

**FORMS AND DISTRIBUTION OF INORGANIC PHOSPHORUS IN
SOIL PLANTED TO PLANTAIN IN UNIVERSITY OF BENIN,
NIGERIA.**

BY

**Similoluwa Esther FOLUSO-ADEDAPO (Miss)
AGR2004415**

**DEPARTMENT OF SOIL SCIENCE AND LAND MANAGEMENT
FACULTY OF AGRICULTURE
UNIVERSITY OF BENIN
BENIN CITY**

OCTOBER, 2025.

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**A PROJECT SUBMITTED TO THE DEPARTMENT OF SOIL SCIENCE AND
LAND MANAGEMENT, FACULTY OF AGRICULTURE, UNIVERSITY OF BENIN,
BENIN CITY, NIGERIA**

**IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF
BACHELOR OF AGRICULTURE (B. AGRIC. HONS) DEGREE WITH OPTION IN
SOIL SCIENCE.**

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CERTIFICATION

This is to certify that this Project work titled: Forms and distribution of inorganic Phosphorus in soil planted to plantain in University of Benin, Nigeria was carried out by Similoluwa Esther FOLUSO-ADEDAPO (Miss) with Matriculation Number AGR2004415 in the Department of Soil Science and Land Management, Faculty of Agriculture, University of Benin, Benin City, Nigeria.

.....
Prof. E. R. Orhue
Project Supervisor

+
Dr. (Mrs.) V. I. O. Edosa
Head of Department

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Date

.....
Date

DEDICATION

This project dedicated to God Almighty for his infinite blessings and protection and also to my family for their unwavering love and support throughout my course of study in the University of Benin. I am forever grateful to you Heavenly Father.

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ABSTRACT

Phosphorus (P) is a critical macronutrient essential for plant growth, it involved in energy transfer, cell division, and development of root systems. This study was conducted to examine different forms of inorganic phosphorus in soils planted to plantain. The study was conducted between April-October 2025, on twelve (12) soil samples collected from five (4) depths, three (3) replicates in soils planted to plantain within University of Benin, Edo States, Nigeria. Some soil properties were determined using standard laboratory procedures, Forms of inorganic P were determined by six step sequential fractionation using suitable chemical extractants, while the relationship between some soil properties and forms of inorganic P was evaluated by simple linear correlation. Genstat (12th edition) statistical package was employed for data analysis, Duncan multiple ranged test was used to separate means at 5%. Results revealed that various forms of inorganic P were distributed in the soils with the Al and Fe bound P forms occurring in the largest amount with grand mean values of 88.83 and 51.80 mg kg⁻¹ respectively. The forms of P in the soils were influenced negatively and positively by some soils properties across the various soil depths, however at 0-30 cm soil depths Ca bound P correlated positively with Ca+Mg ($r= 0.997^*$), saloid bound P showed significant positive and negative relationship with sand ($r = -1.000^{***}$) and Organic carbon ($r = 1.000^{***}$) respectively, the relation between other soil properties, with some forms of inorganic P were also obtained. Proper P management is required to enhance P availability, optimum growth of P beneficial crops.

CHAPTER ONE

1.0

INTRODUCTION

Phosphorus (P) is a critical macronutrient for plant growth, involved in energy transfer, cell division, and development of root systems (Zhang *et al.*, 2020). Although most soils contain phosphorus, it is often poorly available in a form that plants can use, mainly due to strong fixation processes and low solubility of P in soils, especially in very acidic or alkaline soil conditions, where it reacts with other elements to form compounds that are insoluble for plants absorption (Li *et al.*, 2021). In the soil, phosphorus exists in two major forms: inorganic forms like calcium, iron, and aluminum bound phosphates, and organic forms, which are formed from dead plant, animal materials and microbial biomass (Oburger and Schmidt, 2016). The behavior of these phosphorus forms differs across environments, as they are influenced by factors such as soil pH, texture, organic matter, and microbial activities (Zhu *et al.*, 2018).

As an essential nutrient element for plant, its application is inevitable. However, a significant portion of the applied phosphorus becomes fixed in the soil or is lost through erosion and runoff, particularly during periods of heavy rainfall. This not only reduces fertilizer efficiency but also contributes to pollution of rivers and lakes (Chen *et al.*, 2022). The Study of phosphorus forms, distribution, and mobility in different soil types helps scientists and land managers to create targeted, efficient, and environmentally friendly fertilizer strategies. Certain techniques like spectroscopy and fractionation have helped give a clearer of how phosphorus is stored and transformed in soils over time (Zhou *et al.*, 2023). This makes the study of phosphorus forms, distribution and mobility very relevant and necessary, especially as man look for ways to improve food production without harming the environment.

1.1 OBJECTIVES

The broad objective of the study was to evaluate the forms and distribution of inorganic phosphorus in soil planted to plantain in University of Benin-city Nigeria while specific objectives were to;

1. determine some physical and chemical properties of the soil
2. evaluate the forms and distribution of inorganic phosphorus in the soil
3. investigate the relationship between some soil properties and forms of inorganic P in the soil.

CHAPTER TWO

2.0

LITERATURE REVIEW

2.1 PHOSPHORUS

Phosphorous (P), is a reactive non-metal found in Group 15 of the periodic table with atomic number 15. It occurs in several allotropic forms, the most notable being white, red, and black phosphorus, each with distinct physical and chemical properties. Phosphorus (P) is essential to all life form. Industrially, phosphorus (P) is vital in the production of fertilizers, given its role in plant development, as well as in steel hardening, flame retardants, and electronics (Cherlinka, 2025). However, its environmental impact is significant; excessive phosphorus runoff, from agriculture may contribute to nutrient enrichment in water bodies, leading to harmful algal blooms and oxygen depletion (Kim, 2024). Proper management of phosphorus is therefore essential for both agricultural productivity and environmental sustainability.

2.2 ROLES OF PHOSPHORUS IN SOIL

Phosphorus is a key macronutrient essential for plant growth and soil fertility. It plays a major role in important plant functions such as energy transfer through ATP, photosynthesis, cell division, and root development (Zhou *et al.*, 2021). In soils, phosphorus is found in both organic and inorganic forms, but only a small portion is readily available to plants because of fixation by soil minerals, making phosphorus management important for sustaining soil productivity (Wang *et al.*, 2023). Apart from its direct impact on plant nutrition, phosphorus may also influences soil microbial activity and soil chemicals properties. In many ecosystems, phosphorus acts as a limiting nutrient, growth and diversity of soil microbes. These microbes are important in nutrients recycle and organic matter decomposition, both of which are

essential for maintaining healthy soil (Liu *et al.*, 2022). In addition, P can impact soil pH and structure, which are important for maintaining good soil health (Singh *et al.*, 2020).

2.3 SOURCES OF PHOSPHORUS IN SOIL

Phosphorus in soil originates from both natural and anthropogenic sources. Naturally, it is released slowly through the weathering of phosphate-rich rocks like apatite and from the decomposition of organic matter, whichever mineralizes organic phosphorus into plant-available forms (Zhang *et al.*, 2022). Anthropogenic sources include the addition of fertilizers, manure, and biosolids, which can enhance soil fertility but may also cause nutrient runoff if mismanaged (Kumar and Singh, 2021). Phosphate-solubilizing microorganisms (PSMs) further improve phosphorus availability by releasing organic acids and enzymes that convert insoluble phosphorus into forms plants can use (Fernandez *et al.*, 2023).

