

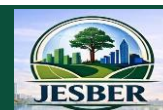
JOURNAL OF ENVIRONMENTAL SCIENCES AND BUILT ENVIRONMENT RESEARCH (JESBER)

2026, Vol. 1, No. 1, pp. 51-65

Published by Faculty of Environmental Sciences, University of Calabar, Nigeria

Print ISSN: 3141-5547 | OPEN ACCESS

DOI: <https://doi.org/10.83109/jesber.vol1no1.10>



Research article

EVALUATION OF MICROBIAL CHARACTERISTICS OF SOIL INFLUENCED BY DECOMPOSED LEAF LITTER IN IBIAE OIL PALM PLANTATION, CROSS RIVER STATE, NIGERIA

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ABSTRACT

This study evaluated the microbial characteristics of soil influenced by decomposed oil palm leaf litter in Ibiae Oil Palm Plantation, Cross River State, Nigeria. The study examined soil physical and chemical properties, microbial population, microbial biomass carbon and nitrogen, and enzyme activities across lower, middle and upper slope positions at 0-15 cm and 15-30 cm depths, using an adjacent non-oil-palm plot as control. Thirty-six soil samples were collected and analysed using standard laboratory procedures, while descriptive statistics and analysis of variance supported interpretation. Results showed that plantation soils were sandy loam, slightly acidic (pH 5.5-6.2) and richer in organic carbon, available phosphorus, exchangeable bases, microbial biomass and enzyme activity than the control. The lower slope and surface depth generally recorded the strongest biological performance, with higher bacterial counts, microbial biomass carbon (196.8 mg/kg), microbial biomass nitrogen (29.2 mg/kg), dehydrogenase, urease, amylase and lipase activities. The findings demonstrate that decomposed oil palm leaf litter improves soil biological quality and nutrient cycling, supporting its use as a sustainable residue-management strategy in tropical oil palm systems.

KEYWORDS

Oil palm; decomposed leaf litter; microbial biomass; soil enzymes; soil fertility; nutrient cycling; toposequence; Cross River State

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Introduction

Soil quality is a central determinant of agricultural sustainability because it controls crop nutrition, water storage, root development, microbial processes and the long-term resilience of agroecosystems. In perennial plantation systems, soil is not only a growth medium but also a biological reactor where plant residues are decomposed, nutrients are mineralised and organic matter is transformed into stable and labile pools that support crop productivity. The biological dimension of soil quality is especially important in humid tropical environments, where high rainfall, intense weathering and rapid organic matter turnover can accelerate nutrient losses when residue management is poor. For oil palm plantations, the interaction between soil texture, acidity, organic carbon, nutrient availability, microbial biomass and enzyme activity determines whether the system remains productive without excessive dependence on external fertiliser inputs (Brady & Weil, 2016; Udo et al., 2009; Eneyo et al., 2022; Inah et al., 2022; Obong et al., 2012)

Oil palm (*Elaeis guineensis* Jacq.) is one of the most economically important perennial crops in the humid tropics. It supports rural livelihoods, agro-industrial processing, employment, household income and local trade across many producing regions. In Nigeria, Cross River State lies within a favourable rainforest agro-ecological zone where oil palm production has both historical and contemporary significance. However, the sustainability of oil palm production depends on the ability of producers to maintain soil fertility under repeated harvest, pruning, weed control and traffic pressure. Where soil organic matter is depleted and biological processes are weakened, nutrient cycling becomes less efficient, soil structure declines, and fertiliser demand increases. This makes residue return and biological soil management key issues in sustainable plantation agriculture.

Oil palm plantations generate large quantities of organic residues, especially fronds and leaf litter from pruning and natural senescence. These residues are frequently stacked or left on the soil surface, where they undergo decomposition. Decomposed oil palm leaves can function as organic amendments by adding carbon substrates, improving soil moisture retention, moderating temperature, increasing exchangeable bases and stimulating microbial activity. Recent work on tropical land-use systems has shown that leaf litter can be strongly linked with microbial biomass and carbon processing, particularly in tropical systems where roots, litter and soil compartments interact in complex ways (Zhou et al., 2024; Eneyo et al., 2022; Udonwa et al., 2022). Similarly, studies on oil palm residues indicate that lignocellulosic biomass can alter soil microbial community structure, increase groups involved in decomposition and influence nutrient availability during residue breakdown (Uke et al., 2021; Ochiche et al., 2021; Offiong et al., 2022; Udonwa et al., 2022; Udonwa et al., 2024).

The value of decomposed leaf litter is not restricted to nutrient addition. Its ecological importance lies in the capacity to support soil organisms that regulate decomposition, mineralisation and biochemical transformation. Soil microorganisms decompose complex organic materials, release plant-available nutrients, immobilise nutrients during periods of excess supply, and contribute to soil aggregation through microbial metabolites and biomass turnover. Microbial biomass carbon and microbial biomass nitrogen are therefore useful indicators because they represent the living fraction of soil organic matter and respond more rapidly than total organic matter to changes in residue input, depth and land management (Brookes et al., 1985; Vance et al., 1987). Soil enzyme activities provide another important biological lens. Enzymes such as dehydrogenase, urease, phosphatase, amylase and lipase indicate microbial metabolism and nutrient cycling. Dehydrogenase is associated with oxidative microbial respiration, urease with nitrogen transformation, phosphatase with organic phosphorus mineralisation, amylase with carbohydrate decomposition and lipase with lipid breakdown. Contemporary soil health literature treats microbial biomass and enzyme activity as sensitive indicators of the effect of agricultural practices on soil ecological functioning because they respond to substrate supply, pH, moisture, aeration and organic matter quality (Li et al., 2025; Wang et al., 2023). In this study, these indicators are used to evaluate whether decomposed oil palm leaf litter improves the biological quality of plantation soil in Ibiae.

