Physiographic Modulation of Compost-induced Biochemical Responses, Nutrient Uptake and Vegetative Growth of Okra Under Contrasting Soil Moisture Conditions

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PHYSIOGRAPHIC POSITION MODULATES COMPOST INDUCED BIOCHEMICAL RESPONSES, NUTRIENT UPTAKE AND VEGETATIVE GROWTH OF OKRA UNDER CONTRASTING SOIL MOISTURE CONDITIONS

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Abstract

Physiographic variation influences soil hydro-environmental conditions and associated biogeochemical processes, yet its role in regulating poultry-manure-based compost-induced soil biochemical responses in tropical savanna soils remains poorly understood. This study investigated how physiographic position modulates compost-induced changes in soil moisture, estimated redox potential (Eh), microbial frequency of occurrence, enzyme activities, nutrient uptake, and vegetative growth of okra (*Abelmoschus esculentus* L.) in a southern Guinea savanna soil. A 3 × 2 factorial screenhouse experiment comprising three physiographic positions (crest, backslope, and toeslope) and two compost levels (0 and 20 t ha^{-1}) arranged in a completely randomised design with three replications was conducted over eight weeks. The compost was produced through aerobic decomposition for 12 weeks before application. Compared with the unamended control, compost amendment significantly increased soil moisture, cellulase and protease activities, nutrient uptake, and vegetative growth across all physiographic positions ($P \leq 0.05$). Soil moisture consistently followed the order toeslope > backslope > crest, whereas moisture-derived estimates of Eh exhibited an inverse trend. At 8 WAP, enzyme activities were highest in compost-amended toeslope soils and were positively associated with soil moisture, nutrient uptake, and growth variables. In contrast, fungal and bacterial frequencies displayed weak relationships with enzyme activities and plant performance. Compost application increased nitrogen, phosphorus, and potassium uptake by 28-36%, resulting in improved plant height, stem girth, leaf production, leaf area, and leaf area index. These findings suggest that landscape position influences the agronomic effectiveness

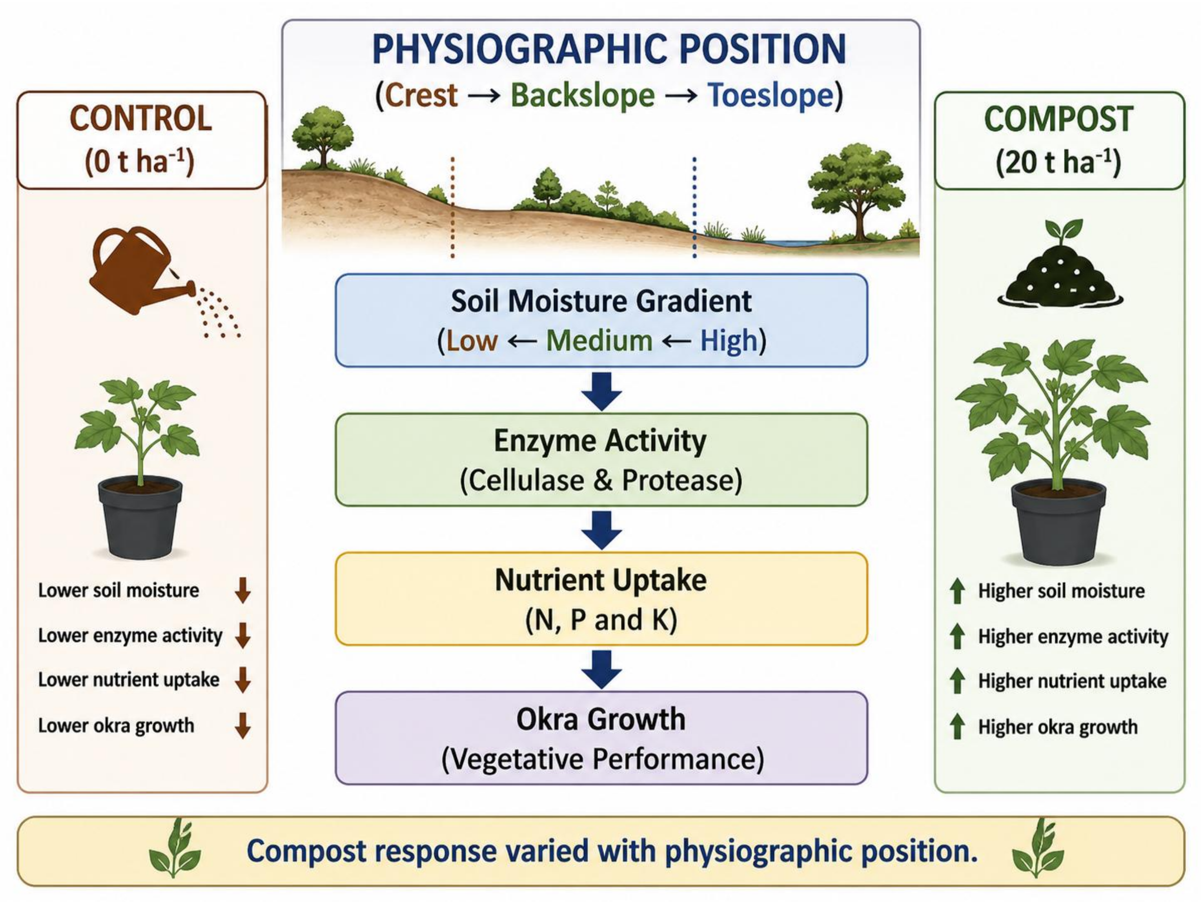
of poultry-manure compost through differences in soil moisture availability and associated biochemical processes, highlighting the need for site-specific organic amendment strategies in tropical agroecosystems.