2.4 FORMS OF PHOSPHORUS IN SOIL

Phosphorus in soil mainly exists as inorganic and organic forms, with inorganic phosphorus including soluble orthophosphate (H_2PO_4^- , HPO_4^{2-}) ions that plants can absorb, and insoluble forms like calcium, iron, or aluminum phosphates depending on soil pH (Wang *et al.*, 2023). The insoluble forms become plant-available only after microbial mineralization (Liu *et al.*, 2022).

2.4.1 Inorganic Phosphorus:

Inorganic phosphorus includes all phosphate forms not bound to carbon. It is the main form absorbed by plants, typically as orthophosphate (H_2PO_4^- , HPO_4^{2-}) ions present in soil solution (Turner and Richardson, 2022). However, inorganic phosphorus exists in several sub-forms that differ significantly in their availability to plants, depending on factors such as soil pH, mineral composition, and chemical interactions with metal ions like iron, aluminum, and

calcium (Chen *et al.*, 2021; Zhang *et al.*, 2020). Inorganic P is primarily associated with mineral phases and can be further classified into:

2.4.1.1 Soluble Phosphorus

Soluble phosphorus, primarily existing as orthophosphate ions (H_2PO_4^- , HPO_4^{2-}) in soil solution, is the most bioavailable form of P for plant uptake, directly fueling critical processes like energy transfer (ATP synthesis), root development, and photosynthesis (Zhu *et al.*, 2024, Pang *et al.*, 2024). In acidic soils, soluble phosphorus binds tightly to iron (Fe) and aluminum (Al) oxides, forming insoluble compounds like strengite (FePO_4) or variscite (AlPO_4), while in alkaline soils, it precipitates as calcium phosphates e.g apatite (Penn and Camberato, 2019, Jahan *et al.*, 2025). This reactivity means that even in fertilized soils, less than 25% of applied phosphorus remains plant-available, with the rest becoming "fixed" in mineral or organic forms (Liang *et al.*, 2025, Pang *et al.*, 2024). Recent research highlights innovative strategies to preserve soluble phosphorus, such as using organic amendments (e.g., compost) to compete with fixation sites or inoculating phosphate-solubilizing microbes that secrete organic acids to liberate bound phosphorus (Pang *et al.*, 2024). In agricultural systems, soluble phosphorus is often supplied through fertilizers like monoammonium phosphate (MAP) or diammonium phosphate (DAP), which dissolve quickly in soil moisture (Johnston and Bruulsema, 2024).

2.4.1.2 Adsorbed Phosphorus

Adsorbed phosphorus refers to phosphate ions (PO_4^{3-}) that attach to the surfaces of soil particles, particularly clay minerals, iron (Fe), and aluminum (Al) oxides, through chemical bonding (Arai and Sparks, 2023). Unlike soluble phosphorus, which is readily available for plant uptake, adsorbed phosphorus is temporarily immobilized, acting as a reservoir that slowly releases phosphate into the soil solution as conditions change (Hansen *et al.*, 2021;

Wang *et al.*, 2023). This adsorption process is highly dependent on soil pH whereby acidic soils favor binding with Fe and Al oxides, while alkaline soils promote calcium (Ca) phosphate precipitation (Zhang *et al.*, 2024). The mineral composition plays an equally critical role as well especially in soils containing clay minerals like kaolinite or iron/aluminum oxides such as goethite which exhibit particularly high phosphorus adsorption capacities (Sanyal and De-Datta, 2023). Adsorbed phosphorus plays a crucial role in regulating phosphorus availability in ecosystems, preventing immediate leaching while still contributing to long-term fertility (Hansen *et al.*, 2021). However, in heavily fertilized agricultural soils, saturation of adsorption sites can lead to increased phosphorus runoff, contributing to water pollution (McDowell *et al.*, 2022).

2.4.1.3 Mineral-Bound Phosphorus

Mineral-bound phosphorus, often called "fixed phosphorus," consists of phosphorus atoms tightly held by soil minerals through strong chemical bonds. These compounds are largely insoluble in water and considered non-labile, meaning they don't readily move through soil or become available to plants (Mitchell and Huluka, 2018). This fixed form accounts for a substantial portion of total soil phosphorus. About 80% of this exists in immobile forms that plants can't directly access. The major types of mineral-bound Phosphorus include;

- **Iron-Bound Phosphorus**

Iron-bound phosphorus is a dominant form of inorganic phosphorus in acidic and waterlogged

Soils, where phosphate (PO_4^{3-}) strongly adsorbs to iron (Fe) oxides/hydroxides or forms insoluble precipitates like vivianite ($\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$) and strengite ($\text{FePO}_4 \cdot 2\text{H}_2\text{O}$) (Tao *et al.*, 2025, Yang *et al.*, 2024). This happens because in acidic conditions, iron oxides become the primary phosphorus-adsorbing phases in soil (Yang *et al.*, 2024). This fixation reduces phosphorus availability for plants, as iron phosphorus is stable under aerobic conditions but can release soluble P when soils become anoxic (e.g., during flooding), through reductive dissolution of Fe^{3+} to Fe^{2+} (Yuan *et al.*, 2023). The surface of these iron phosphorus complexes often gets coated with a hydrated iron oxide layer, creating a sort of sealed state that further decreases their availability to plants. Recent research shows that the stability of these iron-phosphorus bonds makes them particularly difficult to break, requiring either highly acidic conditions ($\text{pH} < 2$) or specialized biological processes to release the phosphorus (Du *et al.*, 2024).

- **Aluminum-Bound Phosphorus**

Aluminum-bound phosphorus is a dominant form of inorganic phosphorus in acidic soils ($\text{pH} < 5.5$), where aluminum oxides and hydroxides strongly adsorb phosphate ions to form insoluble compounds like variscite ($\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$) (Yi *et al.*, 2023). This fixation reduces phosphorus availability for plants, particularly in highly weathered tropical and subtropical soils rich in aluminum oxides. While aluminum-bound phosphorus is generally considered unavailable, some plants and microorganisms have developed strategies to access it. Certain microbes can secrete organic acids that help dissolve these aluminum-phosphorus complexes, making the phosphorus available for uptake (Yang *et al.*, 2024). Recent studies highlight that organic acids (e.g., citrate) from root exudates or microbial activity can partially solubilize aluminum phosphorus, enhancing its bioavailability (Lanno *et al.*, 2021). Biochar amendments has also demonstrate significant potential in reducing aluminum-bound phosphorus fixation by raising soil pH to reduce Al^{3+} solubility and competing with

phosphate for adsorption sites on aluminum oxides through its high surface area and negative charge (He *et al.*, 2025).

