

**SOIL CARBON STORAGE IN FOREST ECOSYSTEMS**

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NIGERIA**

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**A PROJECT WORK SUBMITTED TO THE DEPARTMENT OF  
SOIL SCIENCE AND LAND MANAGEMENT, FACULTY OF  
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**OCTOBER, 2025**

## CERTIFICATION

This is to certify that this research project " SOIL CARBON STORAGE IN FOREST ECOSYSTEMS" was carried out by PATIENCE EKEMEHEN ALLI of the department of soil science and land management, Faculty of Agriculture, University of Benin, Benin City, Edo State, Nigeria.

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*Head of Department*

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**DATE:**

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**DATE:**

## **DEDICATION**

This project work is dedicated to God Almighty for making my undergraduate year a success and for the successful completion of this project.

## ACKNOWLEDGEMENT

I give all thanks and glory to Almighty God for His grace, guidance, and strength throughout the course of this project and my academic journey.

My sincere gratitude goes to my project supervisor, Prof. J. S. Ogeh, for his invaluable guidance and encouragement. I would also like to extend my profound gratitude to the lecturers and staff of the prestigious Department of Soil science and Land Management, to the H. O. D, Dr. (Mrs) V. I. O. Edosa, and all my highly esteemed lecturers Prof. E. R. Orhue, Prof. Ehigiator, Dr. Ikpomwosa Ogbemudia , my course adviser Dr. (Mrs) Faith, Dr. E.O Airueghian, Dr. Adams, Dr. (Miss) Esther and lastly but specially Dr. Kadiri for all their positive impacts in my academic journey so far.

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## ABSTRACT

Soil carbon storage is a key component of the global carbon cycle and plays a vital role in climate regulation, particularly within forest ecosystems. This study assessed soil organic carbon (SOC) and associated soil properties in a teak (*Tectona grandis*) plantation at the University of Benin, Edo State, Nigeria. A plot measuring 50 m × 50 m was marked out in the plantation and divided into three sections to represent replicates, with two plots each, resulting in six georeferenced sampling points which include USS1 - USS6 (Uniben Soil sample). Soil samples were collected from the top 0–15 cm layer, processed, and analyzed for physical and chemical properties. Standard laboratory procedures were followed, and results were subjected to statistical analysis using ANOVA. Results revealed significant differences ( $p \leq 0.05$ ) among plots and replicates in most soil properties. SOC and organic matter were highest in USS1 and USS4, indicating greater litter input and reduced decomposition, while USS3 recorded the lowest values alongside higher bulk density and exchangeable acidity. Total nitrogen and exchangeable cations followed SOC patterns, reflecting the close linkage between carbon and nutrient dynamics. USS2 and USS5 showed relatively higher total nitrogen and cation exchange capacity, suggesting better nutrient retention. Available phosphorus remained low across all sites, indicating potential nutrient limitation. Soil pH and electrical conductivity varied significantly among sampling points, highlighting micro-site differences influenced by litter accumulation, root activity, and localized decomposition. Soil texture showed no significant variation, confirming uniform parent material. Overall, the results demonstrate that teak plantations enhance soil organic carbon and nutrient status, contributing to carbon sequestration and sustainable land management, while localized conditions drive variations in soil fertility and nutrient distribution.

## CHAPTER ONE

### INTRODUCTION

Soil organic carbon (SOC) represents one of the most vital components of the global carbon cycle, containing more carbon than is stored in both the atmosphere and vegetation combined (Lal, 2004). Forest ecosystems serve as major contributors to carbon sequestration, functioning simultaneously as carbon sinks and sources depending on factors such as land use patterns, forest type, and management practices (Pan *et al.*, 2011). Approximately two-thirds of all terrestrial carbon is stored underground, with forest soils contributing about 70% of the total carbon found in forest ecosystems (Batjes, 2014).

The level of SOC within forest soils is influenced by a range of ecological and environmental factors, including vegetation composition, climate, soil texture, topography, and microbial activity (Yao *et al.*, 2023; Hu *et al.*, 2025). In addition to regulating the global climate, SOC plays an essential role in maintaining soil fertility, enhancing water-holding capacity, improving soil structure, and supporting microbial and faunal biodiversity (Hao *et al.*, 2025). Through photosynthetic processes, trees capture atmospheric carbon dioxide, which is later transferred into the soil via litter deposition, root turnover, and decomposition. These continuous biological and chemical processes make forests among the most efficient and largest long-term carbon sinks on Earth. Globally, forest ecosystems account for the largest share of carbon among all terrestrial ecosystems, holding over 86% of vegetation carbon and about 73% of total soil carbon (Kuuluvainen and Gauthier, 2018). They also play a significant role in annual carbon fixation, contributing substantially to the global carbon balance. In tropical countries such as Nigeria, however, forest ecosystems are increasingly threatened by human activities such as illegal

logging, agricultural expansion, and rapid urban development. These disturbances not only reduce forest cover but also degrade soil structure and nutrient content, resulting in the release of stored carbon into the atmosphere and further exacerbating greenhouse gas emissions. Despite the vital role forests play in capturing and storing atmospheric carbon, there remains a scarcity of reliable, site-specific SOC data across Nigeria's forest zones. This lack of comprehensive data hampers the development of effective forest management policies, limits the country's capacity to engage in international carbon trading mechanisms, and weakens global climate action efforts.

Changes in land use including deforestation, reforestation, and conversion to agricultural land can cause dramatic shifts in SOC levels depending on the management approaches adopted. However, research findings differ across regions due to variations in soil properties, climate, and methodological approaches (Don *et al.*, 2011). Furthermore, the limited availability of regional SOC datasets poses a major challenge to understanding carbon cycling and predicting long-term ecosystem responses to disturbance. Without consistent monitoring and restoration efforts, continuous forest exploitation and degradation could lead to higher CO<sub>2</sub> emissions, reduced soil productivity, and accelerated climate change impacts.

## **1.1 Objectives of the study**

Main objective

To determine the soil carbon storage potential in a single specie forest stand.

Specific Objectives are to:

1. Determine the soil physical and chemical properties of the field under study
2. Determine the soil carbon stock of the field at 0 -15cm soil depth

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1 Soil Carbon Storage

Soil carbon storage is the process by which atmospheric carbon dioxide (CO<sub>2</sub>) is absorbed and stabilized in the soil, primarily as soil organic carbon (SOC). This mechanism forms a critical component of the global carbon cycle, helping to regulate atmospheric CO<sub>2</sub> levels and mitigate climate change. Forest soils, in particular, serve as one of the planet's most important carbon reservoirs, storing more carbon than is contained in both the atmosphere and living vegetation combined (Lal, 2005). The carbon stored in soils is largely found within soil organic matter (SOM), a complex mixture of decomposed plant and animal residues, microbial biomass, and humic substances that play key roles in nutrient cycling, soil structure, and ecosystem functioning.