Keywords: Toposequence, Organic amendment, Soil moisture, Enzyme activity, Nutrient cycling, *Abelmoschus esculentus*, Southern Guinea Savanna

Highlights

i. Physiographic position influenced soil and plant responses to compost application.
ii. Compost increased soil moisture, enzyme activity, nutrient uptake, and okra growth.
iii. Enzyme activity showed stronger associations with plant performance than microbial frequency.
iv. Soil moisture patterns varied consistently across crest, backslope, and toeslope positions.
v. Landscape position should guide compost-based fertility management strategies.

Graphical Abstract



Introduction

Sustainable soil fertility management remains a major challenge in tropical agroecosystems, where continuous cultivation, nutrient depletion, and declining soil organic matter often constrain crop productivity. Organic amendments such as compost are widely promoted as environmentally sustainable alternatives to sole reliance on mineral fertilisers because they improve soil structure, increase organic matter content, enhance nutrient retention, and stimulate biological activity (Zhou et al., 2021; Yang et al., 2023). Among organic amendments, poultry-manure-based compost is particularly valued because of its relatively high nutrient content and its capacity to support microbial processes involved in nutrient cycling (Adewole and Ilesanmi, 2012; Nengi-Benwari and Abah, 2025). However, the effectiveness of compost application is often influenced by local soil and environmental conditions, resulting in variable crop responses across landscapes (Belay et al., 2025; Cai et al., 2025). Okra (*Abelmoschus esculentus* L. Moench) is an economically important vegetable crop requiring adequate nutrient supply and favourable soil conditions for optimum growth. Soil conditions that restrict nutrient availability, microbial activity, or root development can substantially reduce crop performance (Adekiya et al., 2020; Ahmed et al., 2023; Huang et al., 2025). Therefore, management practices that improve soil biological activity and nutrient supply are essential for sustainable okra production, particularly in tropical soils where fertility constraints are common (Borowik & Wyszkowska, 2016; Zhang et al., 2018; Bufebo et al., 2021; Bogati et al., 2025).

Landscape position is an important source of spatial variability in soil properties and ecological processes. Along toposequences, differences in elevation and slope influence water movement, soil moisture distribution, aeration status, organic matter accumulation, and nutrient dynamics (Bufebo et al., 2021; Suvendran et al., 2025). Crest positions are often characterised by lower moisture retention and greater drainage, whereas lower slope positions, such as backslopes and toeslopes, generally accumulate water and dissolved materials transported from upslope areas. These variations create distinct soil microenvironments that can influence microbial activity, enzyme expression, nutrient transformations, and plant nutrient acquisition (Bhanwaria et al., 2022; Omokaro, 2023). The application of mature compost can further modify these soil environments by supplying organic substrates, improving aggregate stability, and increasing soil water-holding capacity. Compost amendments frequently stimulate the development of microbial communities involved in decomposition and nutrient cycling. Previous studies have identified fungal genera such as *Aspergillus, Penicillium, Trichoderma,* and *Cladosporium*, and bacterial groups including *Bacillus, Pseudomonas,* and *Streptomyces*, as important decomposers of organic residues which contribute to the release of plant-available nutrients (Chauhan et al., 2023; Chen et al., 2023). Soil enzymes such as cellulase and protease serve as important indicators of microbial functioning because they participate directly in carbon decomposition and nitrogen mineralisation processes (Li et al., 2021; Chen et al., 2023; Xu et al., 2023). Their activities are influenced by environmental conditions, particularly soil moisture and aeration status, which vary across landscape positions (Tamura and Suseela, 2021; Solangi et al., 2024).

