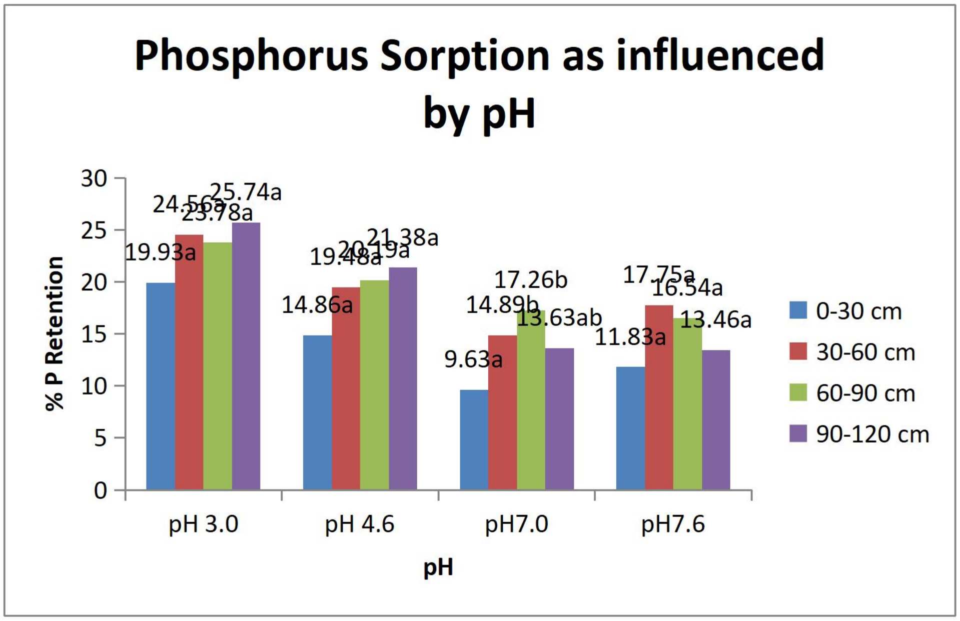

Fig 1: % P retention at different pH levels

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The study shows that some physical and chemical properties of kulfo soil series were within the normal range suitable for crop production. It revealed that within the soil series at various soil depths, P sorption decreases with increasing soil pH to neutral soil pH, which calls for a comprehensive P management approach for the soil. The study also confirmed that kulfo soil series has the capacity to adsorb more P at acidic soil pH. Therefore, the sorption capacity of the kulfo soil series as influence by pH must be taken into consideration when deciding the P fertilizer rate for the soil, designing the best P management practice to reduce the risk of P loss.

5.2 RECOMMENDATIONS

From the findings of this study, it is recommended that proper management practices that will maintain a neutral soil pH and other soil physical and chemical parameters should be adopted. Liming and organic manure application are some of the management practices that can be adopted in order to increase the soil pH from acidic level to a neutral level and also to increase the soil organic matter respectively. These will help to reduce the adsorption of Phosphorus in the soil. Moreover, a neutral soil pH should be maintained before P fertilizer application so as to reduce the P adsorption in soils.

REFERENCES

Agmon, N., Bakker, H. J., Campen, R. K. (2016). Protons and hydroxide ions in aqueous system. *Chemical Reviews,* 116: 7642–7672.

Ajibola, A., Adeoye, O. A. and Bello, S. O. (2017). Adsorption of dyes using different types of clay: a review in *Applied Water Science,* 7: 543–568.

Aslam, M., Rahmatullah, M. S. and Yasin, M. (2000). Application of Freundlich adsorption Isotherm to Determine Phosphorus Requirement of several Rice soils. *Interational Journal of Agricutural Biology*, 2: 286–288.

Asmare, M., Heluf, G., Markku, Y. and Birru, Y.(2015). Phosphorus Status, Inorganic Phosphorus Forms, and Other Physicochemical Properties of Acid Soils of Farta District, Northwestern Highlands of Ethiopia. *Applied and Environmental Soil Science,* 4: 1-11.

Asomaning, S. K. (2020). Processes and Factors Affecting Phosphorus Sorption in Soils. In: Sorption in 2020s. *IntechOpen*.

