JOURNAL OF ENVIRONMENTAL SCIENCES AND BUILT ENVIRONMENT RESEARCH (JESBER)
2026, Vol. 1, No. 1, pp. 214-226
Published by Faculty of Environmental Sciences, University of Calabar, Nigeria
Print ISSN: 3141-5547 | OPEN ACCESS
DOI: https://doi.org/10.83109/jesber.vol1no1.22

Research article

TOPOSEQUENCE-DEPTH DYNAMICS OF SOIL MICROBIAL BIOMASS, ENZYME ACTIVITIES AND FERTILITY INDICES UNDER DECOMPOSED OIL PALM LEAF LITTER IN IBIAE PLANTATION, NIGERIA

Peter, P. G.[1]; Akpan, J. F.[1]*; Akpan, J. L.[2]; & Dijeh, A. E.[3]

[1] Department of Soil Science, University of Calabar, Calabar, Nigeria
[2] Department of Pharmacology, University of Calabar, Calabar, Nigeria
[3] Department of Home Economics Education, University of Calabar, Calabar, Nigeria
*Corresponding author: joyceakpan60@gmail.com

ABSTRACT

This study quantified the toposequence- and depth-mediated response of soil microbial properties to decomposed oil palm leaf litter in Ibiae Oil Palm Plantation, Cross River State, Nigeria. Soil samples were collected from lower, middle and upper slope positions at 0-15 cm and 15-30 cm depths, with adjacent non-oil-palm soil used as a control. Physico-chemical properties, microbial population, microbial biomass carbon and nitrogen, and selected enzyme activities were determined using standard soil analytical and microbiological protocols. Results showed that all plantation soils were sandy loam, but residue-influenced surface soils had stronger fertility and biological signals. Soil pH ranged from 5.5 to 6.2, while organic carbon and available phosphorus were highest at the lower slope surface horizon. Bacterial counts dominated the microbial community, and microbial biomass carbon and nitrogen declined with depth. Dehydrogenase, urease, lipase, amylase and phosphatase activities indicated active carbon, nitrogen and phosphorus turnover. The study demonstrates that decomposed oil palm leaf litter functions as a biologically active amendment for soil fertility restoration, residue recycling and sustainable plantation management.

KEYWORDS

Elaeis guineensis; decomposed leaf litter; microbial biomass carbon; microbial biomass nitrogen; soil enzyme activity; toposequence; nutrient cycling; sustainable soil fertility

Introduction

Sustainable plantation agriculture depends on soils that can maintain nutrient supply, biological activity, aggregate stability and organic matter turnover under continuous crop demand. In perennial tree-crop systems, soil quality is best understood as an integrated function of physical structure, chemical fertility and microbial process intensity rather than as a single nutrient status (Eneyo, et al., 2022; Eno & Edet, 2019; Hadi et al., 2024; Hofhansl et al., 2022; Ibanga & Okon, 2004; Inah et al., 2022). Oil palm plantations are particularly sensitive to these interactions because nutrient export, residue management, rainfall redistribution and root activity operate continuously across the plantation floor. A technical evaluation of soil microbial response is therefore essential for determining whether decomposed leaf residues are functioning as passive litter or as active drivers of biogeochemical cycling. Oil palm (Elaeis guineensis Jacq.) remains a strategic crop in humid tropical agriculture because it supports household livelihoods, agro-industrial processing and raw-material supply chains. In Nigeria, and particularly in the rainforest belt of Cross River State, oil palm cultivation occurs under warm and high-rainfall conditions that accelerate weathering, leaching and biological decomposition. These environmental conditions can either weaken soil fertility where residues are removed or strengthen soil function where organic inputs are retained and transformed into microbial biomass, humified carbon and plant-available nutrients (Adetunji et al., 2017; Alloway, 2013; Brady & Weil, 2016; Brookes et al., 1985).

A defining feature of oil palm management is the continuous production of pruned leaves, senesced litter and root-derived organic inputs. Where these materials are retained in the field, they form residue mats that modify soil microclimate, reduce direct raindrop impact, supply substrates for decomposers and create nutrient-enriched microsites (Chikwendu & Ogbonna, 2018; Corley & Tinker, 2016; Dick, 2011; Dick et al., 1996; Eneyo et al., 2017; Eneyo, et al., 2022). Their decomposition releases nitrogen, phosphorus, potassium, calcium and magnesium in synchrony with microbial turnover. This process is agronomically important because it reduces exclusive dependence on mineral fertilisers and supports internal nutrient recycling within the plantation ecosystem. The microbial importance of decomposed leaf litter lies in its role as an energy source, nutrient reservoir and habitat modifier. Microorganisms convert complex organic compounds into mineral nutrients through extracellular enzyme production, biomass turnover and respiration. Bacteria, fungi and actinomycetes respond differently to residue quality, moisture conditions, pH and substrate accessibility. Consequently, microbial population counts, microbial biomass carbon and microbial biomass nitrogen provide sensitive indicators of whether oil palm litter is improving soil biological quality or merely accumulating as undecomposed surface material.

Soil enzyme activities strengthen this interpretation because they measure functional biochemical processes. Dehydrogenase reflects overall microbial oxidative metabolism; urease is linked to urea hydrolysis and nitrogen transformation; phosphatase mediates organic phosphorus mineralisation; amylase supports carbohydrate degradation; and lipase participates in lipid decomposition (International Institute of Tropical Agriculture [IITA], 1979; Iren & Amalu, 2012; Joergensen & Mueller, 1996; Khalil & Rozman, 2019; Li et al., 2025). These enzyme systems provide a technical bridge between microbial abundance and nutrient cycling, allowing soil response to decomposed litter to be evaluated at a process level rather than through fertility chemistry alone.