Despite substantial evidence that compost improves soil fertility and crop performance, relatively few studies have examined how physiographic position influences compost-mediated changes in soil biological activity, nutrient dynamics, and plant growth within tropical savanna environments (Bhattacharyya & Furtak, 2023; Huang et al., 2025). Most previous studies have focused either on amendment effects or on landscape effects independently, providing limited information on how these factors interact to influence soil functioning and crop response (Frimpong et al., 2017; Adekiya et al., 2020; Ahmed et al., 2023; Huang et al., 2025). Furthermore, information remains scarce regarding the relationships among soil moisture conditions, estimated redox status, microbial occurrence, enzyme activity, nutrient uptake, and vegetative growth under compost amendment across contrasting slope positions. This study was conducted to evaluate the influence of physiographic position on compost-induced changes in soil biological activity, nutrient uptake, and vegetative growth of okra in a southern Guinea savanna soil. Therefore, the study hypothesised that compost application would enhance soil biological functioning and plant performance across all slope positions, but that the magnitude of these responses would vary among physiographic positions because differences in soil moisture availability create contrasting soil environmental conditions (Dorau et al., 2018; Elbl et al., 2019; Guo et al., 2022).

Specifically, the objectives were to: (i) assess the physicochemical characteristics and maturation dynamics of poultry-manure-based compost; (ii) evaluate changes in soil moisture, estimated redox potential, microbial frequency, and enzyme activity following compost application across physiographic positions; (iii) determine the effects of compost and slope position on nutrient uptake and vegetative growth of okra; and (iv) examine relationships among soil environmental variables, biological indicators, nutrient uptake, and plant growth. The findings are expected to contribute to the development of landscape-specific organic amendment strategies for improving soil fertility and crop productivity in tropical agroecosystems. To our knowledge, few studies have simultaneously evaluated compost-induced changes in soil moisture, enzyme activity, microbial occurrence, nutrient uptake and crop growth across contrasting physiographic positions in tropical savanna soils. By integrating these variables within a single experimental framework, the present study provides new insights into how landscape-driven hydro-environmental heterogeneity regulates the agronomic effectiveness of poultry-manure compost.

Materials and Methods

Study area and soil sampling

The study was carried out in the screenhouse of the Department of Agronomy, Faculty of Agriculture, University of Ilorin, Nigeria (8º29′ N, 4º40′ E; 307 m above sea level), located within the southern Guinea savanna agroecological zone. The region is characterised by a tropical wet-and-dry climate with mean annual rainfall of approximately 1200 mm and average temperatures ranging from 25 to 34 °C.

Surface soils (0-20 cm) were collected from three physiographic positions within the University of Ilorin Teaching and Research Farm: crest (8º29′35″ N, 4º39′55″ E), backslope (8º29′28″ N, 4º40′05″ E) and toeslope (8º29′22″ N, 4º40′13″ E). Five subsamples were collected along a 50 m transect at each position using a soil auger and composited to obtain representative samples. Soils were transported to the laboratory immediately after collection. Samples designated for physicochemical analyses were air-dried, gently crushed, and passed through a 2-mm sieve. Samples intended for microbial and enzyme analyses were stored at 4 °C and analysed within seven days of collection to minimise alterations in microbial activity. Particle-size distribution was determined using the Bouyoucos hydrometer method (Gee & Bauder, 1986), and soil textural classes were assigned using the USDA textural triangle. Baseline soil properties, including pH, moisture content, bulk density, organic carbon, total nitrogen, available phosphorus, exchangeable potassium, calcium, magnesium, and sodium, were determined before compost application (Table 1). Particle-size distribution and corresponding USDA textural classes are presented in Table 2.

Poultry manure-based compost production and characterisation.

Compost was prepared from poultry manure, grass clippings, rice bran, cassava peels, and sawdust using an aerobic composting system. Poultry manure was obtained from the University of Ilorin Teaching and Research Farm, while plant residues were sourced from local agricultural processing centres and markets within Ilorin. Feedstocks were mechanically shredded. Poultry manure and plant residues were combined at an overall ratio of 1:5 (w/w). Materials were layered sequentially in a cylindrical pit (50 cm × 100 cm) equipped with a perforated central aeration chamber to facilitate passive airflow. Moisture content during composting was maintained at approximately 60% water-holding capacity, determined gravimetrically. Moisture losses were replenished using measured volumes of water whenever moisture content fell below the target level. Compost piles were manually turned every two days during the thermophilic phase and weekly thereafter.

Temperature was monitored twice weekly using a calibrated compost thermometer inserted into the centre of the pile. Compost samples were collected at weeks 0, 2, 4, 6, 8, 10, and 12 for analysis. Organic carbon was determined using the Walkley and Black (1934) method, total nitrogen by the Kjeldahl procedure (Bremner, 1965), available phosphorus by the Bray-1 extraction method (Bray and Kurtz, 1945), and exchangeable bases using 1 M ammonium acetate extraction (Black, 1965). Heavy metals were quantified following wet HNO_3-$HClO_4$ digestion and atomic absorption spectrophotometry. Compost pH was measured in a 1:2.5 compost-to-water suspension. At week 12, mature compost was air-dried, sieved through a 2-mm mesh, and analysed for proximate composition according to AOAC (2004). Carbohydrates were computed by difference following FAO (2004):

$$\%Carbohydrate = 100 - (\%Moisture + \%Ash + \%Protein + \%Fat)$$

The physicochemical properties of the feedstocks and the temporal changes in compost properties, heavy metal concentrations, and exchangeable bases are presented in Tables 3, 4, 5 and 6. All heavy metal concentrations in mature compost remained below internationally recommended limits for agricultural application (FAO, 2003).