Several environmental and edaphic factors determine the amount and stability of carbon stored in soils. These include soil texture, moisture availability, temperature, mineral composition, and biological activity (Hao, Zhang, and Wang, 2025). For example, temperature and moisture regulate microbial decomposition rates, while mineralogy and texture influence the degree to which organic carbon becomes physically or chemically protected within the soil matrix. Clay-rich soils tend to sequester and stabilize more carbon than coarse-textured sandy soils because clay particles provide greater surface area for organic matter adsorption and protection from microbial degradation (Schapel *et al.*, 2018). In contrast, sandy soils, with their lower nutrient and water-holding capacities, tend to lose carbon more rapidly.

The type of forest ecosystem also plays a significant role in determining SOC levels, as differences in vegetation composition, litter quality, root biomass, and decomposition rates influence the amount of carbon that enters and remains in the soil (Churchman, 2020). For instance, deciduous forests often contribute more easily decomposable organic inputs than evergreen species, leading to faster carbon turnover, while evergreen forests may favor more stable carbon accumulation due to their slower litter decay. Furthermore, variations in forest management, stand age, and canopy density can significantly affect organic matter input and below-ground carbon dynamics. Human activities and land-use changes strongly influence whether soils function as carbon sinks or sources. Unsustainable land-use practices such as deforestation, overgrazing, and intensive cultivation tend to accelerate organic matter decomposition and erosion, leading to substantial SOC loss (Kasel and Bennett, 2007). In contrast, land restoration strategies like reforestation, afforestation, and agroforestry enhance soil carbon sequestration by increasing organic inputs and reducing carbon losses (Choudhury *et al.*, 2014). These practices promote root development, litter accumulation, and microbial diversity, all of which contribute to the buildup of stable soil carbon pools.

Sustainable soil management techniques such as conservation tillage, mulching, crop rotation, and the incorporation of organic residues are widely recognized as effective means of maintaining or increasing SOC stocks (Lal, 2020). These methods reduce soil disturbance, protect surface organic matter, and foster the accumulation of stable carbon fractions over time. By improving SOC, these approaches not only enhance soil fertility, structure, and water retention but also play a crucial role in reducing greenhouse gas emissions and mitigating the adverse effects of global climate change.

In essence, soil carbon storage is both an ecological and environmental asset. The ability of forest soils to capture and retain carbon contributes directly to ecosystem resilience, agricultural sustainability, and global climate stability. Effective management of soil carbon through responsible land-use planning and conservation practices is therefore essential for ensuring long-term productivity, environmental health, and carbon balance across terrestrial ecosystems.

## **2.2 Forests and Carbon Storage**

Forests are crucial components of the global carbon cycle because they absorb large quantities of atmospheric carbon dioxide (CO<sub>2</sub>) through photosynthesis and store it in different ecosystem pools such as aboveground biomass, litter, roots, and soil organic matter (Pan *et al.*, 2011). The distribution of carbon within forests varies considerably across bioclimatic zones. Tropical forests, for example, store more carbon in aboveground biomass due to their dense vegetation and rapid growth rates, whereas boreal forests accumulate larger carbon stocks within soils as a result of cooler temperatures that slow organic matter decomposition (Keith *et al.*, 2009).

Contrary to the earlier assumption that mature forests reach a carbon equilibrium, recent evidence shows that old-growth forests can continue to sequester carbon over extended periods, thereby serving as long-term carbon sinks (Lewis *et al.*, 2015). The capacity of forests to store carbon is influenced by several factors, including forest type, age structure, species composition, and management practices. Sustainable interventions such as afforestation, reforestation, and the reduction of deforestation significantly enhance both biomass and soil organic carbon (SOC) accumulation.

Globally, soils store approximately 75% of terrestrial carbon roughly three times the amount contained in living organisms. However, when forestlands are converted into croplands or other

land uses, a significant proportion of SOC is lost due to increased oxidation and reduced organic inputs. Poeplau and Don (2023) reported that such conversions can lead to SOC declines ranging between 15% and 75%, depending on soil type, climatic conditions, and management intensity. In Nigeria, Ogeh (2014) observed that *Tectona grandis* (teak) plantations exhibit considerably higher SOC levels than degraded or cultivated lands, particularly within the upper 0–15 cm of soil where organic matter input is most concentrated.

### **2.3 The Global Carbon Cycle and Forest Ecosystems**

The global carbon cycle describes the continuous exchange of carbon among the atmosphere, terrestrial biosphere, oceans, and geosphere. Forest ecosystems are key regulators of this process because they act as both carbon sinks and sources, depending on their level of disturbance and management practices. Through photosynthesis, forests absorb atmospheric CO<sub>2</sub> and convert it into organic carbon stored in biomass and soils, while respiration, decomposition, and disturbance events such as fire or logging return part of this carbon to the atmosphere (Pan *et al.*, 2011; FAO, 2020).

Globally, soils contain an estimated 2,500 gigatons (Gt) of carbon, making them the largest terrestrial carbon reservoir surpassing the combined carbon content of the atmosphere and vegetation (Rodrigues, Brito, and Nunes, 2023; Lal, 2004). The Intergovernmental Panel on Climate Change (IPCC, 2014) attributes the imbalance in the global carbon cycle primarily to human-induced activities, including fossil fuel combustion, deforestation, and land-use conversion. These processes elevate atmospheric greenhouse gas concentrations, which intensify climate warming.

Approximately 1,240 petagrams (Pg) of carbon are stored in global forest vegetation and soils, with about 37% located in tropical forests, 14% in temperate forests, and 49% in boreal regions (Pan *et al.*, 2011; FAO, 2020). The sustainability of these carbon pools depends largely on forest health and the chemical stability of soil organic matter. Effective forest management practices such as minimizing soil disturbance, maintaining vegetation cover, and enhancing organic inputs are vital for sustaining and expanding the soil carbon reservoir (Griscom *et al.*, 2017; Lal, 2020).

#### **2.4 Carbon Sequestration in Forest Soils**

Carbon sequestration refers to the long-term capture and storage of atmospheric CO<sub>2</sub> in vegetation, soils, and other carbon pools. In forest ecosystems, this process occurs through biomass accumulation and the transformation of organic residues into stable soil organic carbon (SOC) compounds (Lal, 2008; Smith *et al.*, 2020). Although disturbances such as fire or logging can release carbon stored in biomass, SOC often remains relatively stable for centuries under favorable environmental conditions.