Awwal, Y.A. (2021). Influence of Toposequence on soil properties, Genesis, suitability and Degradation at Hayin Gada, Zaria, Nigeria. MSC. Dissertation, Department of soil science, Ahmadu Bello University, Zaria.

Ayaga, G., Todd, A. and Brookes, P. C. (2006). Enhanced biological cycling of phosphorus increases its availability to crops in low-input sub-Saharan farming systems. *Soil Biology and Biochemistry*, 38: 81–90.

Babalola, O. O. and Glick, B. R. (2012). Indigenous African agriculture and plants associated microbes current practice and future transgenic prospects. *Science Research Essays,* 7: 2431-2439.

Barrow, N. J., Debnath, A. and Sen, A. (2023). Investigating the dissolution of soil phosphate. *Plant soil.* 490: 591-599

Bolan, N. S., Barrow, N. J. and Posner, A. M. (1985). Describing the effect of time on sorption of phosphate by iron and alumonium hydroxides. *Journal of Soil Science*. 36:187.

Bolland, M. D. A., Allen, D. G. and Barrow, N. J. (2001). Sorption of phosphorus by soils: How it is measured in Western Australia. *Department of Agriculture and Food, Western Australia, Perth. Bulletin,* 4591: 31.

Bouyouvos, C. J. (1951). Recalibration of the hydrometer method of making the mechanical analysis of soils. *Agronomy journal,* 43: 434-438.

Brady, N. C. and Weil, R. R. (2017). Soil Organic matter. In: *The nature and properties of soil.* Pp 545-601.

Brady, N.C. and Weil, R.R. (2007). The nature and properties of soils (13th ed.) Pearson prentice hall Education, Inc. Pp. 620-621.

Bray, R. H. and Kurtz, L. T. (1945). Determination of total, organic and available forms of phosphorus in soils. *Journal of soil science,* 59: 39-45.

Bremner, J. M. and Mulvaney, C. S. (1982). Nitrogen - Total. In: Methods of soil analysis. Part 2. Chemical and microbiological properties. *Soil Science Society of America*, 595-624.

Brevik, E. C. and Hartemink, A. E. (2013). Soil maps of the United states of America. *Soil Science Society of America Journal,* 77:1117-1132.

Burgos, D.W., Pisutpaisal, N. and Mazzarese, C. M. (2002). Adsorption of Quinoline to Kaolinite and Montmorillonite. *Environmental Engineering Science*, 19: 59–68.

Chen, J., Yan, X., Wang, X., Zhang, J., Huang, J. and Zhao, J. (2015). Heavy metal chemical extraction from industrial and municipal mixed sludge by ultrasound-assisted citric acid. *Journal of Industrial and engineering chemistry,* 27: 368–372.

Chen, Q., Tian, Y. and Yan, C. (2017). Study on Shale Adsorption Equation Based on Monolayer Adsorption, Multilayer Adsorption, and Capillary Condensation. *Journal of Chemistry*, 1–11.

Chien, S. H., Sikora, F. J., Gilkes, R. J. and McLaughlin, M. J. (2012). Comparing of the difference and balance methods to calculate percent recovery of fertilizer phosphorus applied to soils: A critical discussion. *Nutrient Cycle in Agroecosystem*, 92: 1–8.

Chude, V.O., Olayiwola, S.O., Oshola, A.O and Daudu, C.K. (2011). Fertilizer use and management practices for crops in Nigeria 4th Edition. Federal Fertilizer Department, Federal ministry of Agriculture and Rural Development, Abuja. Pp 42-43.

Condron, L. M., Newman S. and Revisiting G. (2011). The fundamentals of phosphorus fractionation of sediments and soils. *Journal of Soils and Sediments*. 11(5), 830.

Dabrowski, A. (2001). Adsorption from theory to practice. *Advanced Colloid InterfaceScience,* 93: 135–224.

Daniel, G. (2021). Sorption mechanisms of chemical in soils. *Soil system,* 5(1): 13

Day, P. R. (1965). Particle fractionation and particle size analysis. In: Methods of soil analysis, Black, C. A. (Ed). Part 1 *Agronomy,* 9: 545-547.

Deveau, N., Le Cadre, E. and Hinsinger, P. (2010). A mechanistic model for understanding root induced chemical changes controlling phosphorus availability. *Ann Not (London),* 105: 1183-1197.