Experimental design and screenhouse conditions

The experiment was arranged as a 3 × 2 factorial in a completely randomised design (CRD), consisting of three physiographic positions (crest, backslope, and toeslope) and two compost levels (0 and 20 t ha^{-1}). Each treatment combination was replicated three times, resulting in eighteen experimental units. Plastic pots (15 cm diameter) containing 5 kg of soil were used as experimental units. Compost was incorporated into the upper 10 cm of soil and pre-incubated for two weeks before planting to allow microbial stabilisation. No mineral fertiliser was applied. The screenhouse maintained natural daylight conditions with mean daytime temperatures ranging from 28 to 34 °C and relative humidity between 65 and 80% throughout the study period. Pots were repositioned weekly to minimise positional effects within the screenhouse. Field capacity was determined using the gravimetric drainage method. Saturated soils were allowed to drain freely for 48 h, after which the moisture content was determined. Soil moisture was maintained at approximately field capacity throughout the experiment by daily weighing of pots and replenishing water losses with measured volumes of water.

Planting and growth measurements

Seeds of okra (*Abelmoschus esculentus* L. Moench., variety Clemson Spineless) used in this study were obtained from a certified seed supplier in Ilorin, Nigeria. Three seeds were sown per pot and later thinned to one healthy seedling. Plant height, stem girth, and number of leaves were recorded at 2, 4, 6, and 8 weeks after planting. Leaf area was estimated using the relationship:

$$Leaf\ Area = Length \times Width \times 0.62 \qquad \textit{Equation 1}$$

where 0.62 is the crop correction factor for okra as described by Montgomery (1911) and subsequent agronomic studies. Leaf area index was calculated as the ratio of leaf area to ground area occupied by the plant.

Soil moisture and estimated redox potential

Soil moisture content was measured gravimetrically at 2-week intervals throughout the experiment. Redox potential (Eh) was not directly measured using platinum electrodes in this study. Instead, Eh values were estimated empirically from soil moisture content using site-specific regression models. Empirical prediction of Eh from moisture or water-filled pore space has been applied in ecological and soil biogeochemical studies where direct electrode measurements are unavailable (Patrick & Reddy, 1978; Husson, 2013; Khan & Hossain, 2020).

Given the well-established inverse relationship between soil aeration and moisture content, separate linear models were fitted for each physiographic position (crest, backslope, toeslope), incorporating soil moisture and compost level as predictors (Masschelyleyn et al., 1991; Reddy & DeLaune, 2008).

The general model was:

$$Eh\ (mV)\ = a - b\ (moisture) + c\ (compost) \qquad \textit{Equation 2}$$

was fitted using ordinary least squares (OLS) for each slope position. Compost was coded as 0 (control) or 1 (20 t ha^{-1}).

where Eh represents estimated redox potential (mV), a is the intercept, b represents the rate of Eh decline per unit increase in soil moisture, and c represents the compost-induced redox adjustment factor.

These models provide relative comparisons of redox dynamics across slope positions but should be interpreted as predictive approximations rather than direct electrochemical measurements. Thus, associations between Eh and other variables should be interpreted within the context of model-derived estimation rather than independently measured redox potential. The moisture content and corresponding estimated Eh values for the three physiographic positions are shown in Table 7.

Microbial occurrence and enzyme analyses

Soil samples were collected from each experimental unit at 0, 2, 4, 6, and 8 WAP for microbiological and enzyme analyses. Soil samples collected from each pot constituted biological replicates (n=3), whereas triplicate plates served as analytical replicates. Although measurements were obtained at 0, 2, 4, 6, and 8 WAP, only data collected at 8 WAP are presented because this sampling coincided with crop harvest and therefore provided an integrative assessment of soil biological functioning in relation to nutrient uptake, vegetative growth and post-harvest soil fertility. Temporal trends observed at earlier sampling periods were generally consistent with patterns recorded at 8 WAP. Bacterial populations were isolated using nutrient agar and incubated at 35 ± 2 °C for 24-48 h. Fungal populations were isolated on potato dextrose agar amended with streptomycin and incubated at 28 ± 2 °C for 72-120 h. Microorganisms were identified using standard cultural, morphological, and biochemical characteristics following procedures described by Cappuccino and Sherman (2014).