The sequestration process begins when plants absorb atmospheric CO<sub>2</sub> via photosynthesis and transfer it to the soil through litterfall, root exudation, and microbial decomposition. Soil organic carbon comprises a mixture of decomposed plant residues, microbial biomass, and humic substances that become stabilized through chemical bonding with soil minerals and aggregates (Jandl *et al.*, 2007). The degree of stabilization depends on soil texture, mineral composition, and environmental factors such as temperature and moisture.

Carbon sequestration in soils typically proceeds through three main stages:

1. Organic Input: Incorporation of litter, roots, and plant residues into the soil surface.

2. Decomposition and Humification: Microorganisms decompose organic materials, releasing nutrients and forming humus.

3. Stabilization: Organic molecules bind with soil minerals or form aggregates, enhancing chemical resistance to microbial breakdown.

Management practices such as afforestation, agroforestry, and reduced tillage can significantly enhance SOC accumulation (Lal, 2008; Smith *et al.*, 2020). Soils rich in organic carbon not only mitigate greenhouse gas emissions but also improve fertility, water retention, and ecosystem resilience against climate variability.

## **2.5 Influence of Vegetation and Forest Type on Soil Carbon**

Vegetation type exerts a strong influence on both the quantity and quality of soil organic carbon in forest ecosystems (Laganière, Angers, and Paré, 2010; Dixon, 2021). Deciduous forests tend to produce nutrient-rich litter that decomposes quickly, leading to faster SOC turnover, whereas coniferous forests generate more recalcitrant materials that decompose slowly, thereby promoting long-term carbon stabilization.

In tropical regions, plantation forests like *Tectona grandis* (teak) have gained prominence due to their ecological and economic importance. The SOC levels in such plantations are influenced by multiple factors, including soil texture, stand age, and management practices (Nduwamungu *et al.*, 2018). Well-managed teak plantations with minimal soil disturbance and undergrowth vegetation tend to maintain higher SOC concentrations. However, monoculture systems typically store less SOC than natural or mixed-species forests because they produce less diverse litter and support lower microbial activity.

Natural forests, characterized by rich species diversity and continuous litter input, sustain more stable SOC pools over time. Disturbances such as logging, wildfire, or invasive species introduction can disrupt litter decomposition processes and result in substantial carbon losses from both biomass and soil (Laganière *et al.*, 2010; Dixon, 2021; Nduwamungu *et al.* , 2018). Therefore, maintaining vegetation diversity and minimizing disturbance are essential strategies for enhancing SOC accumulation and overall forest resilience.

## **2.6 Land Use Change and Carbon Loss**

Land-use change remains one of the most significant drivers of soil organic carbon depletion globally. The conversion of forests into agricultural or urban landscapes leads to vegetation removal, soil disturbance, and enhanced erosion all of which contribute to the reduction of SOC. The removal of canopy cover exposes soils to direct solar radiation and rainfall impact, accelerating the oxidation of organic matter and reducing soil structural stability.

Ogeh (2014) demonstrated that forested lands in southern Nigeria contain higher SOC levels than cultivated or degraded areas, underscoring the role of vegetation cover in carbon retention. Similarly, Lal (2005) reported that continuous cultivation following deforestation can result in SOC losses ranging from 20% to 50% within a few years. Although restoration techniques such as afforestation, reforestation, and agroforestry can gradually rebuild SOC stocks, the recovery process is slow and often spans several decades, depending on soil type, management, and climatic conditions. Therefore, proactive measures such as preventing deforestation and promoting sustainable land-use practices remain the most effective strategies for preserving SOC reserves and maintaining soil fertility.

## **2.7 Climate Change and Soil Carbon Dynamics**

Climate change introduces new challenges to the stability of soil organic carbon. Changes in temperature, precipitation patterns, vegetation composition, and microbial activity significantly influence the rate of carbon input and decomposition. Atmospheric CO<sub>2</sub> concentrations are currently rising at approximately 0.4% annually, contributing to both enhanced plant growth and accelerated organic matter decay (Joyce and Birdsey, 2000).

Higher temperatures generally stimulate microbial respiration, increasing the breakdown of organic matter and CO<sub>2</sub> emissions from soil. Similarly, altered precipitation patterns—such as prolonged droughts or intense rainfall events—affect soil moisture, nutrient cycling, and microbial efficiency. Although elevated CO<sub>2</sub> levels can promote photosynthesis and potentially increase organic carbon inputs, the net effect on SOC often depends on the balance between inputs and decomposition rates.

In tropical regions, including Nigeria, continuous deforestation and land degradation are likely to exacerbate SOC losses under future climate scenarios. Understanding how climatic factors interact with soil management and vegetation dynamics is therefore critical for designing adaptive land-use strategies that protect soil carbon and sustain productivity in forest ecosystems.

## **2.8 Gaps in Literature and Need for Local Study**

Despite the growing body of global research on soil organic carbon, significant gaps remain in the understanding of SOC dynamics in tropical regions, particularly within sub-Saharan Africa and Nigeria (Lal, 2019; Awotoye and Dada, 2022). Much of the existing data originates from temperate ecosystems, where climatic conditions, soil properties, and vegetation types differ substantially from those in tropical forests. Consequently, extrapolating such data to tropical

systems often yields inaccurate or incomplete estimates. In Nigeria, studies on SOC are limited in both scope and spatial coverage. Research efforts have primarily focused on a few forest reserves or plantation systems, often neglecting the interactions between vegetation type, land management, and soil properties (Awotoye and Dada, 2022). This lack of comprehensive, region-specific data restricts the formulation of effective soil management and carbon conservation strategies. Furthermore, the absence of standardized SOC monitoring frameworks hampers Nigeria's ability to engage effectively in global carbon accounting and carbon trading mechanisms. There is, therefore, an urgent need for detailed, field-based research that captures the spatial variability of SOC across forest ecosystems in Nigeria. Such studies would provide essential baseline information for modeling carbon fluxes, evaluating land-use impacts, and guiding national climate policies. Strengthening local research capacity and integrating scientific findings into sustainable forest management plans are vital steps toward achieving Nigeria's commitments under the Paris Agreement and the United Nations Sustainable Development Goals (SDGs) (Lal, 2019; IPCC, 2014).

## CHAPTER THREE

### MATERIALS AND METHODS

#### 3.1 Study Area

This study was conducted in a teak (*Tectona grandis*) plantation, University of Benin, Ugbowo Campus, Edo State, Nigeria. The site lies between 6.40121°N to 6.40276°N latitude and 5.62684°E to 5.62751°E longitude, within the humid rainforest zone of southern Nigeria. The terrain is gently sloping, with elevations between 80–95 meters, which supports good drainage and limits erosion. The area has an average annual rainfall around 2,000 mm and high humidity (70–90%). Rainfall is bimodal, occurring mainly from March to October, while the dry season spans November to February. Temperatures range from 24°C to 34°C, supporting lush vegetation and fast litter decomposition. The teak trees are uniformly planted and well-spaced, with minimal disturbance, providing steady organic input through leaf litter, which enhances soil carbon storage potential. The experiment was laid out in RCBD. Treatment includes two plots each and replicated three times.