Topography also shapes soil biological processes. In sloping agricultural landscapes, lower slope positions often receive redistributed organic matter, fine particles, moisture and nutrients from upslope areas. Upper slope positions, by contrast, may experience erosion, thinner surface horizons and reduced organic substrate availability. Soil depth exerts a similar control because the upper 0-15 cm layer normally contains more plant residues, roots, oxygen and microbial substrates than the 15-30 cm layer. Therefore, the influence of decomposed leaf litter in oil palm plantation cannot be fully understood without considering slope position and soil depth. A toposequence approach is useful because it allows the researcher to examine how biological and chemical indicators vary from lower to middle and upper positions.

Despite the recognised importance of oil palm residues, empirical evidence remains limited on how decomposed oil palm leaves influence soil microbial characteristics across depth and toposequence in Cross River State. Previous Nigerian studies have examined soil fertility status, potassium dynamics and physical-

chemical properties of oil palm soils, but fewer studies have integrated microbial population, microbial biomass and soil enzyme activity within the same plantation setting. This gap is important because physical and chemical indicators alone may not show early changes in soil functioning. Biological indicators provide additional evidence on whether residue management is actively supporting nutrient cycling and soil resilience. This study therefore evaluates the microbial characteristics of soil influenced by decomposed leaf litter in Ibiae Oil Palm Plantation, Cross River State, Nigeria. Specifically, it examines the physical and chemical properties of plantation and control soils, compares microbial populations across slope positions and depths, assesses enzyme activities along the toposequence, evaluates microbial biomass carbon and nitrogen at different depths, and discusses the implications of the findings for sustainable soil fertility management in oil palm production systems.

Literature review

Soil biological quality and microbial indicators

Soil biological quality refers to the capacity of soil organisms and microbial processes to maintain nutrient cycling, organic matter turnover, aggregate formation and ecosystem stability. Unlike many physical and chemical properties, biological indicators respond quickly to changes in land management, residue input, moisture and disturbance. This makes them useful for detecting early improvements or degradation in soil functioning. Microbial biomass is especially important because it represents the active living pool of soil organic matter. It acts both as a sink for nutrients during microbial growth and as a source of nutrients when microbial cells die and are mineralised. Thus, increases in microbial biomass often indicate improved substrate availability and greater biological activity.

Microbial biomass carbon and nitrogen are widely used to evaluate soil health because they are connected to organic carbon cycling and nitrogen turnover. The chloroform fumigation-extraction method developed by Vance et al. (1987) and Brookes et al. (1985) remains a standard approach for estimating these pools. Higher values of microbial biomass carbon normally reflect a larger or more active microbial community, while microbial biomass nitrogen indicates the microbial pool of nitrogen that may later become available through mineralisation. In tropical plantation soils, these indicators are useful for assessing whether residue return and organic amendments are supporting biological fertility. Recent reviews further emphasise that microbial biomass, respiration and decomposition rates are among the most interpretable microbiological indicators for agricultural soil health assessment (Li et al., 2025).

Microbial population counts, including bacteria, fungi and actinomycetes, provide complementary information. Bacteria are major decomposers of labile carbon and play important roles in nitrogen cycling and nutrient solubilisation. Fungi are important in the decomposition of more resistant plant materials, particularly lignocellulosic residues. Actinomycetes occupy an intermediate ecological position and are known for decomposing complex organic substances and contributing to soil structure and disease suppression. In residue-rich systems such as oil palm plantations, the balance of bacterial, fungal and actinomycete populations can reveal how organic inputs are processed in the soil. Lignocellulose-rich residues may particularly stimulate decomposer organisms that produce cellulolytic and ligninolytic enzymes (Hadi et al., 2024; Uke et al., 2021).

Oil palm residues, decomposition and soil fertility

Oil palm residues include pruned fronds, senesced leaves, empty fruit bunches, trunks, roots and processing by-products. In plantation fields, leaf litter and fronds are commonly returned to the soil surface rather than removed. This practice can reduce waste, protect the soil surface, increase organic matter and improve nutrient cycling. During decomposition, nutrients contained in plant residues are gradually released, while microbial immobilisation temporarily stores nutrients and reduces immediate losses. The long-term result is often

improved soil organic matter, better nutrient retention and enhanced microbial activity. However, the outcome depends on residue quality, placement, moisture, temperature, microbial community and soil pH.

Oil palm residues are generally rich in lignocellulosic compounds, which decompose more slowly than easily soluble plant materials. Slow decomposition can be beneficial because it provides a sustained carbon input and helps protect the soil surface. At the same time, it may temporarily immobilise nitrogen if residues have high carbon-to-nitrogen ratios. Uke et al. (2021) showed that decomposing oil palm trunk fibre can increase lignocellulolytic bacteria and fungi in soil, although it may also create temporary nutrient limitations under some conditions. This finding is relevant because it shows that organic residues do not simply add nutrients; they restructure microbial processes and can alter nutrient availability depending on the stage and form of decomposition.

In tropical plantation systems, frond stacks and litter layers can create distinct microsites of microbial activity. Hadi et al. (2024) found that sampling depth and oil palm plantation management zones influenced lignocellulolytic microbes, enzyme activities and peat respiration, demonstrating that soil biological properties vary strongly with management position and depth. These findings support the design of the present study, which evaluates slope position and depth rather than treating the plantation as a uniform field. Residue accumulation may be strongest or most biologically active where decomposed leaves, moisture and fine materials concentrate.

Soil enzymes and nutrient cycling

Soil enzymes are proteins produced mainly by microorganisms and plant roots to catalyse biochemical reactions in soil. They are essential for the transformation of organic materials into forms that plants and microorganisms can use. Dehydrogenase activity is often treated as an index of total microbial oxidative activity because it is associated with living microbial cells. Urease catalyses the hydrolysis of urea into ammonium, thereby linking organic and fertiliser nitrogen transformations. Phosphatase releases inorganic phosphate from organic phosphorus compounds, while amylase hydrolyses starch and related carbohydrates into simple sugars. Lipase supports the decomposition of lipids and other ester compounds.