Dodd, R. J. and Sharpley, A. N. (2015). Recognizing the role of soil organic phosphorus in soil fertility and water quality. *Resources, Conservation and Recycling,* 105(B): 282–293.

Egbuchua, C.N. (2012). Pedological characterization of some alluvial complex soils in Delta State, Nigeria. *Nigerian Journal of Soil and Environmental Research*, 9: 65-70.

FAO (Food and Agricultural Organisation), 2005. Trade yearbook. Food and Agricultural Organisation, Rome, Italy.

Feng, Z., Fan, Z., Song, H., Li, K., Lu, H., Lui, Y. and Cheng, F. (2021). Biochar induced changes of soil dissolved organic matter: The release of dissolved organic matter by biochar and soil. *Science of the Total Environment,* 283: 147091

Geonadi, D., Siswanto, H. and Sugiarto, Y. (2000). Bioactivation of poorly soluble rock phosphate with a phosphorous solubilizing fungus. *Soil Science Society of America Journal*, 64: 927–932.

Gregor, M. (2005). Mullite-corundum-spinel-cordierite-plagioclase xenolithsin the Skaergaard Marginal Border Group: multi-stageinteraction between metasediments and basaltimagma. *Contributions to Mineralogy Petrology,* 49: 196–215.

Guedes, R. S., Melo, L. C. A. and Vergütz, L. (2016). Adsorption and desorption kinetics and phosphorus hysteresis in highly weathered soil by stirred flow chamber experiments. *Soil Tillage Resources*, 162: 46–54.

Gustafsson, J., Mwmila, L. B. and Kergot, K. (2012). The pH dependence of phosphate sorption and desorption in Swedish Agriculture soil. *Geoderma* 189(190): 304-311.

Haile A., Gebreyohannes G. and Fisseha H. (2020). The effect of pH on phosphorus adsorption in acidic soils of Tsegede, Western Zone of Tigray, Ethiopia. *Tigray Agricultural Research Institute.* 1-33

Harrison, M.R. (2007). Principles of environmental chemistry. RSC Publishing, UK. P. 363

Hartikainen, H., Rasa, K. and Withers J.A. (2010). Phosphorus exchange properties of European soils*. Journal of Soil Sciences* 6: 1033-1042.

Hasan, H.M. and Raghad, S.M. (2018). Behavior of Phosphorus in the Calcareous Soil. *Advances in Agricultural Technology and Plant Sciences*, 1(4): 180018.

Hopkins, B. G. (2015). "Phosphorus in plant nutrition", in plant nutrition handbook, 2nd edition. Eds. Pilbeam, D. J., Barker, A. V. (Boca Raton, FL, USA: CRC Press; Taylor and Francis Group), 65-126.

Horsfall, M. and Spiff, I. A. (2005). Effects of temperature on the sorption of Pb^{2+} and Cd^{2+} from aqueous solution by Caladium bicolor (Wild Cocoyam) biomass*. Electron Journal of Biotechnology,* 8: 163–169.

Hua, J.Y., Li, J. M., Zhou, H. Y., Wang, C. W. and Du, X. Q. (2008). Enhancement of phosphorus solubility by humic substances in Ferrosols Pedosphere, 18: 533-538.

Hussain, A., Anwar-Ul-Haq, A.M. and Nawaz, M. (2003). Application of the Langmuir and Freundlich Equations for P Adsorption Phenomenon in Saline-Sodic Soils. *International Journal of Agricultural Biology*, 3: 349–356.

Jamal, A., Muhammad, D. and Rahman, M., (2018). Application of adsorption isotherms in evaluating the influence of humic acid and farmyard manure on phosphorous adsorption and desorption capacity of calcareous soil. *World Science News* 107: 136–149.

Janardhanan, L. and Daroup, S. H. (2010).Phosphorus sorption in organic acids in south florida. *Soil Science Society of America Journal*, 74: 1597-1606.

Juo, A. S. R. (1979). Selected Methods for Soil and Plant Analysis. Manual Series No. 1, IITA, Ibadan.

Keller, J. and Staudt, R. (2005). Gas Adsorption Equilibria. USA: Springer Science Business Media.