#### 3.2 Field Sampling

Soil samples were collected on a demarcated plot measuring 50m x 50m area in the teak plantation. Sampling was done at a single soil depth of 0–15 cm (FAO, 2019), which represents the topsoil layer known to have the highest concentration of soil organic carbon (SOC). Soil samples were collected from the three replications with a sample per plot giving a total of six (6) composite soil samples. The sampling points were georeferenced using gps.

## Experimental layout of sampling points

50m

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USS1	USS2	REP 1
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USS4	USS4	REP 2	50m
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USS5	USS6	REP 3
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For this study, two categories of soil samples were collected at separate points:

1. Bulk Density Sampling Points: Core samples were taken using a metal cylinder of known volume. Uniben Core Sampling Locations (UCS):

Latitude	Longitude
UCS1: N 06.40121°	E 005.62684°
UCS2: N 06.40179°	E 005.62692°
UCS3: N 06.40276°	E 005.62736°

2. Soil Organic Carbon Sampling Points: Soil samples were augered and stored separately for each point in labeled polythene bag. Uniben soil sampling Locations (USS):

Latitude	Longitude
USS1: N 06.40179°	E 005.62692°
USS2: N 06.40276°	E 005.62736°
USS3: N 06.40095°	E 005.62686°
USS4: N 06.40105°	E 005.62695°
USS5: N 06.40174°	E 005.62706°
USS6: N 06.40267°	E 005.62751°

The samples were transported to the laboratory immediately after collection to minimize changes in soil properties and ensure accurate analysis.

### **3.3 Laboratory analysis**

#### **Determination of Soil Organic Carbon (SOC)**

Soil samples were air-dried, ground, and sieved through a 2 mm mesh. The Walkley-Black wet oxidation method (Walkley and Black, 1934) was used to determine soil organic carbon content.

The procedure involved:

- 1)Oxidizing 1 g of soil with potassium dichromate ( $K_2Cr_2O_7$ ) and concentrated sulfuric acid ( $H_2SO_4$ ).
- 2)Heating the mixture to aid oxidation.

3) Titrating the remaining dichromate with ferrous sulfate solution to estimate the amount of oxidized carbon.

This method was chosen because it is rapid, widely used, and appropriate for tropical soils (FAO, 2019).

### **Determination of Bulk Density**

Bulk density was determined using the core method. The moist soil from the cores was weighed, oven-dried at 105°C for 24 hours, and reweighed (Blake and Hartge, 1986). Bulk density was calculated as:

For soil, the bulk density formula is:

$$\rho_b = (\text{Mass of dry soil}) / (\text{Volume of soil})$$

$$\rho_b = (M_d) / V$$

Where:

-  $\rho_b$  = bulk density

-  $M_d$  = mass of dry soil

-  $V$  = volume of soil (including pore spaces).

Typically expressed in units like  $\text{g/cm}^3$  or  $\text{Mg/m}^3$ .

### **Determination of soil properties**

Soil physicochemical properties were analyzed using standard laboratory procedures to assess fertility and carbon storage potential. Soil pH was determined in a 1:2.5 soil-to-water suspension

using a calibrated digital pH meter, following the guidelines of the International Institute of Tropical Agriculture (IITA, 1982). The pH of a soil affects nutrient availability, microbial activity, and the chemical processes critical for maintaining soil organic carbon stability.

Total nitrogen (TN) was analyzed using the Kjeldahl digestion method, which involves oxidation of organic nitrogen compounds with concentrated sulfuric acid in the presence of a catalyst, followed by distillation and titration to quantify ammonium content. This method remains one of the most reliable for estimating total nitrogen in agricultural and forest soils (Bremner, 1996).

Exchangeable cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , and  $\text{Na}^+$ ) were extracted with 1 M ammonium acetate ( $\text{NH}_4\text{OAc}$ ) at pH 7.0, and the concentrations of the cations were determined using Atomic Absorption Spectrophotometry (AAS) and Flame Photometry, respectively. The Effective Cation Exchange Capacity (ECEC) was calculated as the sum of exchangeable bases and acidity, providing an index of soil nutrient-holding capacity and fertility potential (Gee and Bauder, 1986).

Overall, these analytical techniques provide comprehensive information on soil fertility and nutrient dynamics, offering valuable insights into soil carbon storage processes and the sustainability of forest ecosystems.

### **3.4 Estimation of Soil Organic Carbon Stock**

Soil organic carbon stock was estimated using the following formula:

$\text{SOC Stock (Mg/ha)} = \text{SOC (\%)} \times \text{Bulk Density (g/cm}^3\text{)} \times \text{Soil Depth (cm)} \times 10$  (IPCC, 2006, Batjes, 2001)

Where: SOC (%) is the percentage of organic carbon determined from the Walkley-Black method,

Bulk Density is in  $\text{g/cm}^3$ ,

Soil Depth is 15 cm,

0.1 is a factor to convert the result to Mg/ha.

This calculation was done using the average values of SOC and bulk density obtained from the respective sampling points.

### **3.5. Data Analysis**

The data collected on soil organic carbon (SOC) and bulk density from the three replicates were subjected to statistical analysis to evaluate differences among the sampling locations. Analysis of variance (ANOVA) was first performed to determine whether significant differences existed among the sites. Where significant differences ( $p < 0.05$ ) were detected, mean separation was carried out using the Least Significant Difference (LSD) test, with means compared and presented using superscript letters to indicate statistically distinct groups. All analyses were conducted following standard soil sampling and laboratory protocols as recommended by the Soil Science Society of America (SSSA) and the Food and Agriculture Organization (FAO) guidelines, ensuring reliability and consistency of results.

## CHAPTER FOUR

### RESULTS AND DISCUSSION

Results of the study on soil physical and chemical properties within the teak (*Tectona grandis*) plantation are presented in table 4.1 and 4.2. Variations in soil properties across sampling sites reflect the heterogeneity typical of managed forest ecosystems, influenced by litter deposition, decomposition, and microbial activity under the teak canopy. Key Soil properties including pH, electrical conductivity (EC), organic carbon, total nitrogen, exchangeable cations, and available phosphorus values provided information on soil chemical and physical properties and their combined effect on carbon storage potential in teak plantations.