Toposequence position adds a spatial dimension to this problem. In sloping plantation landscapes, lower slope soils may receive redistributed organic residues, fine particles, bases and moisture from upslope areas, while upper slopes may be more exposed to runoff and lower residue retention. Depth also mediates microbial response because the 0-15 cm surface layer receives fresh litter, root exudates and decomposed residues more directly than the 15-30 cm layer. A combined toposequence-depth approach is therefore more diagnostic than a single composite soil sample. Although decomposed oil palm residues are widely recognised as useful organic inputs, site-specific evidence on their effects on microbial biomass, enzyme activity and soil fertility gradients remain insufficient in Cross River State. Existing plantation studies often emphasise pH, exchangeable bases and macronutrients, while fewer studies integrate biological indicators with slope position, depth and control-plot comparison (Marschner et al., 2003; Nannipieri et al., 1990; Nigerian Meteorological Agency [NiMet], 2022; Obong, et al., 2012). This gap limits the ability of plantation managers to use microbial evidence in residue-placement, fertility planning and soil conservation decisions. This study therefore reveals the evaluation of decomposed oil palm leaves as a soil biological process assessment. It quantifies the effects of decomposed leaf litter on physico-chemical properties, microbial populations, microbial biomass carbon, microbial biomass nitrogen and selected enzyme activities across lower, middle and upper slope positions and two soil depths in Ibiae Oil Palm Plantation. The study contributes technical evidence for residue-based nutrient management, biological soil health monitoring and sustainable oil palm production in humid tropical environments.

Literature review

Microbial indicators as diagnostic tools for plantation soil quality

Soil biological quality refers to the ability of the living soil component to regulate decomposition, nutrient immobilisation-mineralisation, aggregate formation and rhizosphere functioning. In plantation agriculture, this quality is easily disrupted by erosion, compaction, excessive fertiliser dependence or residue removal (Udonwa et al., 2022; Uke et al., 2021; Utobo & Tewari, 2015; Vance et al., 1987). Microbial indicators are therefore useful because they respond faster than many conventional chemical properties. They capture short-term shifts in organic carbon availability, pH suitability, moisture status and substrate use efficiency within the soil system (Wang et al., 2023; Zhou et al., 2024). Microbial biomass carbon and nitrogen are among the most widely used technical indicators because they estimate the quantity of carbon and nitrogen held in living microbial cells. The chloroform fumigation-extraction method provides a quantitative estimate of this living pool by comparing extractable C and N from fumigated and non-fumigated soils. High microbial biomass suggests active residue transformation and nutrient retention, while low biomass may indicate limited substrate supply, acidity stress, low moisture or reduced soil habitat quality. Microbial population counts provide taxonomic-functional context for interpreting biomass. Bacteria typically respond rapidly to labile substrates and favourable pH conditions, fungi contribute strongly to lignocellulose breakdown and soil aggregation, while actinomycetes degrade more resistant organic compounds and are important in later-stage decomposition. The relative abundance of these groups can therefore indicate whether decomposed oil palm leaves are supporting a broad decomposer community or favouring only a narrow microbial response.

Oil palm litter decomposition and nutrient-return pathways

Oil palm residues include pruned fronds, leaflets, senesced litter, roots and processing by-products. In field situations, pruned leaves and frond stacks become major organic inputs when they are deliberately retained rather than removed or burnt. Their decomposition modifies soil physical and biochemical conditions by increasing organic matter, buffering temperature fluctuations, protecting the surface horizon and supplying cations and plant nutrients. These changes are especially valuable in sandy loam soils, where nutrient retention can be limited by high permeability (Obong et al., 2012; Ochiche et al., 2021; Offiong et al., 2022; Udonwa et al.,2012). The decomposition of oil palm leaf litter is controlled by residue chemistry, microbial decomposer capacity, rainfall, aeration and soil acidity. Lignocellulosic residues decompose progressively, producing an initial phase of labile carbon utilisation followed by slower transformation of cellulose, hemicellulose and lignin-rich fractions. This staged decomposition can stabilise nutrient release and maintain microbial activity over time (Okon & Ibanga, 2004; Tabatabai, 1994; Tao & Slade, 2020; Udo et al., 2009). However, the agronomic benefit depends on whether decomposition occurs in contact with the soil surface and whether nutrients are retained rather than lost through erosion or leaching. Recent studies of oil palm residue systems show that decomposer activity varies with depth, residue placement and microhabitat conditions (Udonwa et al., 2022; Udonwa et al., 2024; Hadi et al., 2024; Hofhansl et al., 2022). Litter layers, palm circles and frond-stacking zones can develop distinct microbial and enzymatic signatures because they differ in moisture, root contact and substrate quality. This evidence supports the need to study residue effects in relation to slope and depth rather than treating the plantation field as a uniform soil environment.