- **Calcium-Bound Phosphorus**

Calcium-bound phosphorus is a critical but often poorly available form of inorganic phosphorus in soils, particularly in alkaline or calcareous environments (pH > 7) (Caballero *et al.*, 2023). In alkaline or calcareous soils (pH above 7), phosphorus predominantly binds with calcium to form various calcium phosphate minerals, particularly hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) and dicalcium phosphate (CaHPO_4), which are highly stable and dissolve slowly, limiting plant uptake (Prasad and Chakraborty, 2019). In calcareous soils, phosphorus readily reacts with calcium ions to form these insoluble compounds, reducing its bioavailability. However, recent research highlights that microbial activity, root exudates (e.g., organic acids), and soil amendments (e.g., sulfur or acidifying fertilizers) can enhance calcium-bound phosphorus solubility by lowering pH or chelating calcium (Almeida *et al.*, 2024, Antonangelo *et al.*, 2025).

2.4.1.4 Occluded Phosphorus

Occluded phosphorus also known as locked phosphorus, is a general term for phosphorus-containing substances such as iron-phosphorus or aluminum-phosphorus, which are coated in an insoluble colloidal film formed by iron oxyhydroxides (Du *et al.*, 2024). This form of phosphorus gets physically trapped within mineral coatings, particularly iron (Fe) and aluminum (Al) oxides, making it temporarily unavailable for plant uptake. Occluded Phosphorus is especially common in highly weathered tropical and subtropical soils, where intense weathering leads to the formation of insoluble Fe/Al oxide coatings that encapsulate

phosphate ions (Johan *et al.*, 2021, Du *et al.*, 2024). Over time, occluded phosphorus can accumulate in both surface and subsoil layers, depending on factors like fertilization practices and the migration of Fe/Al oxides (Du *et al.*, 2024). While occluded P acts as a long-term reservoir in soils, its immediate accessibility is limited, posing challenges for agricultural productivity in regions with high P fixation. Recent studies suggest that microbial activity, root exudates (e.g., organic acids), and soil amendments (e.g., biochar or organic matter) can slowly reactivate occluded phosphorus by breaking down these mineral coatings, though the process remains inefficient under natural conditions (Wang *et al.*, 2024, Scherwietes *et al.*, 2025).

2.4.2 Organic Phosphorus:

Organic phosphorus is the form of phosphorus found within organic compounds in the soil, such as those derived from plant and microbial residues. Unlike inorganic phosphorus, organic Phosphorus is not directly available to plants and must first undergo mineralization, a biological process carried out by soil microbes using enzymes like phosphatases (Chen *et al.*, 2021). Several types of organic phosphorus compounds exist in soils, such as;

2.4.2.1 Phosphomonoesters (50–70% Of Soil Organic P)

Phosphomonoesters are the most abundant form of organic phosphorus in soils, making up 50–70% of total soil organic phosphorus (Jantamenchai *et al.*, 2022). These compounds contain a single phosphate ester bond (C-O-P) and include key forms like:

- i. Phytate (inositol hexakisphosphate) – The most stable and dominant form, especially in acidic soils where it binds tightly to iron (Fe) and aluminum (Al) oxides (Guan *et al.*, 2024). Phytate accumulates in soils due to its resistance to degradation by plant-derived phosphatases and its strong sorption to soil components, including humic

substances and metal oxides (Jørgensen *et al.*, 2015, Gerke *et al.*, 2015). While microbial phytases can hydrolyze phytate into lower inositol phosphates (InsP1–InsP5) and orthophosphate inorganic phosphorus, enhancing its availability, the process is often inefficient in natural systems due to phytate's immobilization in soil matrices (Li *et al.*, 2022).

- ii. Sugar phosphate - They are rapidly mineralized by microbes (Li and Yao, 2022). Sugar phosphate like glucose-6-phosphate and fructose-6-phosphate—are the readily available energy of soil organic phosphorus, acting as highly labile energy sources for microbes and short-term P reservoirs for plants (Pang *et al.*, 2024). These compounds, central to glycolysis and photosynthesis, break down rapidly in soils (within days to weeks) through enzymatic action, releasing plant-available orthophosphate (H_2PO_4^-) (Khan *et al.*, 2023). However, their fleeting nature makes them prone to leaching in sandy soils or strong adsorption to iron/aluminum oxides in acidic conditions, limiting their persistence (Samuel *et al.*, 2020).

2.4.2.2 Phosphodiester (10–30% Of Soil Organic P)

Phosphodiester, like DNA, RNA, and phospholipids (e.g. lecithin) are key in soil organic phosphorus pools, acting as both microbial building blocks and temporary nutrient reservoirs (Wasner *et al.*, 2023). These compounds are more labile than phosphomonoesters (e.g., phytate) but are less readily degraded than sugar phosphates, placing them in an intermediate stability range—stable enough to persist and support microbial activity, yet reactive enough to avoid becoming immobilized by binding to soil minerals (Chen *et al.*, 2023). In well-aerated soils, microbes rapidly cleave phosphodiester into phosphomonoesters using enzymes like phosphodiesterases, but this process can stall in acidic or waterlogged conditions where enzymes are less active (Zhong *et al.*, 2025). . Recent studies using ^{33}P -labeling reveal that some microbes even shortcut mineralization by directly absorbing intact

phosphodiester which is a clever trick to save energy in phosphorus-poor soils (Wasner *et al.*, 2023). While they're less abundant than phosphomonoesters overall, phosphodiester dominate the active organic phosphorus pool in many soils, especially those with fresh organic inputs (like crop residues or manure), making them critical for short-term phosphorus cycling (Pang *et al.*, 2024).

2.4.2.3 Phosphonates (1–5% Of Soil Organic P)

Phosphonates are unique organic phosphorus compounds characterized by a direct carbon-phosphorus (C-P) bond, making them more resistant to chemical and microbial breakdown compared to typical phosphate esters (Kafarski *et al.*, 202) . In soils, they occur naturally (e.g., 2-aminoethylphosphonic acid in microbes and plants) or enter as synthetic inputs from fungicides (e.g., fosetyl-Al) and herbicides like glyphosate (Landschoot and Cook 2023). While phosphonates represent a small fraction of soil organic P (1–5%), their stability allows persistence in soils for months to years, especially in acidic or waterlogged conditions where microbial degradation slows (Nguyen, 2025).

2.5 EXTRACTION OF PHOSPHORUS FROM SOILS

Extracting phosphorus (P) from soils involves various methods designed to target different P pools, with the choice of extractant depending on soil type, pH, and management history.

For inorganic phosphorus, to measure what's actually available to crops, soil scientists use a toolbox of extractants, each designed to different soil types. For calcareous soils, dilute acids like HCl or Mehlich-3 dissolve calcium-bound P (e.g., apatite), while alkaline extractants (e.g., Olsen's bicarbonate) work better in neutral-to-alkaline soils by releasing adsorbed phosphorus (Medeiros *et al.*, 2021) . In acidic soils, reagents like Bray-1 (HCl + NH₄F) target iron/aluminum-bound P, which dominates under low pH conditions (Kiflu *et al.*, 2017).

For organic phosphorus, unlike inorganic phosphorus, organic phosphorus exists as complex compounds like phytates, phospholipids, and nucleic acids, which are tightly bound to soil organic matter or mineral surfaces. To determine organic phosphorus, labs typically use alkaline extractants such as NaOH, sometimes combined with EDTA (a chelating agent) to release organic P bound to soil minerals or humus (Kiflu *et al.*, 2017).