#### 4.1 Soil Physical and Chemical Properties

Soil properties varied across the teak plantation sites, reflecting typical forest ecosystem heterogeneity. . Organic carbon (0.7–1.4 %) and organic matter (1.2–2.4 %) were highest at USS1 and USS4, likely due to litter accumulation and microbial activity, and total nitrogen (0.06–0.21 %) .

**Table 4.1 Soil Chemical properties of the teak plantation**

Sampling points	pH	EC ( $\mu\text{S}/\text{cm}$ )	Org.C (%)	Org.M (%)	T.N (%)	Al <sup>3+</sup> Cmol/kg	H <sup>+</sup> Cmol/kg	Na <sup>+</sup> Cmol/kg	K <sup>+</sup> Cmol/kg	Ca <sup>2+</sup> Cmol/kg	Mg <sup>2+</sup> Cmol/kg	ECEC Cmol/kg	Av.p (Mg/kg)	Clay (%)	Silt (%)	Sand (%)
USS1	4.88 <sup>b</sup>	176.4 <sup>b</sup>	1.40 <sup>a</sup>	2.36 <sup>a</sup>	0.16 <sup>b</sup>	1.10 <sup>b</sup>	0.78 <sup>a</sup>	0.08 <sup>a</sup>	0.21 <sup>a</sup>	0.19 <sup>a</sup>	0.08 <sup>b</sup>	2.46 <sup>b</sup>	0.73 <sup>b</sup>	12.02 <sup>a</sup>	1.57 <sup>b</sup>	86.40 <sup>b</sup>
USS2	5.47 <sup>a</sup>	205.1 <sup>b</sup>	1.00 <sup>b</sup>	1.73 <sup>b</sup>	0.13 <sup>b</sup>	1.09 <sup>b</sup>	0.60 <sup>b</sup>	0.08 <sup>a</sup>	0.18 <sup>a</sup>	0.22 <sup>a</sup>	0.20 <sup>a</sup>	2.38 <sup>b</sup>	1.22 <sup>a</sup>	11.78 <sup>ab</sup>	3.06 <sup>a</sup>	85.12 <sup>b</sup>
USS3	5.03 <sup>b</sup>	162.1 <sup>b</sup>	0.70 <sup>c</sup>	1.21 <sup>c</sup>	0.06 <sup>c</sup>	1.39 <sup>a</sup>	0.90 <sup>a</sup>	0.03 <sup>b</sup>	0.12 <sup>b</sup>	0.09 <sup>b</sup>	0.05 <sup>c</sup>	2.59 <sup>a</sup>	0.73 <sup>b</sup>	12.03 <sup>a</sup>	0.63 <sup>c</sup>	87.43 <sup>a</sup>
USS4	4.93 <sup>b</sup>	235.2 <sup>a</sup>	1.40 <sup>a</sup>	2.41 <sup>a</sup>	0.13 <sup>b</sup>	1.27 <sup>ab</sup>	0.62 <sup>b</sup>	0.09 <sup>a</sup>	0.16 <sup>ab</sup>	0.11 <sup>b</sup>	0.17 <sup>ab</sup>	2.43 <sup>b</sup>	0.79 <sup>b</sup>	10.03 <sup>b</sup>	1.01 <sup>c</sup>	89.01 <sup>a</sup>
USS5	5.39 <sup>a</sup>	174.6 <sup>b</sup>	1.20 <sup>b</sup>	2.12 <sup>b</sup>	0.21 <sup>a</sup>	1.32 <sup>ab</sup>	0.82 <sup>a</sup>	0.06 <sup>ab</sup>	0.22 <sup>a</sup>	0.20 <sup>a</sup>	0.15 <sup>ab</sup>	2.73 <sup>a</sup>	0.92 <sup>b</sup>	10.81 <sup>b</sup>	2.17 <sup>b</sup>	86.97 <sup>b</sup>
USS6	4.82 <sup>b</sup>	249.2 <sup>a</sup>	1.20 <sup>b</sup>	2.09 <sup>b</sup>	0.18 <sup>a</sup>	1.03 <sup>b</sup>	0.54 <sup>b</sup>	0.08 <sup>a</sup>	0.21 <sup>a</sup>	0.15 <sup>ab</sup>	0.11 <sup>b</sup>	2.05 <sup>c</sup>	1.15 <sup>a</sup>	12.29 <sup>a</sup>	1.21 <sup>b</sup>	86.54 <sup>b</sup>
LSD	0.25	18.6	0.18	0.24	0.04	0.10	0.12	0.02	0.03	0.04	0.03	0.12	0.09	0.41	0.32	0.58

**Table 4.2 Soil physical properties of the teak plantation.**

Sampling points	Bulk Density (g/cm <sup>3</sup> )	Clay(%)	Silt(%)	Sand(%)	Textural Class
USS1	1.0 <sup>a</sup>	12.02 <sup>a</sup>	1.57 <sup>b</sup>	86.40 <sup>b</sup>	Sandy Loam
USS2	1.0 <sup>a</sup>	11.78 <sup>ab</sup>	3.06 <sup>a</sup>	85.12 <sup>b</sup>	Loamy Sand
USS3	1.1 <sup>b</sup>	12.03 <sup>a</sup>	0.63 <sup>c</sup>	87.43 <sup>a</sup>	Sandy Loam
USS4	1.0 <sup>a</sup>	10.03 <sup>b</sup>	1.01 <sup>c</sup>	89.01 <sup>a</sup>	Loamy Sand
USS5	1.0 <sup>a</sup>	10.81 <sup>b</sup>	2.17 <sup>b</sup>	86.97 <sup>b</sup>	Sandy Loam
USS6	1.0 <sup>a</sup>	12.29 <sup>a</sup>	1.21 <sup>b</sup>	86.54 <sup>b</sup>	Sandy Loam
LSD	0.05	0.41	0.32	0.58	

The ANOVA results for soil properties across the six sampling points (USS1–USS6) revealed significant spatial variability in most chemical properties, while soil texture (clay, silt, sand) showed no significant differences, as indicated by shared superscripts and LSD values (Table 4.1 and Table 4.2). Superscripts denote statistical groupings: sites sharing the same letter are not significantly different, while those with different letters are significantly distinct at the 5% probability level.

Soil pH and EC: Soil pH varied significantly among sites (4.82–5.47), with USS2 and USS5 being slightly more neutral (superscript “a”) compared to the more acidic USS1, USS3, USS4,

and USS6 (“b”). This pattern suggests localized differences in acidity, possibly driven by organic matter decomposition, leaching, or microtopography (Zeng *et al.*, 2021). EC values ranged from 162.14 to 249.21  $\mu\text{S cm}^{-1}$ , with USS4 and USS6 exhibiting the highest values, reflecting localized ionic inputs likely derived from litter decomposition, root exudates, or variations in moisture and cation concentration (Satdichanh *et al.*, 2023).