Enzyme-mediated transformation of organic inputs

Soil enzymes are catalytic proteins produced by microorganisms, roots and soil fauna. They regulate the conversion of organic residues into mineral forms that plants can absorb or that microorganisms can immobilise temporarily. Because extracellular enzymes operate at the interface of organic matter and microbial demand, enzyme assays provide a process-sensitive measure of soil functioning. They are particularly relevant in oil palm residue systems because leaf litter contains carbon-rich and nutrient-bearing compounds that must be enzymatically depolymerised before they enter the nutrient cycle (Ibanga & Okon, 2004; Inah et al., 2022; International Institute of Tropical Agriculture [IITA], 1979). Enzyme activity complements microbial population data by indicating functional intensity. A high microbial count does not automatically mean efficient nutrient cycling; the microbial community must also express enzymes capable of decomposing specific substrate classes. Dehydrogenase, urease, phosphatase, amylase and lipase together describe broad C, N and P transformation pathways. Their variation across slope positions can therefore reveal whether decomposed leaf residues are producing active biochemical hotspots within the plantation soil. In this study (Iren & Amalu, 2012; Joergensen & Mueller, 1996; Khalil & Rozman, 2019), dehydrogenase represents microbial oxidative metabolism and is interpreted as an index of total biological activity. Urease indicates nitrogen-cycling potential through urea hydrolysis. Phosphatase reflects the capacity to release inorganic phosphate from organic P compounds. Amylase indicates polysaccharide degradation, while lipase reflects lipid breakdown. Together, these enzymes provide a technical profile of microbial functionality rather than a simple description of soil fertility status.

Slope-depth gradients in microbial functioning

A toposequence is a spatial sequence of soils formed under similar climate and parent material but differing in position along a slope. In humid tropical plantations, toposequence position influences runoff, infiltration, erosion, deposition, residue accumulation and redox conditions. Lower slopes commonly accumulate organic matter and bases, while upper slopes may experience greater exposure, runoff and nutrient depletion. These processes can generate measurable gradients in microbial population, microbial biomass and enzyme activity. Depth gradients are equally important because microbial activity is normally concentrated in the biologically active surface horizon. The 0-15 cm layer receives direct litter inputs, decomposed residues, root exudates and oxygen. The 15-30 cm layer may contain fewer labile substrates and lower microbial density, although it remains important for root development and nutrient storage. Comparing both depths therefore help distinguish immediate residue effects from deeper soil background conditions. The study (Li et al., 2025; Marschner et al., 2003; Nannipieri et al., 1990; Nigerian Meteorological Agency [NiMet], 2022) is framed by the soil quality and nutrient cycling perspectives. The soil quality framework treats productive soil as a multifunctional biological-chemical-physical system, while nutrient cycling theory explains how organic inputs move through microbial biomass, enzyme-mediated transformations and plant-available pools. These perspectives are appropriate because decomposed oil palm leaves are not only a fertility input; they are a substrate that activates microbial processes and shapes soil health across space and depth.

Methodology

Study area

The field investigation was conducted at Ibiae Oil Palm Plantation in Biase Local Government Area, Cross River State, Nigeria. The plantation lies within the humid tropical rainforest agro-ecological zone, where annual rainfall is high and temperatures generally support rapid biological decomposition. Figure 1 presents the professionally recoloured location and elevation map of Biase Local Government Area, showing the spatial position of Ibiae Oil Palm Plantation and the sampling area within the wider Cross River State context.

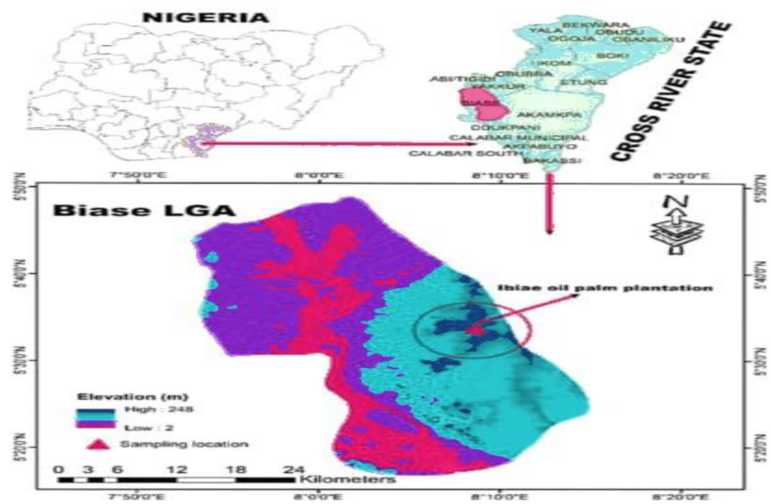

Figure 1. location map of Biase Local Government Area showing Ibiae Oil Palm Plantation and sampling area.
Source: Department of Geography and Environmental Science GIS Laboratory, University of Calabar.

The study area is technically suitable for residue-decomposition assessment because pruned oil palm leaves are routinely returned to the soil surface and decomposed under natural field conditions. The field setting therefore provides an opportunity to examine how litter-derived organic matter modifies soil fertility, microbial biomass and enzyme activity in a real plantation environment rather than under controlled pot or incubation conditions.

Field design and sampling architecture

The study adopted a field-based comparative analytical design supported by laboratory determination of microbial, biochemical and physico-chemical indicators. The design compared plantation soils influenced by decomposed oil palm leaves with adjacent control soils where oil palm production was not practiced. This comparative structure allowed the study to isolate residue-associated differences while also evaluating internal variation across slope position and depth. Soil sampling followed a stratified toposequence-depth framework. Samples were collected at two depth intervals, 0-15 cm and 15-30 cm, representing surface and subsurface horizons. Within the plantation, sampling was conducted at lower, middle and upper slope positions. At each slope position, soil was collected from defined transect distances from the palm base, beginning at 0.5 m and continuing at 2 m intervals. This generated thirty plantation samples, while six additional samples were obtained from corresponding control positions, giving thirty-six samples for laboratory analysis.