2.6 DISTRIBUTION OF PHOSPHORUS IN SOIL

The distribution of phosphorus (P) in soils is influenced by multiple factors, including soil properties, land use, climate, and management practices. Inorganic P (Pi) and organic P (Po) fractions vary significantly, with Pi often bound to calcium (Ca), iron (Fe), or aluminum (Al) depending on soil pH, while Po is derived from organic matter and microbial activity (Anjum *et al.*, 2024). The chemical distribution of phosphorus includes;

- i. **Total Distribution of Phosphorus:** Phosphorus in soils exists in a range of chemical forms that reflect a delicate balance between mineral, organic, and adsorbed pools, all influenced by soil properties like pH, redox potential, and mineral composition. While total soil P may seem abundant, only a small fraction is immediately available to plants—the rest is tied up in stable mineral forms (like apatite), strongly adsorbed to iron and aluminum oxides, or locked within organic matter (Condrón *et al.*, 2022). This distribution creates a chemical barrier, as most of the P is not easily mobilized without biological activity or chemical weathering. Soil pH, in particular, plays a vital role in determining whether P stays in solution or precipitates into insoluble compounds (Zhu *et al.*, 2023).
- ii. **Available Distribution of Phosphorus:** This bioavailable portion is mainly found in the soil solution as orthophosphate ions (H_2PO_4^- and HPO_4^{2-}), whose concentration is influenced by pH, mineral surfaces, and microbial activity. In acidic soils, P often

binds strongly to iron and aluminum oxides, while in alkaline soils, it tends to precipitate with calcium, both of which reduce its availability (Sharma *et al.*, 2023). Organic matter can help by competing for binding sites and slowly releasing P through mineralization, but even then, plants are often left scavenging from a very limited supply. Soil microbes and root exudates also play a crucial role by solubilizing bound forms, especially under P-deficient conditions (Huang *et al.*, 2022).

- iii. **Phosphorus in acidic soil:** In acidic soils (pH < 5.5), phosphorus availability is often severely limited due to its strong interactions with abundant iron (Fe³⁺) and aluminum (Al³⁺) oxides and hydroxides. When phosphate ions (e.g., H₂PO₄⁻) are added, they are rapidly adsorbed onto these oxide surfaces or precipitate into insoluble forms such as FePO₄ and AlPO₄, an effect commonly known as phosphorus fixation, which dramatically reduces soluble P in the soil and its availability to plants (Zhao *et al.*, 2022). In highly weathered tropical soils, which are inherently acidic and rich in sesquioxides, a substantial fraction of total soil phosphorus becomes occluded within Fe/Al oxide coatings, rendering it even more inaccessible to plant uptake (Richardson *et al.*, 2022). Consequently, crops in acidic soils frequently suffer from phosphorus deficiency unless remedial practices such as liming, which raises pH and reduces Al/Fe reactivity, addition of organic amendments like biochar or compost to both neutralize acidity and complex Al/Fe ions, or application of soluble P fertilizers—are employed to increase plant-available phosphorus (Liu *et al.*, 2020; Wang *et al.*, 2023).
- iv. **Phosphorus in Alkaline/Calcareous Soils:** In alkaline soils (pH > 7.5), particularly in calcareous soils rich in calcium carbonate (CaCO₃), phosphorus availability is constrained by rapid precipitation reactions. Phosphate ions—predominantly HPO₄²⁻ at higher pH—react with calcium ions (Ca²⁺) or carbonate surfaces to form sparingly soluble calcium-phosphate minerals such as dicalcium phosphate, octacalcium

phosphate, and more stable forms like hydroxyapatite, which are not easily accessible to plants (Johan, 2021). As a result, despite potentially high total phosphorus reserves, only a minimal fraction remains plant-available, because the majority is locked in these insoluble forms (El-Damarawy *et al.*, 2025). Management strategies often recommended include repeated or localized phosphorus fertilization, use of acid-forming fertilizers, band placement of P sources, or additions of organic matter to chelate calcium and slow the precipitation process (Johan, 2021).

2.7 DETERMINATION OF PHOSPHORUS IN SOILS

The determination of phosphorus (P) in soils involves assessing both total and available P fractions, using methods designed to their distinct chemical forms.

- **Total Phosphorus:** Total P includes both inorganic (mineral-bound) and organic (biologically derived) forms, often locked within stable compounds like apatite or bound tightly to iron and aluminum oxides. To release all these forms, total P is measured using strong acid digestion methods such as perchloric acid (HClO₄) or aqua regia, which aggressively break down mineral and organic matrices to release all phosphorus into solution (Obalum *et al.*, 2023). This is followed by colorimetric detection, typically the molybdenum blue method to quantify P in the digest. Though most of the measured P is not immediately available for plant, total P data help soil scientists assess nutrient depletion or accumulation over time, and can be especially important in soils with a long history of fertilization or manuring (Bünemann *et al.*, 2022).
- **Available Phosphorus:** Available P refers to the portion that is present in the soil solution or easily exchangeable from solid phases, mainly as orthophosphate ions (H₂PO₄⁻ and HPO₄²⁻). Because soil P is highly reactive, it tends to bind tightly with

iron and aluminum oxides in acidic soils or form insoluble calcium phosphates in alkaline soils, making its availability highly pH-dependent (Sharma *et al.*, 2023). To measure this plant-accessible fraction, soil scientists use chemical extractants that mimic root activity. For instance, the Bray-1 and Mehlich-1 methods are effective in acidic soils, while Olsen's sodium bicarbonate extraction works better in neutral to calcareous soils (Zhang *et al.*, 2021). These methods pull out the loosely bound P, which is then quantified using colorimetric techniques like the molybdenum blue method.

Recent techniques, like sequential fractionation, help separate phosphorus into pools (e.g., Fe/Al-bound, Ca-bound). Additionally, phosphorus-31 nuclear magnetic resonance (³¹P-NMR) spectroscopy allows for the detailed identification of organic phosphorus compounds, enhancing our understanding of P cycling and aiding in better soil fertility management (Zhou *et al.*, 2023).

2.8 SEQUENTIAL EXTRACTION PROCEDURE

Sequential Extraction Procedure involves sequentially extracting soil samples with solutions of increasing strength to determine the distribution of phosphorus among different fractions in the soil. The extraction procedure can provide information on the amounts of phosphorus that are weakly, moderately, and strongly adsorbed to soil minerals this providing information of the amount of available and unavailable P in the soil.