Organic Carbon and Organic Matter: SOC and organic matter (Org.C and Org.M) showed clear spatial differences. USS1 and USS4 had the highest values (superscript “a”), indicating greater organic matter accumulation, likely due to thicker litter layers, higher root biomass, or reduced decomposition rates (Zhang *et al.*, 2024). USS3 had the lowest values (superscript “c”), suggesting minimal organic input, more active decomposition, or potential disturbances. USS2, USS5, and USS6 displayed intermediate values (superscript “b”), reflecting moderate organic matter input and decomposition dynamics. These differences emphasize the importance of site-specific management to enhance carbon accumulation, especially in low-SOC areas (Behera *et al.*, 2025).

Total Nitrogen (T.N%): T.N showed SOC patterns, confirming the strong coupling between carbon and nitrogen in soil organic matter. USS5 and USS6 had the highest nitrogen contents (superscript “a”), while USS3 had the lowest (superscript “c”), consistent with its lower organic carbon content. Intermediate values at USS1, USS2, and USS4 suggest moderate nitrogen availability supporting microbial activity and nutrient cycling (Zhang *et al.*, 2024).

Exchangeable Cations and ECEC: Aluminium ( $\text{Al}^{3+}$ ), hydrogen ( $\text{H}^+$ ), potassium ( $\text{K}^+$ ), calcium ( $\text{Ca}^{2+}$ ), magnesium ( $\text{Mg}^{2+}$ ), and effective cation exchange capacity (ECEC) varied significantly among sites. USS3 generally had higher  $\text{Al}^{3+}$  and  $\text{H}^+$  concentrations, consistent with more acidic

conditions that can influence nutrient availability and microbial activity (Zeng *et al.*, 2021). USS1 and USS5 tended to have higher  $K^+$  and  $Ca^{2+}$ , reflecting localized nutrient enrichment, possibly from litter decomposition or root exudates. ECEC followed a similar pattern, highest at USS5 and lowest at USS6, suggesting variation in the soil's capacity to retain exchangeable cations, which can affect fertility and SOC stabilization (Satdichanh *et al.*, 2023).

Available Phosphorus (Av.P): Av.P showed significant differences, ranging from 0.73 to 1.22 mg kg<sup>-1</sup>. USS2 and USS6 had the highest phosphorus levels, while USS1 and USS3 were lowest. The low phosphorus values across all sites highlight potential P limitation, common in highly weathered tropical soils, which may restrict microbial activity, litter decomposition, and ultimately carbon accumulation (Behera *et al.*, 2025).

Soil Texture: Clay, silt, and sand did not differ significantly among sampling points, indicating uniform parent material and textural class across the plantation. Soils were predominantly sandy ( $\approx 86\text{--}89\%$ ), with low silt (0.6–3%) and moderate clay (<13%). The high sand content reduces mineral-associated stabilization of SOC, making carbon more dependent on continuous organic inputs and more susceptible to loss through leaching or erosion (Zhang *et al.*, 2024).

The significant variation in chemical properties but not texture suggests that localized differences in organic inputs, microtopography, litter deposition, and biotic activity drive the observed heterogeneity. Sites with high SOC and nutrient content (e.g., USS1, USS4, USS5) likely benefit from thicker litter layers and more favorable micro-site conditions, whereas low-SOC sites (e.g., USS3) may experience thinner litter cover, higher decomposition rates, or localized disturbances (Satdichanh *et al.*, 2023; Behera *et al.*, 2025).

## 4.2 Soil Organic carbon content and carbon stock

**Table 4.3 Total Organic Carbon, Total Nitrogen, C: N Ratio, Bulk Density, and Soil organic carbon stock**

Sampling points	TOC (%)	T.N(%)	C : N Ratio	Bulk density (g/cm <sup>3</sup> )	SOC Stock (Mg/ha)
USS1	1.40 <sup>a</sup>	0.16 <sup>bc</sup>	8.75 <sup>bc</sup>	1.0 <sup>a</sup>	21.0 <sup>b</sup>
USS2	1.00 <sup>b</sup>	0.13 <sup>c</sup>	7.69 <sup>c</sup>	1.0 <sup>a</sup>	15.0 <sup>c</sup>
USS3	0.70 <sup>c</sup>	0.06 <sup>d</sup>	11.67 <sup>a</sup>	1.1 <sup>b</sup>	11.55 <sup>d</sup>
USS4	1.40 <sup>a</sup>	0.14 <sup>bc</sup>	10.00 <sup>ab</sup>	1.1 <sup>b</sup>	23.10 <sup>a</sup>
USS5	1.20 <sup>ab</sup>	0.21 <sup>a</sup>	5.71 <sup>d</sup>	1.0 <sup>a</sup>	18.0 <sup>bc</sup>
USS6	1.20 <sup>ab</sup>	0.18 <sup>ab</sup>	6.67 <sup>d</sup>	1.0 <sup>a</sup>	18.0 <sup>bc</sup>
LSD	0.18	0.04	1.50	0.05	2.50

The data in Table 4.3 indicate noticeable variations in soil organic carbon, total nitrogen, C:N ratio, bulk density, and SOC stock across the six sampling points (USS1–USS6). Total Organic Carbon (TOC) ranged from 0.70% at USS3 to 1.40% at USS1 and USS4. Higher TOC at USS1 and USS4 suggests greater organic matter accumulation, possibly due to increased plant litter or root residues, whereas the low TOC at USS3 reflects limited organic matter content or higher rates of decomposition (Lal, 2005; Brady and Weil, 2017). Intermediate values of 1.2% at USS5 and USS6 indicate moderate organic carbon levels.

Total Nitrogen (T.N) varied from 0.06% (USS3) to 0.21% (USS5). USS5 had the highest nitrogen content, while USS3 recorded the lowest. The observed pattern of T.N generally corresponds with TOC, reflecting that nitrogen in soils is largely derived from decomposed

organic matter (Chatterjee *et al.*, 2017; Paul, 2014). Other sampling points had intermediate T.N values ranging between 0.13% and 0.18%.

The C:N ratio ranged from 5.71 at USS5 to 11.67 at USS3. USS3 and USS4 had higher C:N ratios, indicating a larger proportion of carbon relative to nitrogen, which may slow nutrient mineralization, whereas USS5 and USS6 had lower ratios, suggesting the presence of more easily decomposable organic matter that can enhance nutrient cycling (Paul, 2014; Brady and Weil, 2017).