Laboratory and microbial analytical protocols

Samples for microbiological analysis were collected aseptically into sterile, labelled polythene bags, sealed and stored in an insulated ice chest to minimise post-sampling alteration. Samples were transported to the microbiology laboratory within 24 hours. Total heterotrophic bacteria, fungi and actinomycetes were enumerated using standard culture-based methods. The approach provided quantitative colony-forming unit estimates that could be compared across slope positions, depths and control conditions. Soil texture was determined by the hydrometer method, while pH, organic carbon, total nitrogen, available phosphorus, exchangeable bases, exchangeable acidity, effective cation exchange capacity and base saturation were determined using standard soil analytical procedures. Microbial biomass carbon and nitrogen were quantified using the chloroform fumigation-extraction method. This method estimates the living microbial pool by measuring extractable C and N released from lysed microbial cells after chloroform exposure.

Microbial biomass carbon was calculated as the difference between fumigated and non-fumigated extractable carbon multiplied by the conversion coefficient 2.46. Microbial biomass nitrogen was calculated as the difference between fumigated and non-fumigated extractable nitrogen multiplied by the conversion coefficient 1.46. These coefficients convert extractable flush values into estimates of microbial biomass pools. Enzyme assays were used to characterise dehydrogenase, urease, phosphatase, amylase and lipase activities as functional indicators of soil biochemical cycling.

Statistical treatment and quality assurance

Data were summarised using means and standard deviations. Analysis of variance was applied to test for differences among slope positions and depths where applicable, with significance interpreted at $P \le 0.05$. Tables were used to report measured values, while Figure 2 was used to show the coupling between microbial biomass carbon and microbial biomass nitrogen. The study followed standard field and laboratory quality-control procedures, including proper labelling, cold-chain handling for microbial samples, duplicate checking of laboratory entries and comparison of plantation results with control soil values.

Results and discussion

Technical interpretation of plantation soil physico-chemical gradients

Table 1 presents the physico-chemical matrix of the oil palm plantation soil across three slope positions and two depth intervals. The soil was dominated by sand, with values between 66% and 72%, while silt ranged from 10% to 20% and clay from 12% to 14%. The consistent sandy loam classification indicates that the parent textural framework remained similar across the toposequence. Therefore, observed fertility and biological differences are better interpreted as management- and residue-mediated responses rather than textural-class differences.

Table 1. Physico-chemical matrix of residue-influenced oil palm plantation soil across toposequence 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

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
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 values of 5.5 to 6.2 indicate slightly acidic conditions suitable for many microbial and nutrient-transformation processes in humid tropical soils. The lower slope surface horizon recorded the strongest organic carbon signal, with 2.8% organic carbon and higher available phosphorus than the corresponding subsurface layer. This pattern is technically important because it shows that decomposed leaf residues are most effective within the biologically active surface layer, where organic inputs, moisture and microbial contact are greatest. Exchangeable base status also supports the residue-effect interpretation. Calcium, magnesium and potassium were generally higher in the plantation soil than in the control soil, while base saturation remained high across the plantation toposequence. These values suggest that retained and decomposed leaves contributed to cation recycling and helped moderate acidity. The lower slope advantage further indicates possible downslope enrichment through residue redistribution, runoff-mediated deposition and enhanced organic matter retention.

Control-soil comparison as evidence of litter-mediated soil improvement

Table 2 presents the physico-chemical characteristics of the adjacent control soil. Although the control soil shared the same sandy loam textural class, it had a more acidic reaction and weaker fertility status than the residue-influenced plantation soil. This comparison is important because it shows that texture alone did not explain soil fertility differences. Rather, the stronger nutrient and base-status profile in the plantation reflects the cumulative effect of oil palm residue return, decomposition and nutrient recycling.

Table 2. Physico-chemical matrix of adjacent control soil across toposequence 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 control pH range of 4.7 to 5.1 indicates stronger acidity than the plantation soil. Such acidity can reduce microbial efficiency, constrain phosphorus availability and increase nutrient imbalance. The control soil also had lower organic carbon, available phosphorus and exchangeable cations in several positions, indicating reduced organic input and lower nutrient-buffering capacity. These results demonstrate the agronomic value of decomposed oil palm leaves as a low-cost biological amendment. Base saturation in the control soil varied more widely and was generally lower than in the plantation soil. This difference suggests that control soils had weaker cation retention and lower buffering capacity. In contrast, the residue-influenced plantation soil maintained a more favourable nutrient environment, supporting the interpretation that oil palm litter contributes to both nutrient return and biological habitat quality.

Microbial population structure under residue influence

Table 3 presents the microbial population profile of the plantation soil. Bacterial counts were consistently dominant across the toposequence, with the highest bacterial density recorded in the lower slope surface horizon. Fungal and actinomycete populations were also present across all slope-depth combinations, confirming that decomposed leaf litter supported a multi-group decomposer community. The surface advantage reflects higher organic substrate input, better aeration and stronger residue-microbe contact in the 0-15 cm layer.

Table 3. Microbial population structure in residue-influenced Ibiae oil palm plantation soil.