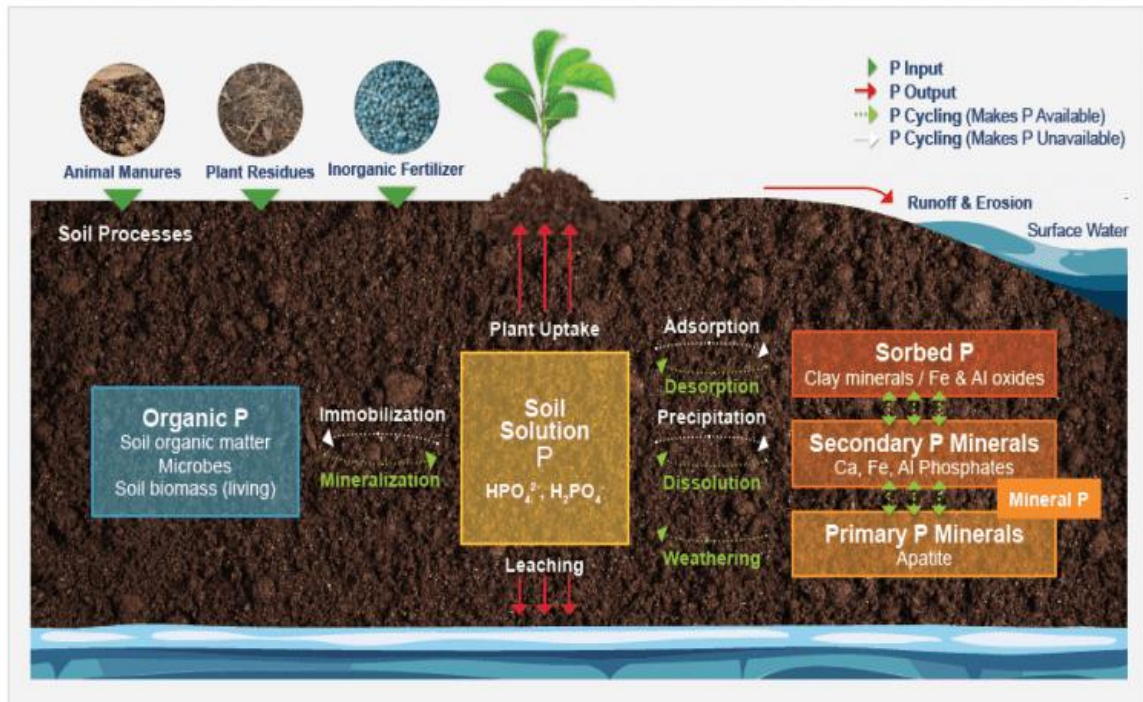
2.9 SOIL TEST

Soil tests that measure soil phosphorus levels, such as the Bray (Bray and Kurtz, 1945), Mehlich (Mehlich, 1984), or Olsen test (Olsen *et al.*, 1954) can also provide information on soil phosphorus sorption. These tests measure the amount of readily available phosphorus in

the soil, which can be related to the overall sorption capacity of the soil (Miller and Arai, 2017).

2.10 PHOSPHORUS CYCLING AND TRANSFORMATION

The phosphorus cycle describes the movement of phosphorus through soil, plants, and water. Unlike nitrogen, phosphorus has no significant gaseous form, so it cycles mainly through biological and geological processes (Condrón and Turner, 2022). Phosphorus enters the soil through mineral fertilizers, atmospheric deposition (dust), and organic inputs like animal manures, biosolids, and plant residues. In soils, it exists in both organic (e.g., microbial biomass, humus) and inorganic forms. Organic phosphorus is converted into plant-available forms (H_2PO_4^- and HPO_4^{2-}) through mineralization, while the reverse—immobilization—locks phosphorus into organic matter (Richardson *et al.*, 2019).



F

figure 1. Phosphorus cycle

Source: Prasad and Chakraborty (2019), Alabama Cooperative Extension System (ACES).

Inorganic phosphorus comes from primary minerals such as apatite and undergoes weathering to release soluble P. This soluble phosphorus can be adsorbed onto clay minerals and Fe/Al oxides, or form secondary compounds (e.g., CaP, FeP), making it less available to plants (Shen *et al.*, 2018). Plants absorb soluble phosphorus, and it exits the cycle through crop harvest. Losses also occur via erosion, surface runoff, and minor leaching, which can lead to environmental issues like eutrophication. Maintaining the phosphorus cycle in balance is essential for sustaining soil fertility and crop productivity.

2.11 IMPLICATIONS OF PHOSPHORUS MANAGEMENT IN SOIL

Effective phosphorus management is vital for crop growth and environmental protection. Despite being present in soil, phosphorus often becomes unavailable due to its low mobility and strong fixation to particles. Poor management can cause surface buildup and runoff pollution (Wang *et al.*, 2023). Key strategies include precise fertilizer use, phosphorus-efficient crops, organic amendments, and maintaining optimal soil pH to improve availability and reduce losses (Chen *et al.*, 2021).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 DESCRIPTION OF STUDY AREA

The study was conducted between April-October, 2025, within the University of Benin, Farm Project, located at an elevation of approximately 114 metres above sea level. The site lies within the geographical coordinates of 6°24'15" to 6°24'20" N latitude and 5°36'37" to 5°36'39" E longitude. Soil samples were collected with an auger at various depths, in the Field, between 10:00 and 11:00 a.m., during which ambient soil temperatures ranged from 28.7 °C to 30.1 °C. The area was primarily a plantation environment, comprising well-drained and seasonal swampy zones, which reflects the site's hydrological variability and heterogeneity in soil moisture conditions.

3.2 COLLECTION OF SAMPLES

Soil samples were collected within the plantain farm from 4 depths (0-30, 30-60, 60-90, 90-120 cm) in 3 replicate, making a total of 12 samples.

3.3 SAMPLE PREPARATION

3.3.1 Soil sample preparation

Soil samples were air-dried, grounded and sieved through a 2 mm sieve, analyzed and stored in a polythene bag for laboratory analysis.

3.4 LABORATORY ANALYSIS

3.4.1 Particle size determination

This was determined using the Hydrometer method of Bouyoucos (1951) as modified by Day (1965). 51 g 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:

$$\% \text{ sand} = 100 [H_1 + 0.3 (T_1 - 20) - 2] / 2$$

$$\% \text{ clay} = [H_2 + 0.3 (T_2 - 20) - 2] / 2$$

$$\% \text{ silt} = 100 - (\% \text{ sand} + \% \text{ clay})$$

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

3.4.2 Textural Classification

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

3.4.3 pH in Water (1:2)

The soil pH (1:2) was determined in 1:2 soil to water suspension ratio using a glass electrode pH meter (Tan, 1996).

3.4.4 pH in Calcium Chloride (CaCl₂)

The soil pH (1:2) was determined in 1:2 soil to Calcium Chloride suspension using a glass electrode pH meter (Tan, 1996).

3.4.5 Soil Organic Carbon (OC)

The soil organic carbon (OC) content was determined by the wet oxidation method of Walkley and Black (1934). 1 g of soil was weighed into a conical flask. 10 ml of 0.167 M K₂Cr₂O₇ was added and swirled. 20 ml of concentrated H₂SO₄ was added and swirled for 1 minute and the mixture was allowed to stand for 30 minutes, after which 100 ml distilled water was added and the swirled, 4 drops of ferroin complex indicator was added. The mixture was swirled and titrated against 0.5 N FeSO₄.7H₂O to a brownish red end point (T).

Blank was prepared and titrated (B) following same procedure without soil.

$$\% \text{ Organic carbon} = M \frac{(V_1 - V_2) 0.3 f}{W}$$

Where

M = Molarity of KMnO₄, V_1 = Volume of KMnO₄ used in sample titration, V_2 = Volume of KMnO₄ used in blank sample titration, f = Correction factor (1.33), W = Weight of soil

3.4.6 Total organic Nitrogen

Total organic nitrogen was computed from total organic carbon by dividing values of organic carbon by 20 (Ibitoye, 2008).