Bulk density (BD) varied from 1.00 g/cm<sup>3</sup> at USS1, USS2, USS5, and USS6 to 1.10 g/cm<sup>3</sup> at USS3 and USS4. Lower BD values indicate better soil structure and porosity, facilitating water movement, root penetration, and carbon stabilization, while higher BD may indicate compaction or higher mineral content, potentially limiting carbon accumulation (Lal, 2005; Brady and Weil, 2017).

SOC stock ranged from 11.55 Mg/ha at USS3 to 23.10 Mg/ha at USS4. High SOC stocks at USS4 and USS1 reflect their elevated TOC and favorable bulk density, whereas USS3, with low TOC and higher BD, recorded the lowest SOC stock. USS5 and USS6 had intermediate SOC stocks (18 Mg/ha), and USS2 had 15 Mg/ha, showing that SOC storage is influenced by both organic carbon content and soil physical properties (Lal, 2005; Smith *et al.*, 2019).

USS1 and USS4 consistently exhibited higher TOC, T.N, and SOC stocks, indicating relatively fertile sites with higher carbon storage potential. USS3 consistently had the lowest values, suggesting reduced soil fertility and carbon sequestration capacity. Intermediate values at USS5

and USS6 reflect moderate soil quality, while USS2 displayed low SOC stock despite moderate nitrogen content, highlighting the influence of soil properties on carbon accumulation.

### 4.3 Soil Organic Carbon (SOC %)

**Table 4.4 Mean soil organic carbon (%) of the teak plantation at 0–15 cm depth**

Sampling points	SOC (%)
USS1	1.40 <sup>a</sup>
USS2	1.00 <sup>b</sup>
USS3	0.70 <sup>c</sup>
USS4	1.40 <sup>a</sup>
USS5	1.20 <sup>ab</sup>
<b>USS6</b>	<b>1.20<sup>ab</sup></b>
<b>LSD</b>	<b>0.18</b>

The ANOVA results for soil organic carbon revealed significant variation among the six sampling points, as indicated by the superscripts in the table. Superscripts are used to denote statistical groupings based on multiple comparison tests: sites sharing the same letter are not significantly different, whereas sites with different letters differ significantly at the selected confidence level. This statistical distinction highlights that SOC content is spatially heterogeneous even within a single-species forest stand.

USS1 and USS4, both labeled with the superscript “a,” exhibited the highest SOC values and were statistically similar, suggesting that these sites receive greater organic matter inputs and/or

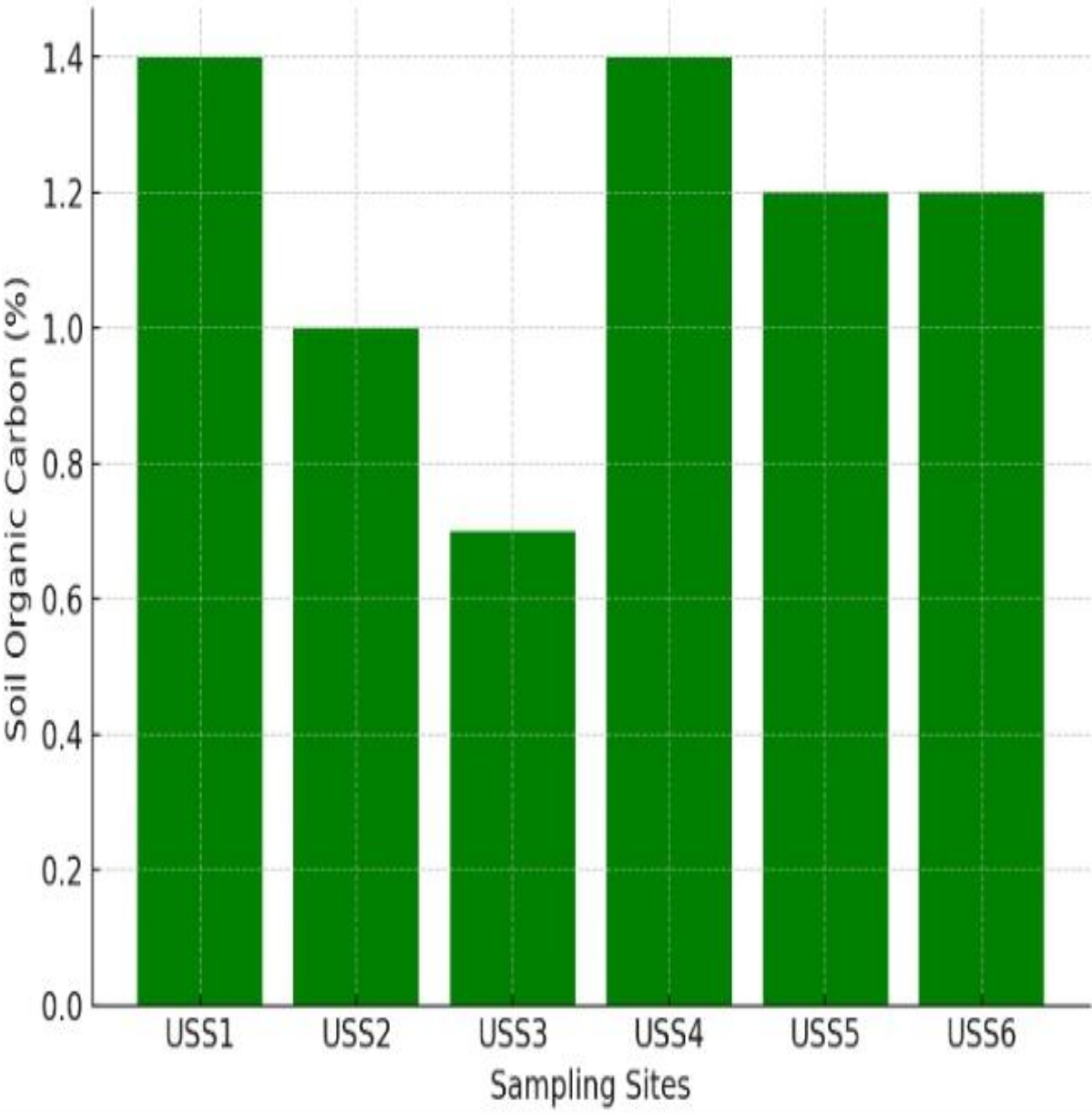
experience slower decomposition. Factors such as thicker litter layers, higher root biomass, or favorable microclimatic conditions (e.g., moisture retention, temperature moderation) likely contribute to enhanced carbon accumulation at these points. The high SOC in these sites indicates an optimal balance between organic matter input and microbial activity, allowing carbon to be stabilized in the soil.