Frequency of occurrence was calculated as:

$$Frequency\ (\%)\ = \frac{Number\ of\ isolates\ of\ a\ species}{Total\ isolates\ recovered} \times 100 \qquad \textit{Equation 3}$$

Cellulase activity was determined using the dinitrosalicylic acid method, while protease activity was determined using casein hydrolysis following the procedures of Tabatabai (1994) and Alef and Nannipieri (1995). Enzyme activities were expressed as μg glucose g^{-1} soil h^{-1} and μg g^{-1} soil h^{-1}, respectively.

Nutrient uptake and post-harvest soil analysis

Plants were harvested at eight weeks after planting. Shoots and roots were washed, oven-dried at 65 °C to a constant weight, and then ground for nutrient analysis. Nitrogen concentration was determined by the Kjeldahl method (Bremner, 1965), phosphorus by the molybdenum blue procedure (Murphy and Riley, 1962), and potassium by flame photometry (Black, 1965). Nutrient uptake was calculated as:

$$Uptake\ (mg\ plant^{-1}) = Dry\ matter\ yield\ (g\ plant^{-1}) \times Nutrient\ concentration\ (mg\ g^{-1})$$

Equation 4

Following harvest, soils were sampled and analysed for pH, organic carbon, total nitrogen, available phosphorus, and exchangeable potassium using standard procedures.

Statistical analysis

Data were analysed using GenStat version 12 (VSN International Ltd, Hemel Hempstead, UK). Treatment effects were evaluated using two-way analysis of variance (ANOVA) appropriate for a 3 × 2 factorial arrangement in a completely randomised design, with physiographic position (crest, backslope and toeslope) and compost level as fixed factors. Vegetative variables measured at 0, 2, 4, 6 and 8 weeks after planting (WAP) were analysed separately for each sampling occasion, and temporal trends were illustrated graphically to facilitate comparison of treatment responses during crop growth. Microbial frequency and enzyme activity were monitored at 0, 2, 4, 6 and 8 WAP using repeated sampling from the same experimental units. However, only observations obtained at 8 WAP were graphically illustrated in this study because it represented the terminal growth stage and allowed direct evaluation of associations among soil biological indicators, nutrient uptake, vegetative growth and post-harvest soil properties. Means were separated using Tukey's Honest Significant Difference (HSD) test at $P \leq 0.05$ whenever ANOVA indicated significant treatment effects. Pearson correlation coefficients were used as exploratory analyses to identify associations among soil moisture, moisture-derived estimates of redox potential, microbial frequency of occurrence, cellulase activity, protease activity, nutrient uptake, and vegetative growth variables. Because redox potential values were derived from moisture-based predictive models rather than direct electrode measurements, correlations involving estimated Eh were interpreted as associations with relative hydro-environmental conditions rather than direct electrochemical responses. Graphical presentations, including temporal response curves and a correlation heat map, were produced using GraphPad Prism version 8.0.2.

Results

Baseline soil physicochemical properties across physiographic positions

Significant differences were observed among the three physiographic positions before compost application (Table 1). Soil moisture, organic carbon, total nitrogen, available phosphorus and exchangeable bases increased progressively downslope, whereas bulk density decreased. The toeslope contained the highest levels of soil moisture (18.5%), organic carbon (22.0 g kg^{-1}), total nitrogen (1.9 g kg^{-1}) and available phosphorus (16 mg kg^{-1}), while the crest recorded the lowest values. These differences indicate pre-existing hydro-environmental heterogeneity among the three physiographic positions before compost application. The crest and backslope soils were classified as sandy loam, whereas the toeslope soil was sandy clay loam, reflecting greater clay accumulation in the lower landscape position (Table 2).

Table 1: Baseline physicochemical properties of soils across crest, backslope, and toeslope positions before compost application

Sampling points	Moisture	pH	Bulk Density	Organic C	Total N	Available P	C/N ratio	K	Ca	Mg	Na
	(%)		(kg m^{-3})		(mg kg^{-1})				(cmol kg^{-1})		
Crest	8.5	6.2	1520	15000	1200	9	12.5	0.19	4.25	1.15	0.13
Backslope	12.0	6.5	1310	18500	1500	12	12.3	0.28	6.00	1.65	0.20
Toeslope	18.5	6.8	1030	22000	1900	16	11.6	0.38	8.00	2.30	0.26
Tukey HSD ($P \leq 0.05$)	**0.076*****	**0.089*****	**2.749*****	**1049.20*****	**8.950*****	**0.549*****	**0.087***	**0.0004*****	**0.033*****	**0.014*****	**0.001*****

*** = significance at $P \leq 0.001$; * = significance at $P \leq 0.05$

Table 2: Particle-size distribution and textural classes of soils from crest, backslope, and toeslope positions

Sampling points	Sand	Silt	Clay	Textural class
		(%)		
Crest	68	18	14	Sandy loam
Backslope	65	16	19	Sandy loam
Toeslope	58	14	28	Sandy clay loam