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 dominance of bacteria suggests that the plantation soil contained sufficient labile and moderately decomposed organic substrates to support rapid microbial growth. Fungi and actinomycetes, although lower in colony counts, remain ecologically significant because they contribute to the degradation of more resistant plant compounds and to aggregate stabilisation. The microbial distribution therefore indicates an active decomposer system rather than a chemically enriched but biologically weak soil environment. Table 4 provides the control-soil microbial population profile. Microorganisms were present in the control soil, but the counts were generally lower than those measured in the plantation soil. This contrast reinforces the interpretation that decomposed leaf litter increased microbial substrate availability, improved pH conditions and supported a broader biological response. Lower microbial abundance in the control plot also corresponds with its lower organic carbon and weaker exchangeable base status.

Table 4. Microbial population structure in adjacent control soil across toposequence 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 plantation-control contrast demonstrates that oil palm residue retention can strengthen the biological component of soil fertility. It also indicates that microbial population data should be included in soil-quality assessment for plantation systems. Chemical properties may show nutrient availability, but microbial counts reveal whether the soil has an active biological engine capable of sustaining decomposition and nutrient release over time.

Functional enzyme response across the toposequence

Table 5 reports the enzyme activity profile along the toposequence. Dehydrogenase activity increased from the upper slope to the lower slope, suggesting stronger microbial respiration and oxidative metabolism in depositional zones. Urease and lipase were also high in the lower slope, reflecting active nitrogen transformation and lipid degradation under residue-enriched conditions. Amylase activity peaked in the lower slope, indicating stronger carbohydrate decomposition where decomposed leaf substrates were more available.

Table 5. Functional enzyme activity profile along the toposequence of Ibiae Oil Palm Plantation.

Enzyme	Upper slope	Middle slope	Lower slope	Unit
Dehydrogenase	46.2 ± 3.1b	62.8 ± 4.4ab	78.4 ± 5.1c	µg TPF g^{-1} soil 24 h^{-1}
Urease	147.6 ± 11.1b	187.5 ± 14.3a	195.2 ± 13.2b	µg NH_4^+-N g^{-1} soil 2 h^{-1}
Phosphatase	421.5 ± 21.6a	398.2 ± 19.4a	316.3 ± 18.4a	µg p-nitrophenol g^{-1} soil h^{-1}
Amylase	98.4 ± 6.2c	124.7 ± 8.1b	148.3 ± 8.4b	µg glucose g^{-1} soil 24 h^{-1}
Lipase	64.3 ± 4.8c	81.5 ± 5.6b	104.9 ± 6.7bc	µg p-nitrophenol g^{-1} soil h^{-1}

Source: Authors' laboratory analysis and fieldwork, 2025/2026. Note: Means ± SD; different letters indicate statistical differences at $P < 0.05$.

The dehydrogenase gradient is particularly important because dehydrogenase is widely interpreted as an indicator of total microbial oxidative activity. Higher values in the lower slope suggest that residue accumulation, moisture retention and organic matter enrichment created a more active microbial habitat. This functional response corresponds with the higher organic carbon and microbial population values recorded in the lower slope surface soil. Phosphatase activity showed a different spatial tendency, with stronger values in the upper slope. This may reflect greater microbial and plant demand for phosphorus mobilisation where available P is comparatively lower. The result indicates that enzyme expression is not always highest where nutrient concentration is highest; rather, it can increase where microorganisms and roots intensify biochemical acquisition of limiting nutrients. Overall, the enzyme data demonstrate that decomposed oil palm leaves modified soil function, not merely soil chemistry. The plantation soil exhibited evidence of carbon oxidation, nitrogen cycling, phosphorus mineralisation, carbohydrate decomposition and lipid transformation. This multi-enzyme response provides stronger technical evidence for residue-based biological improvement than a single nutrient measurement would provide.

Microbial biomass coupling across soil depth

Table 6 presents microbial biomass carbon and nitrogen at two depth intervals in both plantation and control soils. In the plantation, microbial biomass carbon declined from 196.8 mg/kg at 0-15 cm to 120.0 mg/kg at 15-30 cm. Microbial biomass nitrogen declined from 29.2 mg/kg to 18.5 mg/kg over the same depth range. Control values were lower at both depths, confirming that residue-influenced soils contained a larger living microbial pool.

Table 6. Depth-dependent microbial biomass carbon and nitrogen in plantation and control soils.

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 decline in microbial biomass with depth reflects the vertical concentration of litter-derived substrates, root exudates and oxygen in the surface layer. The 0-15 cm horizon is the principal interface between decomposed leaf material and soil microbial communities. The control soil showed the same downward trend but from a much lower baseline, indicating that depth effects are natural but residue inputs strongly determine the magnitude of microbial biomass. Figure 2 presents a professional MBC-MBN coupling plot for plantation and control soils across the two sampled depth intervals. The overall association is strongly positive (r = 0.955), indicating that microbial biomass carbon and nitrogen generally increased or declined together, while the plantation soil maintained higher biological biomass than the control at both depths.