USS2, assigned the superscript “b,” had significantly lower SOC compared to USS1 and USS4. This may reflect reduced litter deposition, faster microbial decomposition, or differences in soil texture that limit organic carbon stabilization. USS3, with the superscript “c,” had the lowest SOC content and was significantly different from all other sites. The low SOC at USS3 could result from a combination of minimal organic input, rapid decomposition due to high microbial activity, or a more sandy soil texture that favors leaching of dissolved organic carbon.

USS5 and USS6, labeled with the superscript “ab,” represent intermediate SOC values that are not significantly different from either the high or lower SOC groups. This indicates that these sites receive moderate organic inputs and have decomposition dynamics that place them between the extremes observed at USS1/USS4 and USS3. Environmental heterogeneity, including variations in litter quality, soil moisture, and microtopography, likely explains why SOC at these sites overlaps statistically with both high and moderate sites.

The LSD value of 0.18 reinforces that these differences are statistically meaningful, and not due to random variation. Overall, the variation in SOC across sampling points underscores the site-specific nature of carbon storage, shaped by organic matter input, decomposition rate, soil texture, microbial activity, and microclimatic factors. Understanding these spatial differences is

critical for accurately assessing carbon sequestration potential and guiding management practices aimed at enhancing soil carbon storage within forest ecosystems.



#### **Figure 4.1 Soil Organic Carbon (%) Across sampling points**

Measured soil organic carbon (SOC) at 0–15 cm depth ranged from 0.70% at USS3 to 1.40% at USS1 and USS4. Using measured bulk density values ( $1.0\text{--}1.1\text{ g cm}^{-3}$ ), the computed SOC stocks ranged from 105.0 to 210.0  $\text{Mg C ha}^{-1}$  for the 0–15 cm layer (Table 4.3). These SOC values are moderate for plantation soils, consistent with the variability widely reported in tropical plantations and natural forests. Zeng *et al.* (2021) observed topsoil SOC concentrations often exceeding 2% in undisturbed tropical forest soils, while Satdichanh *et al.* (2023) identified litter input, soil texture, and moisture as major drivers of SOC stocks. Compared to these findings, the teak plantation in this study stores less SOC, which is expected for managed monoculture systems (Zhang *et al.*, 2024).

Higher SOC at USS1 and USS4 likely reflects favorable micro-site conditions, including thicker litter layers, higher root density, or localized reduced decomposition due to microclimatic shade or increased soil moisture. USS3, with the lowest SOC, may experience thinner litter cover, more active decomposition, or localized disturbance. Sites USS2, USS5, and USS6 exhibited intermediate SOC, reflecting moderate organic matter input and decomposition dynamics. Topsoil represents the most dynamic carbon pool, and management actions that increase organic inputs such as mulching, retaining litter, or promoting understory vegetation can meaningfully increase SOC over decadal timescales in sandy tropical soils (Behera *et al.*, 2025).

Measured bulk density values ( $\sim 1.00\text{--}1.10\text{ g cm}^{-3}$ ) are typical of sandy loam soils, indicating moderate pore space and minimal compaction. Soil texture was overwhelmingly sandy ( $\approx 86\text{--}89\%$ ), with low silt and moderate clay ( $<13\%$ ). The high sand fraction limits mineral-associated protection of SOC, making carbon more labile and susceptible to loss if organic inputs decline or

if erosion occurs (Matus *et al.*, 2021; Khosravi *et al.*, 2024). Fine fractions such as clay and silt play a critical role in stabilizing SOC through organo-mineral associations (Matus *et al.*, 2021), partially explaining the moderate SOC values observed.

Soil pH ranged from 4.8 to 5.5, reflecting slight to moderate acidity, which may limit phosphorus availability and influence microbial communities responsible for decomposition (Xu *et al.*, 2023). Electrical conductivity (EC) values ranged from 162 to 249  $\mu\text{S cm}^{-1}$ , indicating non-saline soils but revealing micro-site variability that likely reflects localized ionic inputs from litter decomposition or root activity.

Total nitrogen (0.06–0.21%) closely mirrored SOC distribution, highlighting the strong link between carbon and nitrogen pools. Low available phosphorus (0.73–1.22  $\text{mg kg}^{-1}$ ) indicates potential P limitation, common in tropical soils, which can constrain microbial activity, litter decomposition, and carbon accumulation (Behera *et al.*, 2025). Exchangeable cations and effective cation exchange capacity (ECEC  $\sim 2.05\text{--}2.73 \text{ cmol kg}^{-1}$ ) were low to moderate, consistent with weathered, sandy tropical soils. These properties influence nutrient retention, long-term productivity, and SOC stabilization.

Previous studies in Nigeria report higher SOC in undisturbed forests compared to plantations or cultivated lands. Salami *et al.* (2021) highlighted that SOC in teak plantations depends on stand age and management practices, with younger stands storing less carbon than older ones. The observed SOC range (0.7–1.4%) aligns with other West African teak plantations but remains lower than intact secondary forests. Global syntheses indicate planted forests typically store less SOC than natural forests due to reduced litter diversity, simplified root structure, and lower understory vegetation (Zhang *et al.*, 2024).

The high sand fraction in the soils reduces stabilization through mineral associations, emphasizing that SOC in this plantation is more dependent on continuous organic inputs. Microtopography and litter patchiness likely explain spatial variability, with elevated SOC at USS1 and USS4 (Satdichanh *et al.*, 2023). Integrating practices such as increasing organic inputs, reducing soil acidity (e.g., liming), promoting mixed-species underplanting, and long-term monitoring can enhance SOC accumulation, nutrient retention, and plantation sustainability (Behera *et al.*, 2025).

## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATIONS

#### 5.1 Conclusion

This Study assessed soil organic carbon (SOC) and associated soil characteristics within a teak (*Tectona grandis*) plantation located at the University of Benin. The SOC content in the 0–15cm were consistent. The greatest carbon stocks was also consistent with what was observed by other scientists. The soils were generally acidic (pH 4.8–5.4), predominantly sandy and exhibited low levels of extractable phosphorus and exchangeable cations. These features suggest that the soils have moderate fertility but limited capacity for mineral stabilization of organic carbon, indicating that most of the SOC is likely derived from organic inputs. Chemical properties, including SOC, highlighted the importance of site-specific conditions.

When compared with earlier studies on tropical forests and teak plantations, the SOC levels observed here were lower than those found in undisturbed forest ecosystems but comparable to those reported in managed teak plantations. This reflects the influence of land use and management practices on carbon storage potential. Although teak plantations serve mainly for timber production, they still hold potential for increased carbon sequestration through appropriate management. Regular soil monitoring would further to monitor improvement in fertility and carbon storage in teak plantation systems.

#### 5.2 Recommendations

1. The role of trees will help improve soil fertility
2. Teak plantation studied can further contribute to improvement of carbon storage in the soil.

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