Compost feedstock characteristics and maturation dynamics

The compost feedstocks differed significantly in their physicochemical composition (Table 3). Poultry manure contained the highest nutrient concentrations and lowest C: N ratio, whereas sawdust had the highest organic carbon content and the widest C: N ratio. During composting, temperature increased rapidly from 28.5 °C at initiation to 68.9 °C after two weeks before declining progressively to 29.0 °C at week 12 (Table 4). Organic carbon decreased by 47.7%, whereas total nitrogen and available phosphorus increased by 43.2% and 100%, respectively. Consequently, the C: N ratio declined from 17.4 to 6.4, indicating compost stabilisation and maturity. Apparent reductions in extractable heavy metal concentrations and progressive increases in exchangeable Ca, Mg, K and Na were observed throughout composting (Table 5). The mature compost contained 25% ash, 16% crude fibre and 23.2% carbohydrate (Table 6).

Table 3: Physicochemical characteristics of compost feedstocks used in formulation

Parameters	Moisture	pH	Bulk Density	Organic C	Total N	Ash	C/N ratio	Available P	K	Ca	Mg	Na
	(%)		(kg m^{-3})		mg kg^{-1}					cmol kg^{-1}		
Poultry Manure	70.2	7.1	550	380000	26500	250000	14.34	4800	12.28	107.50	289.30	36.52
Cassava Peels	68.5	5.3	420	410000	9200	60000	44.57	2300	5.88	79.00	78.97	20.43
Saw Dust	55.7	5.8	310	465000	2100	20000	221.43	900	2.30	17.50	34.57	6.96
Rice Bran	64.3	6.2	380	395000	11800	100000	33.47	2700	6.90	91.00	119.34	26.96
Grass Clippings	73.9	6.5	290	360000	17200	120000	20.93	3100	7.93	98.00	105.36	22.17
Tukey HSD ($P \leq 0.05$)	**0.071*****	**0.067*****	**2.530*****	**129.7*****	**197.1*****	**1025.5*****	**0.472*****	**8.470*****	**6.820*****	**4.700*****	**9.390*****	**7.006*****

*** = significance at $P \leq 0.001$

Table 4: Temporal variation in physicochemical properties of composting materials during aerobic decomposition (0-12 weeks)

Time	Temperature	pH	Moisture content	Total N	Total OC	Available P	C/N ratio
(week)	(°C)		(%)		mg kg^{-1}		
0	28.50	6.80	55.00	1480	25800	450	17.4
2	68.87	7.52	35.70	1580	23600	520	14.6
4	62.00	7.21	34.31	1830	21400	610	11.7
6	48.00	7.16	33.07	1950	19800	700	10.2
8	39.50	7.05	31.90	2010	18200	780	9.1
10	33.00	6.95	30.80	2070	16700	840	8.1
12	29.00	6.85	29.50	2120	13500	900	6.4
Tukey HSD (P ≤ 0.05)	**0.568*****	**0.066*****	**0.346*****	**2.963*****	**109.8*****	**4.359*****	**0.066*****

*** = significance at P ≤ 0.001

Table 5: Temporal changes in extractable heavy metal concentrations and exchangeable base cations during composting (0-12 weeks)

Time	Extractable heavy metal concentrations						Exchangeable bases			
(week)	(mg kg^{-1})						(cmol kg^{-1})			
	Zn	Pb	Cd	Cr	Cu	Ni	Ca	Mg	K	Na
0	145	62	4.8	22	118	18	12.5	4.2	2.8	0.6
2	132	56	4.2	20	110	16	13.6	4.5	3.4	0.7
4	120	49	3.7	18	101	14	14.4	4.9	4.0	0.8
6	109	43	3.3	16	94	13	15.1	5.2	4.5	0.9
8	98	38	2.9	15	87	12	15.8	5.5	4.8	1.0
10	89	34	2.6	14	81	10	16.3	5.7	5.0	1.0
12	82	30	2.3	12	75	9	16.7	5.9	5.2	1.1
Tukey HSD (P ≤ 0.05)	**0.872*****	**0.655*****	**0.141*****	**0.491*****	**0.097*****	**0.412*****	**0.146*****	**0.083*****	**0.056*****	**0.072*****

*** = significance at P ≤ 0.001

Table 6: Proximate composition of matured compost at week 12 (wet basis)

Parameters	% Composition (w/w)
Moisture	32.00
Ash	25.00
Protein	1.33
Fat	2.50
Crude fibre	16.00
Carbohydrates	23.17

Soil moisture and estimated redox dynamics under compost application

Compost amendment significantly increased soil moisture across all physiographic positions throughout the experimental period (Table 7). Moisture consistently followed the order toeslope > backslope > crest irrespective of sampling time. Moisture-derived estimates of redox potential showed an inverse relationship with soil water content, with lower estimated Eh values occurring in wetter soils and under compost amendment. By 8 WAP, moisture content in compost-amended soils reached 20.47%, 23.60% and 27.80% at the crest, backslope and toeslope, respectively, compared with corresponding Eh values of 449, 414 and 371 mV. Compost amendment significantly increased soil moisture and decreased moisture-derived estimates of Eh across physiographic positions, although significance levels varied among positions.