Enzyme activity is useful because it links microbial presence with function. A soil may contain microorganisms, but enzyme measurements show the intensity of biochemical processes. Studies in tropical forests show that extracellular enzyme activity can vary seasonally with litterfall, precipitation and nutrient demand, linking carbon, nitrogen and phosphorus cycling to microbial activity (Hofhansl et al., 2022). Reviews also caution that enzyme activity should be interpreted alongside physical and chemical indicators because enzymes respond to substrate availability, pH, soil moisture and management history (Wang et al., 2023). In the context of this study, enzyme activity is interpreted together with organic carbon, pH, available phosphorus, exchangeable bases and microbial biomass.

The selected enzymes in this study represent key nutrient pathways. Higher dehydrogenase activity suggests more active microbial respiration and organic matter oxidation. Higher urease activity indicates stronger nitrogen transformation potential. Higher amylase and lipase activities suggest more active decomposition of carbohydrate and lipid fractions of plant residues. Phosphatase activity can increase where phosphorus demand is high or where organic phosphorus is being mineralised. Therefore, slope variation in these enzymes provides evidence of how decomposed oil palm leaves influence biochemical functioning across the landscape.

Toposequence, soil depth and microbial functioning

Toposequence refers to the ordered change in soil properties along a slope. In humid tropical environments, slope position affects water movement, erosion, deposition, leaching, organic matter accumulation and nutrient redistribution. Lower slope soils often receive eroded materials, water and organic residues from upslope positions, while upper slopes may lose fine particles and organic matter through runoff. These differences influence soil pH, exchangeable bases, available phosphorus, microbial biomass and enzyme activity. A

toposequence approach is therefore important for explaining why soils within the same plantation may differ in fertility and biological activity. Depth is equally important. The surface layer receives decomposed leaves, root exudates and organic residues. It also tends to have better aeration and more active microbial communities. The subsoil generally has lower organic matter, lower root density, fewer fresh substrates and less oxygen, which can reduce microbial biomass and enzyme activity. The depth gradient can be especially clear in systems where residues are left on the surface rather than incorporated. In such systems, the surface soil acts as the main zone of residue decomposition and microbial activity. The present study is anchored conceptually on the soil quality framework and nutrient cycling perspective. The soil quality framework holds that sustainable agricultural management should maintain physical structure, chemical fertility and biological functioning. The nutrient cycling perspective explains how decomposed residues enter microbial pathways and are transformed into plant-available nutrients. Together, these perspectives guide the interpretation of oil palm leaf litter as a biological input that can improve soil fertility when returned to the field and protected from erosion and excessive disturbance.

Methodology

Study area

The study was conducted at Ibiae Oil Palm Plantation in Biase Local Government Area, Cross River State, Nigeria. The area lies within the humid tropical rainforest zone and is characterised by high rainfall, warm temperature, dense vegetation and weathered soils typical of southeastern Nigeria. Rainfall ranges between approximately 2,500 mm and 3,500 mm annually, while temperature commonly ranges from about 22.2°C to 32.2°C (NIMET, 2022). The climatic conditions support oil palm growth but also encourage rapid organic matter decomposition, leaching and nutrient redistribution along slopes. Figure 1 shows the location of the study area within Biase Local Government Area and Cross River State.

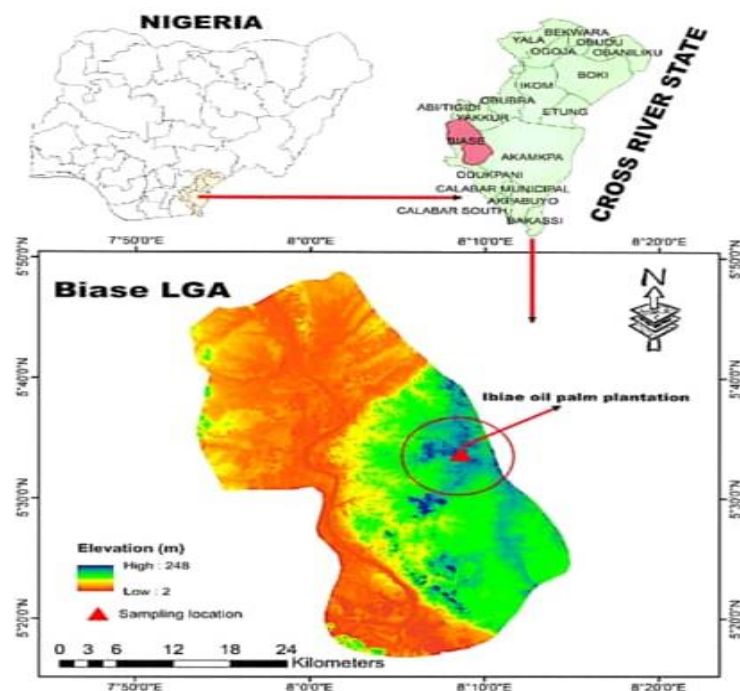


Figure 1. Map of Biase Local Government Area showing the Ibiae Oil Palm Plantation study area.

Source: Department of Geography and Environmental Science GIS Laboratory, University of Calabar, 2026.

The study area was appropriate because Ibiae Oil Palm Plantation provides a field setting where oil palm residues are returned to the soil and decomposed under natural tropical conditions. The plantation is also

characterised by observable slope positions, making it suitable for evaluating lower, middle and upper toposequence effects. An adjacent plot without oil palm production was used as a control to distinguish the soil conditions associated with decomposed oil palm leaf residues from those in a non-plantation setting.

Research design and sampling procedure

The study adopted a field-based experimental survey design supported by laboratory analysis. The design was appropriate because the research sought to compare soil properties across slope positions, depths and management conditions. Soil samples were collected within the oil palm plantation and from an adjacent control plot. The oil palm planting arrangement in the plantation was approximately 9 m by 9 m by 9 m in a triangular spacing pattern. This spacing allowed sampling along transects between palms while capturing the zone influenced by decomposed leaves and field residues.