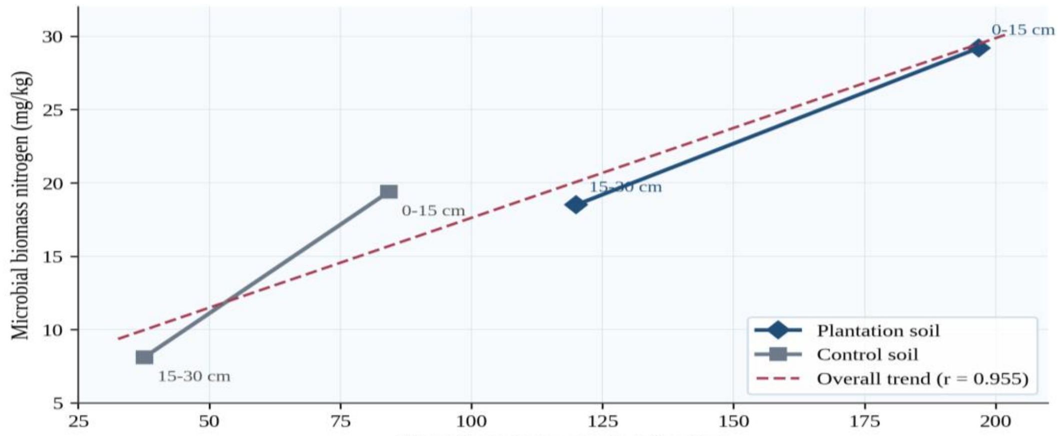

Figure 2. Professional plot of microbial biomass carbon-nitrogen coupling by management system and soil depth.
Source: Authors' laboratory analysis and fieldwork, 2025/2026.

The strong MBC-MBN relationship indicates that residue-influenced microbial growth was balanced rather than carbon-rich but nitrogen-poor. Where microbial C and N increase together, the microbial biomass can immobilise nutrients during active growth and subsequently release them through turnover. This cycling pathway is central to organic residue management because it helps synchronise nutrient supply with plant demand and reduces the risk of abrupt nutrient loss.

Integrated biogeochemical synthesis

The combined evidence shows that decomposed oil palm leaf litter improved soil biological functioning in Ibiae Oil Palm Plantation. The strongest signals occurred in the lower slope and in the 0-15 cm depth, where organic carbon, available phosphorus, bacterial counts, microbial biomass and several enzyme activities were comparatively higher. These patterns support the interpretation that residue return created biologically active nutrient-cycling zones within the plantation. Texture remained sandy loam in both plantation and control soils, meaning that the observed differences were not caused by a change in particle-size class. This is important for technical interpretation because sandy loam soils are generally well aerated but may have limited nutrient-retention capacity. Decomposed leaf litter therefore provides a compensatory function by improving organic carbon, cation retention and microbial habitat quality within a coarse-textured soil matrix. The lower slope response is consistent with toposequence theory. Downslope positions commonly receive organic particles, moisture and dissolved nutrients transported from upper positions. When decomposed oil palm leaves are retained in the plantation, this natural redistribution can intensify biological activity in lower slope areas. Plantation managers should therefore recognise that residue effects may be spatially heterogeneous and that upper slopes may require additional conservation attention.

The surface-depth pattern has direct management significance. Since microbial biomass and enzyme activities were stronger in the 0-15 cm horizon, residue placement should prioritise surface retention, even distribution and protection from burning or removal. Disturbance that buries or removes leaf litter may reduce the microbial advantage observed in the surface horizon. The findings therefore support minimal-disturbance residue management in oil palm systems. The control plot strengthened the causal interpretation by showing that similar-textured soils without oil palm residue influence had lower pH, lower nutrient status and weaker microbial indicators. This comparison demonstrates that decomposed leaf litter was associated with improved biological and chemical soil quality. It also shows that microbial indicators are useful for detecting residue effects that may not be fully captured by conventional soil fertility tests.

The findings align with contemporary soil-health literature, which emphasises microbial biomass and enzyme activity as sensitive indicators of sustainable management. In tropical plantations, biological indicators are especially useful because nutrient cycling is rapid and chemical fertility can change quickly under high rainfall. Integrating biological measurements into plantation soil monitoring can therefore improve the diagnosis of fertility constraints and guide organic-input management. A technical caution is necessary. High microbial activity is generally beneficial, but it can also indicate rapid organic matter turnover. If residue inputs are not continuous, microbial decomposition may reduce organic carbon stocks over time. Sustainable management should therefore maintain regular residue return, protect surface litter, control erosion and combine organic inputs with balanced mineral fertilisation where nutrient demand exceeds litter-derived supply. The broader implication is that oil palm plantations in humid tropical zones can convert routine pruning residues into a biological soil amendment. Instead of treating leaves as field waste, plantation systems can use them as functional inputs for microbial activation, nutrient recycling and soil conservation. This approach is environmentally preferable to burning and economically relevant where fertiliser costs are high or supply is uncertain.

Implications and conclusion

Technical implications for plantation soil-health management

The study has clear implications for sustainable oil palm management. First, decomposed oil palm leaves should be retained within the plantation as a routine soil-health input. Residue retention supports organic carbon accumulation, improves microbial habitat quality and contributes to nutrient cycling. Second, lower and upper slope positions should not be managed identically. Lower slopes showed stronger biological response, while upper slopes require better residue protection and erosion control to prevent nutrient depletion.

Third, plantation soil testing should include biological indicators in addition to pH, organic carbon, nitrogen and exchangeable bases. Microbial biomass carbon, microbial biomass nitrogen and enzyme activity provide early evidence of soil functional change. Their inclusion would help managers detect whether a soil is biologically active enough to support residue decomposition and nutrient release.

Fourth, integrated nutrient management remains necessary. Decomposed leaf litter improved several soil indicators, but residue return should complement rather than completely replace nutrient budgeting. Mineral fertilisation, where required, should be calibrated to soil-test results and combined with residue retention to avoid nutrient mining, excessive acidity or inefficient fertiliser use.

Fifth, residue management should be connected to conservation planning. Sandy loam soils under humid rainfall are vulnerable to leaching and erosion. Retaining decomposed leaves on the surface can reduce runoff energy, increase infiltration and improve nutrient retention. This makes leaf-litter management both a fertility intervention and a soil-conservation strategy.