Table 7: Soil moisture content (%) and redox potential (Eh, mV) across physiographic positions under compost treatments during 8 weeks of okra growth

Time	Compost level	Crest		Backslope		Toeslope	
		Moisture	Eh	Moisture	Eh	Moisture	Eh
(week)	($t\ ha^{-1}$)	(%)	mV	(%)	mV	(%)	mV
0	Control (0)	15.80	522.00	18.80	488.00	22.30	434.00
	20	17.20	514.00	20.30	476.00	24.50	425.67
2	Control (0)	16.27	511.00	19.50	472.00	23.10	421.00
	20	18.93	498.33	21.80	455.67	25.17	409.00
4	Control (0)	17.10	496.33	20.57	461.00	23.90	405.67
	20	19.60	472.33	22.50	436.33	26.50	396.00
6	Control (0)	17.77	478.00	21.20	448.00	24.67	392.33
	20	20.07	455.33	23.10	422.33	27.20	384.33
8	Control (0)	18.17	465.00	21.80	438.00	25.10	379.00
	20	20.47	449.00	23.60	414.00	27.80	371.33
Tukey HSD ($P \leq 0.05$)		**0.349*****	**3.463*****	**0.276****	**2.950*****	**0.268****	**3.125***

*** = significance at $P \leq 0.001$; ** = significance at $P \leq 0.01$; * = significance at $P \leq 0.05$

Occurrence patterns of dominant microbial taxa across physiographic positions

At 8 WAP, frequencies of fungal and bacterial taxa were generally higher in compost-amended soils than in the corresponding controls and followed the spatial pattern toeslope > backslope > crest (Figures 1-2). Among fungi, *Aspergillus, Penicillium, Cladosporium, Trichoderma* and *Rhizopus* were the most frequently isolated genera. Similarly, *Bacillus, Pseudomonas, Streptomyces, Enterobacter* and *Paenibacillus* dominated bacterial communities. Despite the consistent increase in microbial frequencies under compost amendment, subsequent correlation analysis revealed weak associations between microbial occurrence and plant performance variables.

Soil enzyme activities

Cellulase and protease activities at 8 WAP were significantly higher in compost-amended soils than in the corresponding controls across all physiographic positions (Figure 3). Enzyme activities were consistently highest in the toeslope and lowest in the crest, and their distribution closely reflected the pattern observed for soil moisture.

Vegetative growth responses of okra

Compost significantly improved all vegetative growth parameters measured during the experiment (Figures 4-5). Plant height, stem girth, leaf number, leaf area and leaf area index increased progressively with plant age and were consistently greater in compost-amended soils. Growth responses followed the same physiographic trend observed for soil moisture and enzyme activity, with the greatest values recorded in the toeslope, intermediate values in the backslope and the lowest values in the crest. Significant effects of compost, physiographic position and their interaction were detected for most growth variables ($P \leq 0.05$).

Nutrient Uptake by Okra

Nitrogen, phosphorus and potassium uptake increased significantly following compost application across all physiographic positions (Table 8). Compared with the control, compost increased nitrogen uptake by 28-36%, phosphorus uptake by 24-35%, and potassium uptake by 20-28%. Nutrient uptake was generally greater in backslope soils and was enhanced in compost-amended toeslope soils compared with the crest position, indicating greater nutrient acquisition in the more favourable hydro-environmental condition.

Table 8: Nitrogen, phosphorus, and potassium uptake by okra under compost treatments across physiographic positions

Physiographic positions	Compost level	N	P	K
	($t\ ha^{-1}$)		mg plant^{-1}	
Crest	Control (0)	35.63	18.70	26.80
	20	48.27	26.40	33.93
Backslope	Control (0)	44.73	24.10	34.83
	20	58.43	32.57	41.70
Toeslope	Control (0)	42.10	21.30	31.60
	20	55.20	29.40	38.90
Tukey HSD (P ≤ 0.05)		**0.550***	**0.387***	**0.402***

* = significance at $P \leq 0.05$

Post-harvest soil fertility status

Post-harvest soil analyses showed significant improvements in soil fertility following compost application (Table 9). Compost-amended soils exhibited higher pH, organic carbon, total nitrogen, available phosphorus and exchangeable potassium than the corresponding controls. Across all physiographic positions, increases in organic carbon ranged from 18 to 31%, while total nitrogen increased by 18-30%. Available phosphorus and exchangeable potassium also increased substantially, demonstrating residual fertility benefits of the compost amendment.