Soil samples were collected using a soil auger at two depth intervals: 0-15 cm, representing the topsoil, and 15-30 cm, representing the subsoil. Sampling was conducted across three toposequence positions: lower slope, middle slope and upper slope. At each toposequence position, sampling commenced at 0.5 m from the base of the oil palm tree and proceeded along a transect at 2 m intervals, namely 0.5 m, 2.5 m, 4.5 m, 6.5 m and 8.5 m. This generated 30 soil samples from the plantation field. Six additional soil samples were collected from the adjacent control plot, corresponding to the same slope positions and depth intervals. In total, 36 soil samples were collected for physical, chemical, microbial and biochemical analyses.

Laboratory analysis

Samples intended for microbial analysis were placed immediately in sterile, well-labelled polythene bags, sealed and kept in an insulated ice chest to maintain field conditions during transport. The samples were taken to the Department of Microbiology Laboratory, Faculty of Biological Sciences, University of Calabar, within 24 hours of collection for microbial enumeration. Total heterotrophic bacteria, fungi and actinomycetes were enumerated using standard microbiological procedures based on serial dilution and culture techniques. Results were expressed as colony-forming units per gramme of soil. Soil physical properties were determined using the hydrometer method, while soil chemical properties were analysed using standard procedures for pH, organic carbon, total nitrogen, available phosphorus and exchangeable bases. Soil microbial biomass carbon and nitrogen were determined using the chloroform fumigation-extraction method described by Vance et al. (1987) and Brookes et al. (1985). Field-moist soil was sieved through a 2 mm sieve and separated into fumigated and non-fumigated portions. Fumigated samples were exposed to ethanol-free chloroform vapour for 24 hours to lyse microbial cells, after which chloroform was removed and samples were extracted with 0.5 M K₂SO₄.

Extractable carbon and nitrogen were determined for both fumigated and non-fumigated samples. Microbial biomass carbon was calculated as the difference between extractable carbon in fumigated and non-fumigated soil multiplied by the standard conversion coefficient, while microbial biomass nitrogen was calculated using the corresponding nitrogen extraction difference. Soil enzyme activities, including dehydrogenase, urease, phosphatase, amylase and lipase, were determined using established colorimetric and incubation procedures for soil enzyme assays. These enzymes were selected because they represent carbon, nitrogen, phosphorus and organic residue decomposition pathways.

Data analysis and ethical considerations

Data obtained from laboratory analysis were summarised using descriptive statistics, particularly means and standard deviations. Analysis of variance was used to evaluate differences among slope positions and soil depths, and differences were considered significant at $P \leq 0.05$. The results are presented in tables and figures to show the physical, chemical and biological patterns across the plantation and control plots. The discussion interprets numerical results in relation to residue decomposition, nutrient cycling, soil health and toposequence effects. Although the study involved soil sampling rather than human subjects, permission was obtained from the

relevant plantation authorities before fieldwork, and laboratory procedures were carried out in accordance with standard safety and quality-control practices.

Results and discussion

Physico-chemical properties of plantation soils influenced by decomposed leaf litter

Table 1 presents the physico-chemical properties of soil in the Ibiae oil palm plantation across slope positions and depth intervals. The particle-size distribution shows that sand content ranged from 66% to 72%, silt from 10% to 20% and clay from 12% to 14%. All samples were therefore classified as sandy loam. This textural class is important because sandy loam soils generally have moderate drainage and aeration, but they may require sustained organic inputs to improve water retention and nutrient-holding capacity. The return of decomposed oil palm leaves is therefore particularly relevant because it can increase organic matter and improve the functional quality of soils that are naturally dominated by sand.

Table 1. Soil physico-chemical properties in Ibiae Oil Palm Plantation across slope positions and depths.

Parameter	Lower 0-15 cm	Lower 15-30 cm	Middle 0-15 cm	Middle 15-30 cm	Upper 0-15 cm	Upper 15-30 cm
Sand (%)	72	68	66	66	70	70
Silt (%)	16	18	20	10	18	18
Clay (%)	12	14	14	14	12	12
Textural class	SL	SL	SL	SL	SL	SL
pH	5.6	5.5	5.9	5.8	6.2	6.1
Organic carbon (%)	2.8	1.5	2.0	2.0	2.1	2.0
Total nitrogen (%)	0.25	0.18	0.22	0.20	0.22	0.21
Available P (mg/kg)	18	12	16	16	15	15
Exchangeable Ca ²⁺ (cmol/kg)	7.5	7.2	6.2	6.0	7.2	7.11
Exchangeable Mg ²⁺ (cmol/kg)	2.8	2.1	2.5	2.4	2.7	2.5
Exchangeable K ⁺ (cmol/kg)	0.55	0.28	0.33	0.31	0.42	0.41
Exchangeable Na ⁺ (cmol/kg)	0.29	0.28	0.19	0.20	0.42	0.21
Exchangeable acidity (cmol/kg)	1.2	1.8	1.3	1.2	0.90	0.90
ECEC (cmol/kg)	11.05	9.56	10.54	10.11	11.44	11.13
Base saturation (%)	90.28	84.93	96.96	88.13	91.19	91.91

Source: Authors' laboratory analysis and fieldwork, 2025/2026. Note: SL = sandy loam.

The pH of the plantation soil ranged from 5.5 to 6.2, indicating slightly acidic conditions. This range is generally suitable for nutrient availability in many tropical plantation soils and is less restrictive than strongly acidic conditions observed in many weathered soils. Organic carbon was highest at the lower slope surface soil (2.8%) and lower in the 15-30 cm layer (1.5%). This shows the influence of surface residue deposition and downslope accumulation. Total nitrogen followed a similar pattern, with the lower slope surface layer recording the highest value, while available phosphorus was also highest at the lower slope surface soil (18 mg/kg). These results support the interpretation that decomposed leaf litter enhances nutrient availability, particularly in the surface layer and lower slope positions where organic residues and moisture are likely to accumulate.