Conclusion

This study assessed the toposequence- and depth-dependent response of soil microbial properties to decomposed oil palm leaf litter in Ibiae Oil Palm Plantation, Cross River State, Nigeria. The findings show that residue-influenced plantation soils maintained sandy loam texture but exhibited stronger biological and chemical fertility signals than the adjacent control soil. Soil pH in the plantation was less acidic, and organic carbon, available phosphorus and exchangeable base status were generally more favourable. Microbial population, microbial biomass and enzyme activity results confirm that decomposed oil palm leaves stimulated soil biological functioning. Bacteria dominated the microbial population, microbial biomass carbon and nitrogen were higher in the surface layer, and enzyme activities indicated active carbon, nitrogen, phosphorus, carbohydrate and lipid transformation. The lower slope and surface horizon emerged as the strongest zones of biological response. The study concludes that decomposed oil palm leaf litter is a technically valuable organic resource for improving soil microbial activity, nutrient cycling and fertility resilience in humid tropical oil palm plantations. Its use should be formalised as part of residue-based soil management, biological soil-health monitoring and integrated nutrient management. Future studies should include seasonal monitoring, molecular microbial profiling, litter decomposition-rate measurement and longer-term carbon-stock assessment to strengthen mechanistic understanding of residue-microbial interactions.

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.

References

Adetunji, A. J., Lewu, F. B., Mulidzi, R., & Ncube, B. (2017). The biological activities of β-glucosidase, phosphatase and urease as soil quality indicators: A review. Journal of Soil Science and Plant Nutrition, 17(3), 794-807.

Alloway, B. J. (2013). Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability (3rd ed.). Springer.

Brady, N. C., & Weil, R. R. (2016). The nature and properties of soils (15th ed.). Pearson Education.

Brookes, P. C., Landman, A., Pruden, G., & Jenkinson, D. S. (1985). Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biology and Biochemistry, 17(6), 837-842. https://doi.org/10.1016/0038-0717(85)90144-0

Chikwendu, M. U., & Ogbonna, A. N. (2018). Soil properties in oil palm ecosystems. Journal of Forestry Research, 10(3), 55-61.

Corley, R. H. V., & Tinker, P. B. (2016). The oil palm (5th ed.). Wiley-Blackwell.

Dick, R. P. (2011). Methods of soil enzymology. Soil Science Society of America.

Dick, R. P., Breakwell, D. P., & Turco, R. F. (1996). Soil enzyme activities and biodiversity measurements as integrative microbiological indicators. In J. W. Doran & A. J. Jones (Eds.), Methods for assessing soil quality (pp. 247-271). Soil Science Society of America.

Eneyo, V. B., Onyejekwe, I. H., & Ekpenyong, E. J. (2017). The impact of globalization on African heritage: Case study of Igbo cultural heritage. *Multi-Disciplinary Journal of Research and Development Perspectives, 6*(1).

Eneyo, V. B., Talib, J., Attah, F. M., & Offiong, E. E. (2022). Iran's nuclear policy: Nature, ambition, and strategy. *Journal of Liberty and International Affairs, 8*(2), 202–222.

Eneyo, V. B., Ushie, M. A., Akeh, L. B., Udonwa, R. E., Esuabana, S. B., & Idika, D. O. (2022). Analysis of geographical distribution and patronage of fast food in Calabar Urban, Nigeria. *African Journal of Hospitality, Tourism and Leisure, 11*(6), 1969–1989.

Eno, E. E., & Edet, U. A. (2019). Soil fertility status and management practices in oil palm plantations of southern Nigeria. Nigerian Journal of Soil Science, 29(2), 45-54.

Hadi, M. N., Pulunggono, H. B., Indriyati, L. T., Widiastuti, H., & Zulfajrin, M. (2024). Factors regulating lignocellulolytic microbes, their degrading enzymes, and heterotrophic respiration in oil palm cultivated peatlands. Journal of Degraded and Mining Lands Management, 11(2), 5195-5210. https://doi.org/10.15243/jdmlm.2024.112.5195

Hofhansl, F., Valverde-Barrantes, O., Camargo, P. B., & Hoosbeek, M. R. (2022). Seasonal fluctuations of extracellular enzyme activities are related to the biogeochemical cycling of C, N and P in a tropical terra-firme forest. Biogeochemistry. https://doi.org/10.1007/s10533-022-01009-4

Ibanga, I. J., & Okon, E. C. (2004). Effects of oil palm on soil properties. Global Journal of Agricultural Sciences, 3(2), 63-69.

Inah, E. O., Eneyo, V. B., Odey, S. A., Ushie, M. A., Udonwa, R. E., Esuabana, S. B., Ekpo, E. E., Akintoye, O. A., & Ajake, A. O. (2022). Anthropogenic impacts on water quality of Kedong Stream in Idomi, Yakurr, Nigeria. *Environment and Ecology Research, 10*(6), 738–748.

International Institute of Tropical Agriculture. (1979). Selected methods for soil and plant analysis. IITA Manual Series.

Iren, O. B., & Amalu, U. C. (2012). Forms and status of potassium in some soils supporting oil palm (Elaeis guineensis Jacq.) plantation in Cross River State, Nigeria. Communications in Soil Science and Plant Analysis, 43(14), 1949-1962.