Kinniburgh, D. G. (1985). Isotherm, A computer program for analyzing adsorption data. Report WD/ST/85/02. Version 2.2.British Geological Survey, Wallingford, England.

Kreszies, T., Schreiber, L. and Ranathunge, K. (2018). Suberized transport barriers in Arabdopsis, barley and rice roots. *Journal of plant and physiology,* 227: 75-83.

Lemanowicz, J. and Krzyżaniak, M. (2015). Vertical distribution of phosphorus concentrations, phosphatase activity and further soil chemical properties in salt-affected Mollic Gleysols in Poland. *Environmental Earth Science,* 74(27): 19–2728.

Li, H., Liu, J., Li, G., Shen, J., Bergstrom, L. and Zhang, F. (2015). Past, present, and future use of phosphorus in Chinese agriculture and its influence on phosphorus losses. *Ambiology,* 44: 274–285.

Limousin, G., Gaudet, J. P., Charlet, L. (2007) Sorption isotherms: A review on physical bases, modeling and measurement. *Applied Geochemistry*, 22: 249–275.

Lin, J., Zhe, Z. and Zhan, Y (2017). Effect of humic acid preloading on phosphate adsorption onto zirconium-modified zeolite. *Environmetal Science Pollution*, pp. 1-17.

Lopez-Hernandez, D. A. N. I. L. O., & Burnham, C. P. (2006). The effect of pH on phosphate adsorption in soils. *Journal of Soil Science*, 25(2),(207-216.)

Mbene, K., Tening, S. A., Cheo, E. S., Fomenky N. N. and Che, B. V. (2017). Phosphorus fixation and its relationship with physicochemical properties of soils on the Eastern flank of mount Cameroon. *African journal of Agricultural Research*, 12(36); Pp 2742-2753.

Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Commuication in Soil Science and Plant Analysis,* 15: 1409-1416.

Miller, A. P. and Arai, Y. J. (2017). Effect of extraction time and phosphorus specification on soil test phosphorus data: a case study of Illinois agricultural soils. *Geoderma,* 305: 62-69.

Moazed, H., Hoaseini, Y., Nseri A. A., and Abbasi F. (2010). Determining phosphorus adsorption isotherm in soil and its relation to soil characteristics. *Journal of Food and Agricultural Environment*, 8:1153-1157.

Muindi, E. M., Mrema, J. P., Semu, E., Mtakwa, P. W., Gachene, C. K. and Njogu, M. K. (2015). Phosphorus adsorption and its relation with soil properties in acid soils of Kenya. *International Journal of Plant and Soil Science*, 4(3):203-211.

Murphy, J. and Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. *Analytical Chemistry* ACTA, 27: 31–36.

Negassa, W. and , P. (2009). How does the Hedley sequential phosphorus fractionation reflect impacts of land use and management on soil phosphorus: a review. *Journal of Plant Nutrition and Soil Science*, 172: 305–325.

Njoyim, E. B. T., Mvondo-Ze, A. D. and Alakeh, M. N. (2016). Phosphorus adsorption isotherms in relation to soil characteristics of some selected volcanic affected soil of foumbot in the west region of Cameroon. *International Journal of Soil Science*, 11: 19–28

Okalebo, J. R., Gathua, K. W. and Woomer, P. L. (2002). Laboratory methods of soil and plant analysis: A working manual second edition TSBF CIAT and Sacred Africa Nairobi, Kenya, 128.

Olibone, D. and Ciro, A.R. (2010). Phosphate fertilization and phosphorus forms in an Oxisol under no-till. *Scientia Agricola*, 67: 465 – 471.

Oslen, S. R., Cole, C. V. Watanabe, F. S. and Dean, L. A. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *United States Department of Agriculture Circle*, Pp.939.

Penn, C. J. and Camberato, J. J. (2019). A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. *Agriculture* 9: 120.

Pierzynski, G., McDowell, R. and Sims, J. T. (2005). Chemistry, cycling, and potential moment of inorganic phosphorus in soils. In: JT Sims, AN Sharpley, eds, Phosphorus: Agriculture and the Environment. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Inc., Madison, WI, 53–86.

Plante, A. F. (2007). Soil biogeochemical cycling of inorganic nutrients and metals. In*: Soil Microbiology, Ecology and Biochemistry*; Academic Press: Cambridge, MA, USA; Pp. 389–432.