Exchangeable bases also varied across the slope. Calcium was relatively high in the lower and upper slope positions, while potassium was highest in the lower slope surface layer. Effective cation exchange capacity ranged from 9.56 to 11.44 cmol/kg, and base saturation was generally high. The relatively favourable exchangeable base status suggests that decomposed oil palm leaves may contribute to nutrient recycling and buffering capacity in the plantation. The observed higher organic carbon and nutrient levels in the lower surface

position are consistent with toposequence theory, which explains that lower slopes receive materials transported by runoff and erosion from upper positions.

Comparison with control soil properties

Table 2 presents the physico-chemical properties of the adjacent control plot. The control soil was also sandy loam, with sand content ranging from 71% to 72%, silt from 18% to 20% and clay from 8% to 10%. The similarity in texture between the plantation and control plots indicates that the differences observed in organic carbon, pH, nutrient status and biological activity are less likely to be caused by textural class and more likely to be associated with management effects, residue input and slope position. However, the control soil showed lower pH, lower available phosphorus, lower exchangeable bases and lower base saturation than the plantation soil.

Table 2. Physico-chemical properties of adjacent control soil across slope positions and depths.

Parameter	Lower 0-15 cm	Lower 15-30 cm	Middle 0-15 cm	Middle 15-30 cm	Upper 0-15 cm	Upper 15-30 cm
Sand (%)	72	72	71	71	72	72
Silt (%)	20	20	20	19	18	18
Clay (%)	8	8	9	10	10	10
Textural class	SL	SL	SL	SL	SL	SL
pH	5.1	5.0	4.9	4.7	4.8	4.7
Organic carbon (%)	2.0	1.9	1.8	1.6	1.3	1.2
Total nitrogen (%)	0.18	0.18	0.07	0.07	0.05	0.05
Available P (mg/kg)	5.00	4.00	3.00	3.00	3.00	3.00
Exchangeable K ⁺ (cmol/kg)	0.35	0.34	0.21	0.20	0.20	0.20
Exchangeable Ca ²⁺ (cmol/kg)	4.00	3.15	2.30	2.21	2.00	2.00
Exchangeable Mg ²⁺ (cmol/kg)	2.00	2.00	0.80	0.72	0.60	0.43
Exchangeable Na ⁺ (cmol/kg)	0.25	0.21	0.15	0.14	0.15	0.13
Exchangeable acidity (cmol/kg)	1.84	1.96	2.43	2.12	3.12	3.10
ECEC (cmol/kg)	8.44	7.66	5.89	5.39	6.07	5.86
Base saturation (%)	78.20	74.41	59.00	60.67	48.60	47.10

Source: Authors' laboratory analysis and fieldwork, 2025/2026.

Note: SL = sandy loam.

The pH of the control soil ranged from 4.7 to 5.1, making it more acidic than the plantation soil. This difference is agronomically important because strong acidity can reduce nutrient availability, increase exchangeable acidity and limit microbial activity. The control soil also had lower available phosphorus, with values between 3 and 5 mg/kg compared with 12 to 18 mg/kg in the plantation soil. This contrast demonstrates the potential role of decomposed oil palm leaves in maintaining phosphorus availability and overall fertility. Although the control soil contained organic carbon, the plantation soil recorded stronger biological and nutrient indicators, suggesting that repeated residue return creates a more favourable environment for microbial growth and nutrient cycling. The control soil had lower exchangeable calcium, magnesium and potassium than the plantation soil. Base saturation values in the control ranged from 47.1% to 78.2%, compared with 84.93% to 96.96% in the plantation soil. The greater exchangeable acidity in the control, especially at the upper slope, also indicates less favourable chemical conditions. These results support the conclusion that decomposed oil palm residues can help improve soil chemical quality by adding organic matter and nutrients and by moderating acidity. However, the improvement is uneven and depends on slope position and depth.

Microbial population in plantation and control soils

Table 3 presents microbial populations in the oil palm plantation soil. Bacterial counts were higher than fungal and actinomycete counts across the slope positions and depths. The lower slope surface soil recorded the highest

bacterial population, followed by the lower slope subsoil and middle slope surface soil. Fungal and actinomycete populations also followed a general pattern of higher values in the surface or lower slope positions. This result indicates that decomposed leaf litter created a biologically active soil environment, particularly where organic matter and moisture were most available.

Table 3. Microbial population in Ibiae Oil Palm Plantation soil across slope positions and depths.

Microorganism	Lower 0-15 cm (cfu/g)	Lower 15-30 cm (cfu/g)	Middle 0-15 cm (cfu/g)	Middle 15-30 cm (cfu/g)	Upper 0-15 cm (cfu/g)	Upper 15-30 cm (cfu/g)
Bacteria	5.6×10^6	4.9×10^6	4.8×10^6	3.5×10^6	3.0×10^6	3.0×10^6
Fungi	3.9×10^4	3.7×10^4	3.2×10^4	3.2×10^4	2.8×10^4	2.6×10^4
Actinomycetes	3.7×10^5	3.1×10^5	3.6×10^5	3.0×10^5	2.9×10^5	2.7×10^5

Source: Authors' laboratory analysis and fieldwork, 2025/2026.

The predominance of bacteria may reflect the availability of labile organic substrates from decomposed leaf residues and the relatively favourable pH range of the plantation soil. Bacteria often respond quickly to fresh organic inputs, while fungi and actinomycetes contribute to the decomposition of more resistant organic materials. The presence of actinomycetes is important because these organisms participate in the decomposition of complex organic residues and can contribute to humus formation. The results align with literature showing that residue-rich oil palm systems stimulate microorganisms involved in lignocellulose degradation (Hadi et al., 2024; Uke et al., 2021). Table 4 presents microbial populations in the control plot. Although microorganisms were present in the control soil, the counts were generally lower than those recorded in the plantation soil. Bacteria ranged from 1.8×10^6 to 3.5×10^6 cfu/g in the control, while fungal and actinomycete counts were also lower than in the plantation. This difference confirms that the decomposed oil palm leaf environment supported a stronger microbial population. It also indicates that the biological improvement observed in the plantation was not simply a function of the background soil texture but was linked to organic residue input and management.