3.4.7 Available Phosphorus (P)

Available P was extracted with Bray-1 solution according to methods of Bray and Kurtz (1945). The P in the extract was determined colorimetrically using the VIS 720 spectrophotometer and developed using the Sulphuric molybdate blue method (Murphy and Riley, 1962).

3.4.8 Exchangeable Bases

Exchangeable bases (Ca, Mg, Na, K) were extracted with 1 N ammonium acetate (1N NH₄OAc), buffered at pH 7. Na and K were read using the flame photometer while Ca and Mg were determined using EDTA Titration method.

3.4.9 Cation Exchange Capacity (CEC)

The cation exchange capacity (CEC) was determined by summation methods. CEC was calculated by summation of values of Ca, Mg, K and Na. (Udo *et al.*, 2009).

3.4.10 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 was 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;

$$EA = \frac{T \times M \times V1}{V2} \times \frac{100}{w}$$

Where:

EA = Exchangeable Acidity, T = titre value, M = molarity of acid used (0.01 M), V₁ = volume of extractant (100 ml), V₂ = final volume of extract used for titration (10 ml), W = weight of soil

3.4.11 Effective Cation Exchange Capacity (ECEC)

Effective Cation Exchange Capacity (ECEC) was calculated by summation of Exchangeable bases (CEC) and Exchangeable acidity (EA).

3.4.12 Base Saturation

Percentage base saturation was determined by the equation given below:

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

3.5 DETERMINATION OF FORMS OF INORGANIC PHOSPHORUS IN SOILS

The forms of inorganic phosphorus which are saloid-bound P, Aluminum-bound P, Iron-bound P, Reductant soluble P, Occluded Fe and Al P and Calcium-bound P were determined by seven step sequential fractionation as follows;

3.5.1 Saloid-bound Phosphorus

Saloid-bound P was first extracted by weighing 1 g of soil into a 100 ml centrifuge tube, 50 ml 1 M ammonium chloride (NH₄Cl) was added, the suspension was shaken for 30 minutes and filtered using the whatman 42 filter paper. P in the extract was determined colorimetrically using Vis 721 spectrophotometer.

3.5.2 Aluminium-bound Phosphorus

50 ml of 0.5 M ammonium fluoride (NH_4F) solution was added to the residue from saloid-bound P, the mixture was and shaken for 1 hour, filtered through, whatman 42 filter paper and P in the extract was determined colorimetrically using Vis 721 spectrophotometer.

3.5.3 Iron-bound Phosphorus

The residue from the Al-P extractant was first washed with 35 ml of saturated sodium chloride (NaCl) solution and decanted, 50 ml 0.1 M sodium hydroxide (NaOH) was added to the residue and shaken overnight. The content was filtered through whatman 42 filter paper into a 50 ml conical flask. 5 drops of conc. H_2SO_4 was added to the turbid supernant and swirl to flocculate organic matter and then filtered through activated charcoal P-free in whatman 42 filter paper to remove the turbid color. The filtrate was determine colorimetrically, using Vis 721 spectrophotometer.

3.5.4 Reductant-soluble Phosphorus

The residue from Fe-bound P was washed with 35 ml saturated NaCl and subsequently suspended in 25 ml 0.3 M sodium citrate solution. 1 g of solid sodium dithionite ($\text{Na}_2\text{S}_2\text{O}_4$) was added and the content was shaken for 5 minutes, heated for 15 minutes in water bath (80-90 °C) and diluted to 50 ml mark with distilled H_2O . The solution was shaken again for 5 minutes and filtered through Whatman 42 filter paper and P in the extract was determined colorimetrically using Vis 721 spectrophotometer.

3.5.5 Occluded Fe and Al-bound Phosphorus

The residue from reductant-soluble P was washed with 35 ml NaCl and suspended in 50 ml 0.1 M NaOH and shaken overnight. The content was filtered through Whatman 42 filter paper, and P in the filtrate was determined colorimetrically using Vis 721 spectrophotometer.

3.5.6 Calcium-bound Phosphorus

Residue from occluded Fe and Al-bound P was washed with 25 ml of saturated NaCl and decanted, 50ml 0.25 M sulfuric acid (H_2SO_4) was added. The mixture was shaken for 1 hour and filtered Through Whatman 42 filter paper. P in the extract was determination colorimetrically using Vis 721 spectrophotometer.

3.6 COLORIMETRIC DETERMINATION OF PHOSPHORUS IN THE EXTRACT

Phosphorus in all extracts were determined by modified ammonium molybdate blue (ie Sulphuric molybdate blue) method. (Murphy and Riley,1962).

3.6.1 Reagents and procedures required

3.6.1.1 Ascobic acid Solution

Ascobic acid solution was prepared by weighing 8.8 g of ascobic acid into a 100 ml volumetric flask and made up to mark with distilled H_2O . The solution was stored in stored in a dark compartment as it is photo sensitive and keeps for only 25 hours.

3.6.1.2 Sulphuric – molybdate solution

Sulphuric-molybdate solution was prepared by dissolving 5 g ammonium molybdate $[(NH_4)Mo_7O_{27} \cdot 4H_2O]$ in a 100 ml volumetric flask and 25 ml H_2O was added, to dissolve the solution. 0.12 g antimony potassium tartrate was weighed into the solution and swirled to dissolve, 70 ml concentrated sulphuric acid (H_2SO_4) was added slowly and gently and mixed well. The solution was allowed to cool and brought to volume with distilled H_2O . Note that this reaction is very violent, thus the H_2SO_4 should be added slowly with great care.

3.6.1.3 Working solution

Working solution was prepared by pipetting 10 ml ascorbic acid solution and 20 ml sulphuric molybdate solution into a 1000 ml volumetric flask and brought to 1 L mark with distilled H₂O. The solution was allowed to stand for 1 hour before use.

3.6.1.4 Standard Phosphorus solution (1000 mg P/L)

Phosphorus standard was prepared by dissolving 1.09 g Potassium dihydrogen phosphate (KH₂PO₄) in 250 ml volumetric flask, and brought to mark using individual (each) extractants.

3.6.1.5 Working Standard (0, 2, 4, 6, 8, 10 mg/l) Phosphorus Solution

Working standard containing standard 100 mg/L P was prepared by diluting 10 ml of 1000 mg/l P in a 100 ml volumetric flask using individual extractant, this solution contains 100 mg/l P. Then working standard containing 0, 2, 4, 6, 8 and 10 ml/l P was prepared by pipetting stock P 0, 1, 2, 3, 4 and 5 ml working standard into a series of separate 50 ml volumetric flask and brought to 50 ml mark, using individual extractants

3.6.2 Color Development

Color was developed from each extractant, by measuring 2 ml extractant into 25 ml conical flask using a syringe, 23 ml working solution was added, the mixture was swirl and allowed to stand for 20 minutes and the absorbance of the blue colored mixture was read at 880 nm using the VIS 720 spectrophotometer which was zeroed against a blank consisting of extractant solution.