Prassad, R. and Chakraborty, D. (2019). Understanding phosphorus forms and their cycling in the soil. *Alabama Agricultural and Mechanical University and Auburn University Extension ANR-2535.* The Alabama Cooperative Extension System; Huntsville, AL, USA.

Puente, M. E., Bashan, Y. and Li, C. (2004). Microbial populations and activities in the rhizoplane of rock-weathering desert plants. I. Root colonization and weathering of igneous rocks. *Plant Biology*, 6: 629–642.

Randhawa, P. S., Condron, L. M. and Di J, et al. (2005). Effect of green manure addition on soil organic phosphorus mineralization. *Nutritional Cycling in Agroecosystem*, 73: 181–189.

Rasul, G. A. M. (2011). The role of magnesium in increasing of phosphorus fertilizer efficiency and wheat yield. *Mesopotamia Journal of Agriculture*, 39: 33–39.

Rayment, G.E. and Lyon, D.J., (2011). Phosphate sorption curve-manual colour in soil chemical methods.

Reddy, K. R. and DeLaune, R. D. (2008). Biogeochemistry of wetlands: Science and applications. CRC Press , Boca Ratoon, F. L.

Reddy, M.S., Kumar, S. and Babita, K. (2002). Bio-solubilization of poorly soluble rock phosphates by Aspergillus tubingenis and Aspergillus niger. *Bioresource Technology,* 84: 187–189.

Richardson, A. E. (2007). Making microorganisms mobilize soil phosphorus. *Development in Plant and Soil Science,* 102: 85–90.

Rishi, P. and Debolina, C. (2019). Phosphorus basics: Understanding phosphorus forms and their cycling in the soil. *Alabama Auburn extension service Annual News Report* 2425, 1-4.

Rowe, H., Withers, P.J.A, Baas, P. (2016). Integrating legacy soil phosphorus into sustainable nutrient management strategies for future food, bioenergy and water security. *Nutritional Cycling in Agroecosystem*, 104: 393–412.

Samal, D. P. K., Sukia, L. B., Pattanaik, A. and Pradhan, D. (2020). Mineralization of phosphorus by phosphate solubilizing microbes affects soil fertility. *Biofuel and bioprocessing research center, institute of technical education and research* . C (18): 1-9.

Sharma, S. B., Sayyed, R. Z., Truedi, M. H. and Gobi, T. A. (2013). Phosphate solubilizing microbes sustable approach for managing phosphorus deficiency in agricultural soils. *Springerplus,* 2: 587-600.

Sheraz Syed Mahdi, M.A Talat, M.Hussain Dar, Aflaq Hamid, Latief Ahmad. (2012). Soil phosphorus fixation chemistry and role of phosphate solubilizing bacteria in enhancing its efficiency for sustainable cropping. *Journal of Pure and Applied Microbiology*, 66: 1905-1911.

Simonson, R. W. (1997). Evolution of soil series and types concept in United States. *Advances in geology,* 29: 79-108.

Soil Survey Staff, (2003). Keys to Soil Taxonomy. 9th Edition, United States Department of Agriculture, United States Department of Agriculture Natural Resources Conservation Service, P. 322 .

Srinivasan, R., Yandigeri, M. S., Kashyap, S. and Alagawadi, A. R. (2012). Effect of salt on survival and P-solubilization potential of phosphate solubilizing microorganisms from salt affected soils. *Saudi journal of Biological sciences*, 19(4): 427-433.

Stevenson, F. J. (2005). Cycles of Soil: Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients. John Wiley and Sons, New York. Subbarao, N. S. 1988. Phosphate solubilizing micro-organism. In: *Biofertilizer in agriculture and forestry*. Regional Biofertiler Development Centre, Hissar, India. Pp. 133-142.

Surchi K (2011). Agricultural Wastes as Low-Cost Adsorbents for Pb Removal: Kinetics, Equilibrium and Thermodynamics. *International Journal of Chemistry*, 3: 103–112.

Swamy, C. A., Raghunandan, B. L. and Chandrashekhar. M. (2010). Bioactivation of Rock Phosphate via seed treatment with P solubilizing microbes (PSM) in enhancing P nutrition in cowpea and ragi. *Indian Journal of Science Technology*, 3: 689–692.