Table 4. Microbial population in adjacent control soil across slope positions and depths.

Microorganism	Lower 0-15 cm (cfu/g)	Lower 15-30 cm (cfu/g)	Middle 0-15 cm (cfu/g)	Middle 15-30 cm (cfu/g)	Upper 0-15 cm (cfu/g)	Upper 15-30 cm (cfu/g)
Bacteria	3.5×10^6	2.8×10^6	2.8×10^6	2.1×10^6	2.1×10^6	1.8×10^6
Fungi	2.7×10^4	2.5×10^4	2.2×10^4	2.0×10^4	2.1×10^4	1.9×10^4
Actinomycetes	2.5×10^5	2.3×10^5	2.4×10^5	2.2×10^5	2.1×10^5	2.0×10^5

Source: Authors' laboratory analysis and fieldwork, 2025/2026.

The lower microbial counts in the control plot are consistent with its lower pH, lower available phosphorus, lower exchangeable base status and reduced organic carbon values. Microorganisms require both carbon substrates and favourable chemical conditions. Where soil acidity is stronger and nutrient availability is lower, microbial growth may be constrained. The comparison between Tables 3 and 4 therefore shows that decomposed oil palm leaf litter is associated with improved microbial abundance, particularly in surface and lower slope soils. This supports the recommendation that oil palm residues should be retained and managed as a soil fertility resource rather than removed or burnt.

Soil enzyme activity along the toposequence

Table 5 presents mean soil enzyme activities along the toposequence. Dehydrogenase activity increased from the upper slope to the lower slope, with the lowest value at the upper slope and the highest at the lower slope. This indicates stronger microbial respiration and oxidative activity in the lower slope. Urease, amylase and lipase followed a similar general pattern, suggesting enhanced nitrogen transformation and organic residue decomposition in the lower slope. These results are consistent with the higher organic carbon and microbial population recorded in lower surface soils.

Table 5. Mean soil enzymatic activities along the toposequence in Ibiae Oil Palm Plantation.

Enzyme	Upper slope	Middle slope	Lower slope	Unit
Dehydrogenase	$46.2 \pm 3.1b$	$62.8 \pm 4.4ab$	$78.4 \pm 5.1c$	$\mu\text{g TPF g}^{-1} \text{ soil } 24 \text{ h}^{-1}$
Urease	$147.6 \pm 11.1b$	$187.5 \pm 14.3a$	$195.2 \pm 13.2b$	$\mu\text{g NH}_4^+-\text{N g}^{-1} \text{ soil } 2 \text{ h}^{-1}$
Phosphatase	$421.5 \pm 21.6a$	$398.2 \pm 19.4a$	$316.3 \pm 18.4a$	$\mu\text{g p-nitrophenol g}^{-1} \text{ soil h}^{-1}$
Amylase	$98.4 \pm 6.2c$	$124.7 \pm 8.1b$	$148.3 \pm 8.4b$	$\mu\text{g glucose g}^{-1} \text{ soil } 24 \text{ h}^{-1}$

Lipase	64.3 ± 4.8c	81.5 ± 5.6b	104.9 ± 6.7bc	µg p-nitrophenol g ⁻¹ soil h ⁻¹
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Source: Authors' laboratory analysis and fieldwork, 2025/2026. Note: Means ± SD; different letters indicate statistical differences at $P < 0.05$.

The higher dehydrogenase activity in the lower slope suggests that decomposed residues and moisture accumulation enhanced microbial respiration. Dehydrogenase is closely linked to living microbial cells, so its increase supports the microbial population results. Urease activity was also higher in the middle and lower slopes than in the upper slope. This suggests improved nitrogen mineralisation potential where organic substrates and microbial activity are greater. Amylase and lipase also increased downslope, showing stronger decomposition of carbohydrate and lipid fractions of leaf litter in lower positions.

Phosphatase showed a different pattern, recording the highest value in the upper slope. This may reflect greater phosphorus demand or stronger enzymatic mobilisation of organic phosphorus where available phosphorus is comparatively lower. High phosphatase activity does not necessarily mean high phosphorus availability; it may indicate that microorganisms and roots are producing more enzyme to access phosphorus from organic compounds. This interpretation is supported by the available phosphorus results in Table 1, where the lower slope surface soil had higher available phosphorus than the upper slope. Therefore, enzyme results should be interpreted together with chemical indicators rather than in isolation.

Table 5 demonstrates that decomposed leaf litter has functional biological significance. The residue-influenced soils are not only chemically richer; they are biochemically active. The activity of dehydrogenase, urease, amylase and lipase confirms that organic residues are being transformed through microbial pathways. This agrees with recent soil enzyme research which emphasises that enzyme activity is a useful indicator of nutrient cycling and soil biological functioning, especially when interpreted alongside soil organic carbon, pH and nutrient availability (Li et al., 2025; Wang et al., 2023).

Microbial biomass carbon and nitrogen across soil depths

Table 6 shows microbial biomass carbon and nitrogen at two soil depths in the plantation and control soils. In the plantation, microbial biomass carbon was 196.8 mg/kg at 0-15 cm and 120.0 mg/kg at 15-30 cm. Microbial biomass nitrogen was 29.2 mg/kg at 0-15 cm and 18.5 mg/kg at 15-30 cm. The control soil recorded substantially lower values, with microbial biomass carbon of 84.3 mg/kg at 0-15 cm and 37.6 mg/kg at 15-30 cm, while microbial biomass nitrogen was 19.4 mg/kg and 8.1 mg/kg at the same depths. This result indicates that decomposed oil palm leaf litter strongly enhanced the living microbial pool in the plantation soil.