3.7 CALCULATION OF PHOSPHORUS FROM SPECTROPHOTOMETER READING

The spectrophotometer reading for standard was used to plot a graph of absorbance (Abs) versus concentration (that is Abs on Y-axis and Concentration on X-axis), to obtain a regression equation, then the P concentration of samples were extrapolated from the regression equation derived from standard reading.

3.8 INVESTIGATION OF RELATIONSHIP BETWEEN SOME SOILS PROPERTIES AND FORMS OF INORGANIC PHOSPHORUS

The relationship between some soils properties and forms of inorganic P determined by simple linear correlation.

3.9 STATISTICAL ANALYSIS

Data obtained from soil analysis were statistically analyzed using the Genstat statistical package (12th edition), while Duncan multiple range test was used to separate means at 5% level of probability in descending order.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 SOME PHYSICAL PROPERTIES OF SOIL PLANTED TO PLANTAIN

Results of some physical and chemical properties of the soils studied are shown in Table 1 and 2. The result showed that sand was the dominant soil fraction and decrease significantly with increased in soil depth. The textural class at 0-30 cm soil depth is sandy loam while at 30-60 cm to 90-120 cm soil depth, the textural class is sandy clay loam respectively. The sand content range between 81.77% and 68.11 % with a mean value of 73.71% across the 4 soil depth. The silt had same value of 5.00% at 0-30 and 30-60 cm soil depths and decrease significantly to 3.33 % and 3.67 % at 60-90, 90-120 cm soil depths respectively. The clay increase significantly with increased soil depth possibly due to clay illuviation. The high sand content observed could be due to the parent material from which the sands are derived from in line with one of Orhue and Emomu (2022). Decrease in sand content with increased soil depth found with this study aligned with the findings of Emomu (2025).

4.2 CHEMICAL PROPERTIES OF SOIL PLANTED TO PLANTAIN

The pH (H₂O) of the soils were moderately acidic while pH (CaCl₂) strongly acidity. pH (H₂O) and pH (CaCl) ranges between 5.00 to 5.15 and 4.04 to 4.22 with mean value of 5.06 and 4.12 respectively. Slightly acidic pH (H₂O) value obtained in this study aligned with findings of Zheng *et al.* (2024) who reported on the distribution and transformation of soil P forms under different land use pattern in an urban area. Soil organic carbon content decrease significantly with increased soil depth and ranges between 1.58 % (0-30 cm) and 0.44% (90-120 cm) soil depth with mean value of 0.82%.

Table 1: Some chemical properties of soil planted to plantain

Depth	pH	pH	OC	TON	Av. P	Ca+Mg	EA
cm	(H ₂ O)	(CaCl ₂)	← g/kg →	← →	mg/kg	← cmol/kg →	
0-30	5.15a	4.22a	15.80a	0.80a	5.76a	0.04a	0.37a
30-60	5.00a	4.04b	7.80b	0.40b	7.84a	0.01b	0.43a
60-90	5.03a	4.07ab	4.90bc	0.30bc	8.89a	0.01ab	0.37a
90-120	5.05a	4.11ab	4.40c	0.20c	9.82a	0.01ab	0.53a
Gmean	5.06	4.12	8.20	0.40	8.08	0.02	0.43
SEm	0.08	0.05	0.90	0.10	1.63	0.01	0.06
cv	2.80	2.00	199.00	199.00	35.0	78.60	26.00

OC= Organic carbon, TON= Total organic nitrogen, Av. P= Available Phosphorus, EA= Exchangeable acidity, CV= Coefficient of variation, SEM= Standard error of mean, Gmean= Grand Mean. Means with same alphabet within row are not significantly different, using Duncan multiple rang test at 5% level of probability.

Table 2: Some physical properties of the soil

Depth	Sand	Silt	Clay	Textural class
cm	←———— g/kg —————→			
0-30	817.70a	50.00a	132.30d	SL
30-60	744.40b	50.00a	205.60c	SCL
60-90	705.30c	33.30b	261.30b	SCL
90-120	681.10d	36.70ab	282.30a	SCL
Gmean	737.10	42.50	220.40	-
SEM	5.60	4.30	4.30	-
cv	13.00	175.00	34.00	-

SL= Sandy Loam, SCL= Sandy Clay Loam, CV= Coefficient of variation, SEM= Standard error of mean, Gmean= Grand Mean. Means with same alphabet within row are not significantly different, using Duncan multiple rang test at 5% level of probability.

The higher organic carbon content observed at the top soil could be due to litters fall from surrounding vegetation, while total organic Nitrogen content follows same trend as organic carbon. Organic carbon has been reported to serve as a source of N. The exchangeable acidity was observed to be inconsistent and did not differ significantly with soil depth.

4.3 FORMS AND DISTRIBUTION OF INORGANIC P.

The saloid-bound P, Iron-bound P and calcium-bound P were inconsistent with depth distribution and ranged between 0.84 to 1.01 ml/kg (saloid-P), 42.20 to 62.80 mg/kg (Fe-P), and 1.01 to 1.25 mg/kg (Ca-P) with mean value of 0.95 mg/kg (saloid-bound P), 51.80 mg/kg (Fe-P) and 1.33 mg/kg (Ca-P) as shown in TABLE 3. Aluminum-bound P was observed to be highest (90.28 mg/kg) at surface (0-30 cm) soil depth and decrease slightly but insignificantly to 89.12 mg/kg at 30-60 cm soil depth and reduced further to a constant value of 87.96 mg/kg at 60-90 cm and 90-120 cm soil depth. Occluded-bound P was not significantly different with respect to soil depth. However, occluded-bound P ranges between 7.80 mg/kg (60-90 cm) to 8.56 mg/kg (90-120 cm) soil depths, with a mean value of 8.09 mg/kg. This variation in forms of inorganic P obtained in this study is in line with the findings of Nwosu *et al.* (2018), who reported variation in forms and profile distribution of P in soils along a toposequence. In comparing the various forms of P with one another, the result shows that at 0-30 cm soil depth, Al-P was highest constituting 51% of total P closely followed by Fe-P which constitute 35.9% of total P while saloid-P was least (0.84%) of total P pool. Highest Aluminum-bound P found in this study is contrary while higher Iron-bound P aligned with the findings of Nwosu *et al.* (2018) who reported on the forms and profile distribution of P in soils along toposequence. At 30-60 cm soil depth, the relative contribution of inorganic P to total P pool were in the sequence of Al-P>Fe-P>Red-P>Occ-P>Ca-P.

Table 3: Forms and distribution of inorganic P in soil planted to plantain.

Depth	Sal-P	Al-P	Fe-P	Red-P	Occ-P	Ca-P	TP
cm	mg/kg						
0-30	0.84a	90.28a	62.80a	5.40a	8.12a	1.25a	168.69
30-60	0.68a	89.12a	45.00a	10.60a	7.86a	1.01a	154.27
60-90	1.25a	87.96a	57.40a	15.20a	7.80a	1.80a	171.41
90-120	1.01a	87.96a	42.20a	6.10a	8.56a	1.25a	147.08
Mean	0.95	88.83	51.80	9.30	8.09	1.33	160.30
SEM	0.16	1.98	7.02	3.25	0.43	0.28	13.12
cv	29.70	3.90	23.50	60.50	9.10	36.1	162.80

Sal-P= Saloid-bound P, Al-P= Aluminum-bound P, Fe-P= Iron-bound P, Red-P= Reductant soluble P, Occ-P= Occluded-bound P, Ca-P= Calcium-bound P, TP= Total P, SEM= Standard error of mean, cv= Coefficient of ariation.