Joergensen, R. G., & Mueller, T. (1996). The fumigation-extraction method to estimate soil microbial biomass: Calibration of the kEC value. Soil Biology and Biochemistry, 28(1), 33-37. https://doi.org/10.1016/0038-0717(95)00102-6

Khalil, H. P. S. A., & Rozman, H. D. (2019). Biodegradation of oil palm residues. Journal of Environmental Science, 54, 345-354.

Li, X., Wang, Y., Zhang, Y., & Chen, J. (2025). Microbiological indicators for assessing the effects of agricultural practices on soil health: A review. Agronomy, 15(2), 335. https://doi.org/10.3390/agronomy15020335

Marschner, P., Kandeler, E., & Marschner, B. (2003). Structure and function of the soil microbial community in a long-term fertilizer experiment. Soil Biology and Biochemistry, 35(3), 453-461. https://doi.org/10.1016/S0038-0717(02)00297-3

Nannipieri, P., Grego, S., & Ceccanti, B. (1990). Ecological significance of the biological activity in soil. In J. M. Bollag & G. Stotzky (Eds.), Soil biochemistry (Vol. 6, pp. 293-355). Marcel Dekker.

Nigerian Meteorological Agency. (2022). Annual meteorological records for Cross River State. NIMET.

Obong, L. B., Aniah, E. J., Okaba, L. A., & Effiom, V. A. (2012). Sustainable livelihood in the Cross River National Park (CRNP), Oban, Nigeria. *Multi-Disciplinary Journal of Research and Development Perspectives, 1*(2), 34–51.

Obong, L. B., Effiom, V. A., & Okon, A. E. (2012). The impact of Marina Tourism Resort on the livelihoods of Duke Town, Cross River State, Nigeria. *Nigerian Journal of Social and Development Issues, 9*(2), 114–123.

Ochiche, C. A., Oko, P. E., Eneyo, V. B., & Terngu, A. (2021). Barriers to solving water problems in Cross River State of Nigeria. In *Proceedings of the 11th Annual Conference of Nigeria Association of Hydrological Sciences* (pp. 455–460). Nigeria Association of Hydrological Sciences.

Offiong, E. E., Eneyo, V. B., Ushie, M. A., Agbor, C. N., Ephraim, I. E., Ajake, A. O., & Antai, A. S. (2022). Survey and ethnobotanical investigations of key non-timber forest products in home gardens and sacred forests in Cross River State, Nigeria. *Environment and Ecology Research, 10*(5), 580–591.

Okon, P. B., & Ibanga, I. J. (2004). Characteristics and management of Ultisols in southeastern Nigeria. Global Journal of Agricultural Sciences, 3(1), 19-24.

Tabatabai, M. A. (1994). Soil enzymes. In R. W. Weaver, J. S. Angle, & P. S. Bottomley (Eds.), Methods of soil analysis, Part 2: Microbiological and biochemical properties (pp. 775-833). Soil Science Society of America.

Tao, H. H., & Slade, E. M. (2020). Oil palm residues and soil fertility. Agronomy Journal, 112(4), 2345-2356.

Udo, E. J., Ibia, T. O., Ogunwale, J. A., Ano, A. O., & Esu, I. E. (2009). Manual of soil, plant and water analysis. Sibon Books.

Udonwa, R. E., Eneyo, V. B., & Asuquo, E. E. O. (2022). Caregivers' variables and health implication of food intake of pre-school children in Calabar South Local Government Area of Cross River State, Nigeria. *World Environment Journal, 2*(2), 44–60.

Udonwa, R. E., Eneyo, V. B., & Iyam, M. A. (2024). Effects of lifestyle factors on weight variations among adolescents in Southern Cross River State, Nigeria. *Nigeria Journal of Home Economics, 12*(10), 25–32.

Udonwa, R. E., Eneyo, V. B., Asuquo, E. E., & Itu, P. C. O. (2022). Family socio-demographic variables and child upbringing in Calabar Metropolis of Cross River State, Nigeria. *World Environment Journal, 2*(2), 61–80.

Uke, A., Nakazono-Nagaoka, E., Chuah, J.-A., Ahmad Zain, N.-A., Amir, H.-G., Sudesh, K., Abidin Zainal Abidin, N. Z. H., Hashim, Z., & Kosugi, A. (2021). Effect of decomposing oil palm trunk fibers on plant growth and soil microbial community composition. Journal of Environmental Management, 295, 113050. https://doi.org/10.1016/j.jenvman.2021.113050

Utobo, E. B., & Tewari, L. (2015). Soil enzymes as bioindicators of soil ecosystem status. Applied Ecology and Environmental Research, 13(1), 147-169.

Vance, E. D., Brookes, P. C., & Jenkinson, D. S. (1987). An extraction method for measuring soil microbial biomass C. Soil Biology and Biochemistry, 19(6), 703-707. https://doi.org/10.1016/0038-0717(87)90052-6

Wang, L., Hamel, C., Lu, P., Wang, J., Sun, D., Wang, Y., Lee, S.-J., & Gan, G. Y. (2023). Using enzyme activities as an indicator of soil fertility in grassland: An academic dilemma. Frontiers in Plant Science, 14, 1175946. https://doi.org/10.3389/fpls.2023.1175946

Zhou, Z., Lu, J.-Z., Widyastuti, R., Scheu, S., Potapov, A., & Krashevska, V. (2024). Plant roots are more strongly linked to microorganisms in leaf litter rather than in soil across tropical land-use systems. Soil Biology and Biochemistry, 190, 109320. https://doi.org/10.1016/j.soilbio.2024.109320