Table 6. Microbial biomass carbon and nitrogen at different soil depths in Ibiae Oil Palm Plantation and control soil.

Soil depth (cm)	Plantation MBC (mg/kg)	Plantation MBN (mg/kg)	Control MBC (mg/kg)	Control MBN (mg/kg)
0-15	196.8	29.2	84.3	19.4
15-30	120.0	18.5	37.6	8.1

Source: Authors' laboratory analysis and fieldwork, 2025/2026.

Note: MBC = microbial biomass carbon; MBN = microbial biomass nitrogen.

The depth pattern is clear: microbial biomass declined with depth in both plantation and control soils. This is expected because surface soils receive more plant residues, root exudates and oxygen. However, the plantation soil maintained much higher values at both depths, indicating that oil palm leaf litter improved the biological environment beyond the immediate surface layer. The higher microbial biomass carbon and nitrogen in the 0-15 cm layer show that surface residue management is especially important for sustaining soil biological fertility. Figure 2 presents the relationship between microbial biomass carbon and microbial biomass nitrogen. The correlation is strongly positive, indicating that both variables changed in the same direction with soil depth. At the surface layer, higher microbial biomass carbon was accompanied by higher microbial biomass nitrogen. At the 15-30 cm layer, both decreased. This proportional relationship supports the interpretation that microbial biomass carbon and nitrogen are linked components of the living microbial pool and are jointly influenced by substrate availability, aeration and depth.

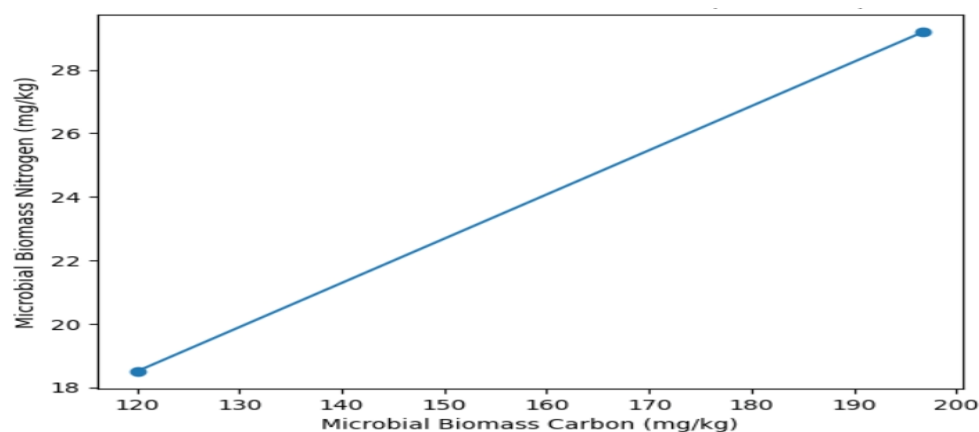


Figure 2. Correlation between microbial biomass carbon and microbial biomass nitrogen ($r = 1.000$).

Source: Authors' laboratory analysis and fieldwork, 2025/2026.

The strong relationship between microbial biomass carbon and nitrogen is agronomically meaningful. Microbial biomass carbon indicates the size of the carbon-dependent microbial community, while microbial biomass nitrogen indicates the nitrogen held in microbial cells. When microbial biomass increases, it can improve nutrient cycling by temporarily immobilising nutrients and later releasing them during turnover. This process can reduce nutrient loss and synchronise nutrient release with crop demand. In the Ibiae plantation, the decomposed leaf litter therefore appears to support a biologically mediated nutrient reservoir in the surface soil.

Integrated discussion of decomposed leaf litter effects

The combined results show that decomposed oil palm leaf litter improved soil fertility and microbial functioning in Ibiae Oil Palm Plantation. The most consistent evidence comes from the higher organic carbon, available phosphorus, exchangeable bases, microbial population, microbial biomass and enzyme activities in the plantation soil relative to the control. The surface lower slope was the strongest fertility zone, indicating that residue accumulation and slope-mediated deposition acted together. These findings confirm that residue management should be considered an integral part of sustainable oil palm soil management. The results also show that soil texture remained sandy loam in both plantation and control plots. This means that decomposed leaf litter did not change the basic textural class of the soil, which is expected because texture is a relatively stable property over short and medium periods. However, organic residues altered the functional behaviour of the soil by improving organic carbon, nutrient supply and biological activity. This distinction is important. A soil may retain the same texture but become more fertile and biologically active when organic matter is returned. Thus, the value of decomposed leaf litter is expressed less through textural transformation and more through chemical and biological enhancement.

The lower slope advantage observed in the plantation is consistent with ecological understanding of toposequence processes. Organic matter, fine particles and nutrients may move downslope through runoff and deposition. Lower slope soils may also retain more moisture, reducing stress on microorganisms and supporting enzyme activity. The higher dehydrogenase, urease, amylase and lipase activities at the lower slope confirm that these positions are more biologically active. In contrast, upper slope positions may be more vulnerable to erosion, lower organic matter retention and reduced microbial functioning. Conservation practices such as mulching, contour management and reduced soil disturbance are therefore needed to protect the upper slope. The surface-depth advantage also has important management implications. Since microbial biomass and enzyme activities were stronger at 0-15 cm, residue placement at the soil surface plays a major role in biological fertility. However, surface residues can be lost through erosion or removed during field clearing if not deliberately protected. Sustainable management should therefore ensure that pruned fronds and leaf litter are returned in organised

stacks or mulch bands that reduce erosion and provide slow-release organic inputs. This strategy can improve soil water retention and create stable microbial habitats.