At 60-90 and 90-120 cm soil depth, the relative contribution of each inorganic P forms to total P pool are in the sequence of Al-P > Fe-P > Red-P > Occ-P > Red-P > Ca-P > Sal-P respectively. The result shows that Al-P and Fe-P constitute the highest forms of P in the soils, indicating that P availability is mainly influenced by Al and Fe in the soils. The result of aligns with the findings of Jin *et al.* (2023) who reported that P is mainly fixed by Fe and Al compounds in acid soils.

4.4 Relationship between some soil properties and forms of inorganic Phosphorus

The result showed that some soil properties significantly correlated (related) positively and negatively with some forms of inorganic P, indicating the influence of soil properties on forms of inorganic P (Table 4). At 0-30 cm soil depth, Reductant-P showed negatively significant correlation with pH (H₂O) ($r=0.997^*$), while calcium-bound P positively

significantly correlated with pH (H₂O) ($r=0.999^*$) and Ca+Mg ($r=0.997^*$). At 30-60 cm soil depth, saloid-bound P highly significantly negatively correlated with sand ($r= -1.000^{***}$ $P \leq 0.1\%$), but highly positively significantly correlated with organic carbon ($r=1.000^{***}$) and total organic nitrogen ($r=1.000^{***}$ $P \leq 0.001$). Calcium-bound P showed significant positive correlation with pH(CaCl₂) ($r=0.997^*$). At 60-90 cm soil depth, Aluminum-bound P and Occluded-bound P showed perfect significant relationship with silt ($r=1.000^{***}$) and exchangeable acidity ($r=1.000^{***}$) respectively at $P \leq 0.001$ significant level (Nwosu *et al.*, 2018). At 90-120 cm soil depth, significant positive relationship between pH (H₂O) and Iron-bound P was obtained with a correlation coefficient value of 0.998^* at 5%

Table 4: Relationship between some soil properties and forms of inorganic P in the soils.

Soil Ppties	Sal-P	Al-P	Fe-P	Red-P	Occ-P	Ca-P
0-30 cm						
Sand	0.829	0.966	-0.125	0.983	0.332	0.538
Silt	0.000	-0.756	0.892	-0.397	0.596	0.397
Clay	-0.935	-0.343	-0.738	-0.717	-0.962	-0.999
pH(H₂O)	-0.945	-0.866	-0.135	-0.997*	-0.564	-0.737
pH(CaCl₂)	0.904	0.269	0.789	0.660	0.981	0.999*
OC	-0.525	0.299	-0.996	-0.144	-0.929	-0.820
TON	-0.525	0.299	-0.996	-0.144	-0.929	-0.820
Ca+Mg	0.945	0.371	0.719	0.737	0.954	0.997*
EA	-0.970	-0.817	-0.225	-0.986	-0.636	-0.795
30-60 cm						
Sand	-1.000***	-0.500	-0.591	-0.500	0.866	0.189
Silt	0.000	0.000	0.000	0.000	0.000	0.000
Clay	1.000***	0.500	-0.591	0.500	-0.866	-0.189
pH(H₂O)	0.959	0.726	-0.796	0.233	-0.688	0.098
pH(CaCl)	-0.115	0.803	-0.734	-0.918	0.596	0.997*
OC	1.000***	0.500	-0.590	0.500	-0.866	-0.189
TON	1.000***	0.500	-0.590	0.500	-0.866	-0.189
Ca+Mg	0.000	0.000	0.000	0.000	0.000	0.000
EA	0.756	-0.189	0.082	0.945	-0.982	-0.786

Ppties= properties, Sal-P= Saloid-bound P, Al-P= Aluminum-bound P, Fe-P= Iron-bound P, Red-P= Reductant soluble P, Occ-P= Occluded-bound P, Ca-P= Calcium-bound P, TP= Total P, OC= Organic carbon, TON= Total organic nitrogen, EA= Exchangeable acidity

Table 4 continue: Relationship between some soil properties and forms of inorganic P in the soils.

Soil Ppties	Sal-P	Al-P	Fe-P	Red-P	Occ-P	Ca-P
60-90 cm						
Sand	0.000	-0.957	-0.841	0.152	-0.957	-0.683
Silt	0.000	1.000***	0.962	0.143	1.000***	0.866
Clay	0.000	0.829	0.644	-0.436	0.829	0.438
pH (H ₂ O)	0.000	0.711	0.492	-0.595	0.711	0.264
pH (CaCl ₂)	0.000	-0.909	-0.762	0.281	-0.909	-0.581
OC	0.000	0.822	0.635	-0.446	0.822	0.427
TON	0.000	0.822	0.635	-0.446	0.822	0.427
Ca+Mg	0.000	0.500	0.718	0.929	0.500	0.866
EA	0.000	1.000***	0.962	0.143	1.000***	0.866
90-120 cm						
Sand	0.698	-0.963	-0.990	0.698	0.922	-0.716
Silt	0.000	-0.500	-0.806	0.000	0.389	-1.000***
Clay	-0.355	0.775	0.964	-0.355	-0.692	0.935
pH	-0.538	0.887	0.998*	-0.538	-0.824	0.843
pH(CaCl)	-0.610	0.132	-0.277	-0.610	-0.253	-0.792
OC	-0.792	0.991	0.961	-0.792	-0.968	0.610
TON	-0.792	0.991	0.961	-0.792	-0.968	0.610
Ca+Mg	0.000	0.500	0.806	0.000	-0.389	1.000***
EA	-0.866	0.500	0.110	-0.866	-0.603	-0.500

significant level. The relationship between Iron-bound P with pH found in the study aligned with the findings of He *et al.* (2025). Generally, the positively and negatively significance

relationships between some soil properties and forms of inorganic phosphorus found in this study aligned with the findings of Zhou *et al.* (2025).

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The result showed that the soil was predominantly sandy with moderately acid (pH (H₂O): 5.00 - 5.15) soil reaction. However, the levels of other soil properties (Organic carbon, total organic nitrogen, Ca+Mg, exchangeable acidity, available P) were within critical level. The forms and distribution of inorganic P shows spatial variation with soil depth with iron and aluminum bound P predominating the total inorganic P across the various soil depth indicating the influence of Al and Fe-bound P on P availability. Significant positive and negative relationship between some soil properties and forms of inorganic P was observed across the various soil depth showing their influence on one another.

5.2 RECOMMENDATIONS

From the findings of this study, the following recommendations are made;

1. Some other soil properties of soil of the study area be evaluated to enhance general knowledge of the soil of the study area.
2. Other forms of P such as Organic P and Residual P be investigated to determine their contribution to the total P pool in the soil of the study area.
3. Evaluation of the relationship between other soil properties with forms of inorganic P and also the relationship between the forms of inorganic P with one another which was not covered by this study is recommended.

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