Tan, I. A. W., Ahmad, A.L. and Hameed, B.H (2008). Adsorption of basic dye using activated carbon prepared from oil palm shell: batch and fixed bed studies. *Desalination*, 225: 13–28.

Tan, K.M. (1996). Soil sampling preparation and analysis. (Mercel Dekkes. Inc: New York. Basel. Hong kong). In *African Research Review*, 3(3): 22–33.

Teing, A.S., Foba-Tendo, J. N.and Yakum-Ntaw, S. Y. (2013). Phosphorus fixing capacity of a volcanic soil on the slope of mount Cameroon. Agricultural Biology Journal of North America, 4: 166–174.

Tilman, D., Cassman, K. G. and Matson, P. A. (2002). Agricultural sustainability and intensive production practices. *Nature,* 418: 671–677.

Tucher S. V., Horndl, D. and schmidhalter, U. (2018). Interaction of soil pH and phosphorus efficacy: long term effect f p fertilizer and lime application on wheat, barley, and sugar beet. *Journal of environment and society.* 47(1):41-9.

Turner, B. L., Richardson A. E. and Mullaney, E. J. (2007). Inositol phosphates in soil: amounts, forms and significance of the phosphorylated inositol stereoisomers. , Inositol Phosphates; Linking Agriculture and the Environment. CABI, Wallingford, UK, P. 304.

Udo, E. J., Ogunwale, J. A., Fagbami, A., Ano, A. O. and Esu, I. E. (2009). *Manual of soil, plant and water resources.* Sibon books limited. P. 177.

Uwumarogie-illori, E. G., Oviasogie, P. O. and Aghimien, A. E. (2012). Evaluation of rock phosphate -Phosphorus sorption and release in basement complex soils Cultivated to the oil palm. *E3 journal of Agricultural research and development*. 2(3).Pp.070-076.

Walkley, A. and Black, I. A. (1934). An examination of Degtjareff method for determining soil organic matter and the proposed modification of the chronic acid wet titration method. *Journal of Soil Science,* 37: 29-38.

Wang L. and Liang T. (2014) Effects of exogenous rare earth elements on phosphorus adsorption and desorption in different types of soils Chemosphere, pp. 148-155.

Wang, C. H., Lurling M., Cai H. Y., Jiang H. L. and Liu, X. (2017). Bioavailable phosphorus (P) reduction is less than mobile P immobilization in lake sediment for eutrophication control by inactivating agents. *Water Research,* 109-196.

Wang, H., Zhu, J., Fu, Q. L., Xiong, J. W., Hong, C., Hu, H. Q. and Violante, A. (2015). Adsorption of phosphate onto ferrihydrite and ferrihydrite-humic acid complexes Pedosphere, 25: 405-41

Wang, Q. and Li, Y. (2010). Phosphorus adsorption and desorption behavior on sediments of different origins. *Journal of Soils Sediments*, 10: 1159–1173.

Wang, T., Camps-Arbestain, M., Hedley, M. and Bishop, P. (2012). Predicting phosphorus bioavailability from high-ash biochars. *Plant and Soil*, 357: 173–187.

Wang, Y., Chen, Y., Xie, H., Zhang, C. and Zhang, L. (2016). Lead adsorption and transport in loess-amended soil bentonite cut-off wall. *Engineering geology,* 265: 69-80

Weeks, J. J. and Hettiarachchi, G. M. (2019). A Review of the Latest in Phosphorus Fertilizer Technology: Possibilities and Pragmatism. *Journal of Environmental Quality*, 48: 1300–1313.

Whitelaw, M. A. (2000). Growth promotion of plants inoculated with phosphate solubilizing fungi. *Advanced Agronomy*, 69: 99-151.

Yang, X., Sun, Z. and Wang, D. (2007). Surface acid–base properties and hydration/dehydration mechanisms of aluminum hydroxides. *Journal of Colloid Interface Science*, 308: 395–404.

Zhang, S., Huffman, T., Zhang, X.and Liu, W. (2014). Spatial distribution of soil nutrient at depth in black soil of Northeast China: a case study of soil available phosphorus and total phosphorus. *International Journal of Soil Sediment and Water*, 14:1775-1789.