The control plot provides important comparative evidence. Although the control soil was also sandy loam, it was more acidic and had lower available phosphorus, exchangeable bases and biological indicators. This suggests that oil palm leaf litter inputs did not merely add organic residues but modified the soil environment in ways that supported microbial activity. The higher base saturation in the plantation soil is particularly useful because it indicates improved nutrient status and reduced relative acidity. These improvements can reduce pressure on inorganic fertiliser use, although they should not completely replace balanced nutrient management where soil tests show deficiencies. The results also align with contemporary literature on soil health. Biological indicators such as microbial biomass and enzyme activity are increasingly recognised as sensitive measures of agricultural management effects (Li et al., 2025). The Ibiae results demonstrate why such indicators are necessary. If assessment relied only on texture, the plantation and control soils might appear similar. When microbial population, microbial biomass and enzymes are included, the positive influence of decomposed leaf litter becomes much clearer. This strengthens the argument for integrating biological indicators into soil fertility assessments in Nigerian plantation systems.

There is, however, a need for careful interpretation. High microbial activity is generally positive, but it can also indicate rapid decomposition and organic matter turnover in humid tropical environments. For long-term sustainability, residue return should be continuous so that microbial decomposition does not exhaust organic inputs faster than they are replenished. In addition, nutrient release from residues should be balanced with crop nutrient demand. Integrated nutrient management remains necessary, combining organic residue return, soil testing, targeted inorganic fertiliser application, erosion control and monitoring of pH and exchangeable bases. The findings have broader relevance beyond Ibiae. Many oil palm plantations in the humid tropics produce large amounts of biomass that may be underutilised. When residues are burnt or removed, the system loses carbon and nutrients that could support soil biological fertility. Returning decomposed leaves to the soil provides a low-cost and environmentally responsible strategy that supports microbial activity and nutrient cycling. It also reduces waste and contributes to sustainable intensification, especially for farmers who cannot depend entirely on expensive fertilisers. Therefore, decomposed oil palm leaf litter should be managed as a resource rather than as field waste.

Implications and conclusion

Implications for sustainable soil management

The study has several implications for oil palm plantation management. First, decomposed oil palm leaves should be retained within the plantation as a regular organic input. The evidence shows that residue return improves organic carbon, available phosphorus, microbial biomass and enzyme activity. Removing or burning residues would reduce these benefits and increase dependence on inorganic fertilisers. Second, residue management should be spatially planned. Upper slopes require particular protection because they are more vulnerable to erosion and lower biological activity. Mulching, contour residue stacking and ground cover maintenance should be encouraged to reduce soil loss and conserve moisture.

Third, soil fertility evaluation in oil palm systems should include biological indicators. Routine assessment often focuses on pH, nitrogen, phosphorus, potassium and exchangeable bases. These indicators are necessary but incomplete. Microbial biomass, microbial population and enzyme activity provide additional information on the functional status of the soil. They can detect whether the soil is actively cycling nutrients or merely containing chemical reserves. Including biological indicators will support more accurate diagnosis and better management decisions.

Fourth, integrated nutrient management remains essential. Although decomposed leaf litter improved soil fertility, total nitrogen remained generally low to moderate, and available nutrients varied across slope positions and depth. This means that organic residue return should be combined with balanced fertiliser use based on soil testing. Organic inputs can improve soil structure and biological activity, while mineral fertilisers can supply nutrients where deficiencies remain. A combined strategy is likely to be more sustainable than relying entirely on either residue return or inorganic fertilisers.

Fifth, plantation managers should pay attention to soil conservation. The lower biological activity in upper slope positions suggests that erosion and lower organic matter retention may be reducing soil quality. Conservation measures such as contour planting, cover cropping, mulching, reduced tillage and controlled traffic should be adopted. These practices will help retain organic residues, improve infiltration and protect microbial habitats. The biological benefits of decomposed leaf litter can only be sustained if the soil surface is protected.

Conclusion

This study evaluated the microbial characteristics of soil influenced by decomposed leaf litter in Ibiae Oil Palm Plantation, Cross River State, Nigeria. The findings show that the plantation soils were sandy loam and slightly acidic, with pH values ranging from 5.5 to 6.2. Decomposed oil palm leaves improved organic carbon, available phosphorus, exchangeable bases, microbial population, microbial biomass carbon and nitrogen, and enzyme activities when compared with the adjacent control plot. The strongest biological and fertility responses were generally recorded in the surface soil and lower slope positions, reflecting the combined effects of residue accumulation, moisture retention and nutrient redistribution. Microbial populations were higher in the plantation than in the control, with bacteria dominating the microbial counts. Microbial biomass carbon and nitrogen were also higher in the plantation surface soil, indicating improved biological fertility and a larger living nutrient pool. Enzyme activities showed that the lower slope was more biochemically active for dehydrogenase, urease, amylase and lipase, while phosphatase was highest at the upper slope, possibly reflecting phosphorus demand or mobilisation processes. These results demonstrate that decomposed oil palm leaf litter strengthens soil biological functioning and supports nutrient cycling in tropical oil palm systems. The study concludes that decomposed oil palm leaf litter is a valuable organic resource for improving soil fertility and microbial activity in Ibiae Oil Palm Plantation. Its retention and proper management can reduce soil fertility decline, improve biological soil quality and support sustainable oil palm production. However, residue return should be combined with erosion control, balanced fertilisation and continuous monitoring of soil health indicators. Future studies should extend the analysis across seasons, include molecular microbial community profiling and examine yield responses to different residue-management arrangements.

Declarations

Ethics approval and consent to participate: The study involved field soil sampling and laboratory analysis. Permission was obtained from the relevant plantation authorities before fieldwork, and the study was conducted according to accepted research and laboratory safety procedures.

Consent for publication: All authors approved the manuscript for journal submission and publication.

Availability of data and materials: The datasets generated and analysed during the study are available from the corresponding author on reasonable request.

Competing interests: The authors declare that they have no competing interests.

Funding: No external funding was declared for this study.

Authors' contributions: The authors contributed to the conception of the study, field sampling, laboratory analysis, data interpretation, manuscript drafting, revision and final approval of the article.

Acknowledgements: The authors acknowledge the support of the Ibiae Oil Palm Plantation management and the laboratory staff who assisted with soil and microbial analyses.

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