Table 9: Post-harvest soil properties under compost treatments across physiographic positions following okra cultivation

Slope positions	Compost level	pH	Organic C	Total N	Available P	Exchangeable K
	($t\ ha^{-1}$)			($mg\ kg^{-1}$)		$cmol\ kg^{-1}$
Crest	Control (0)	6.50	9400	902	10.47	0.38
	20	6.80	12100	1201	14.77	0.51
Backslope	Control (0)	6.60	10200	1002	12.37	0.44
	20	7.10	13400	1310	17.87	0.58
Toeslope	Control (0)	6.70	10800	1102	13.67	0.47
	20	7.00	12800	1201	16.47	0.55
Tukey HSD (P ≤ 0.05)		**0.178***	**217.9*****	**13.09*****	**0.272*****	**0.018*****

*** = significance at $P \leq 0.001$; ** = significance at $P \leq 0.01$; * = significance at $P \leq 0.05$

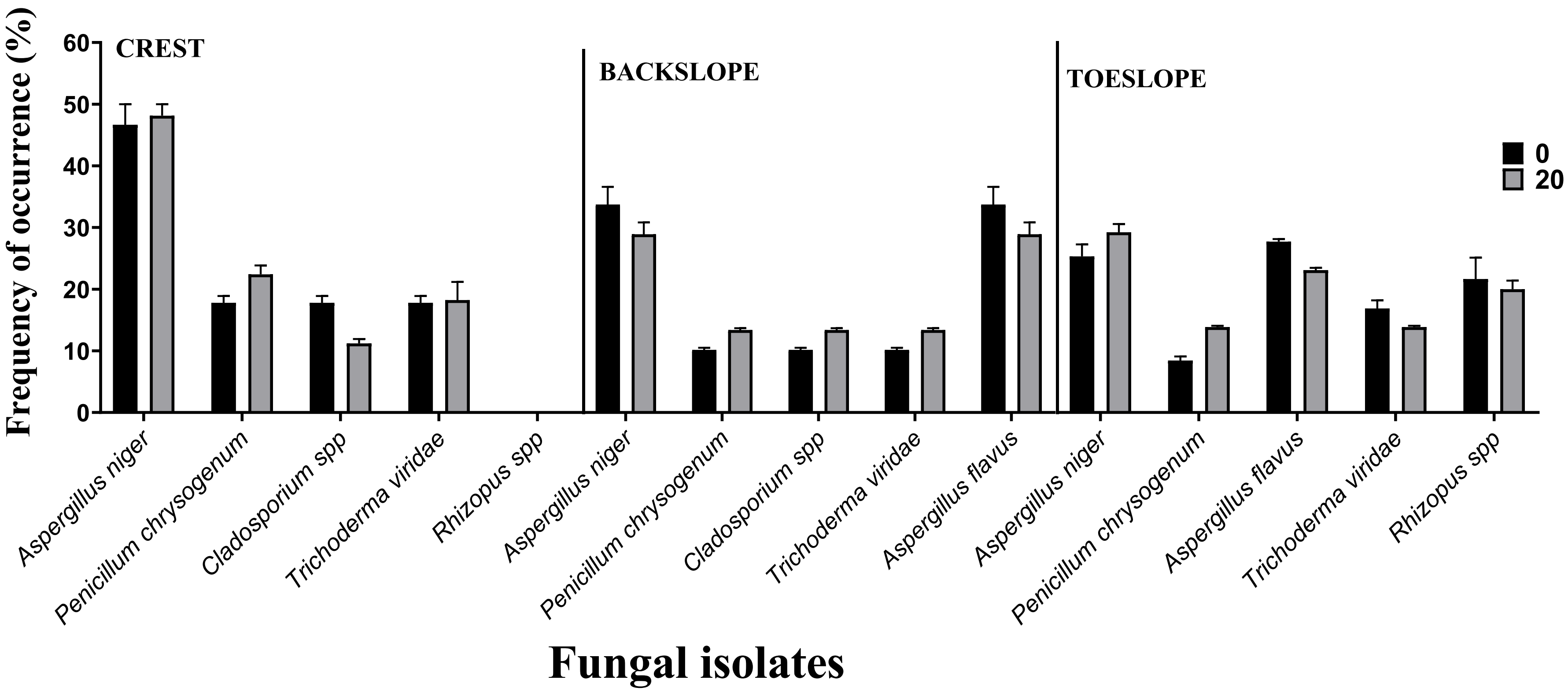


Figure 1: Frequency of occurrence (%) of dominant fungal taxa in crest, backslope, and toeslope soils under 0 and 20 t ha^{-1} poultry-manure compost at 8 weeks after planting.

Error bars = standard errors of the mean (n=3), 20 = applied at 20 t ha^{-1}, 0 = control 0 t ha^{-1}

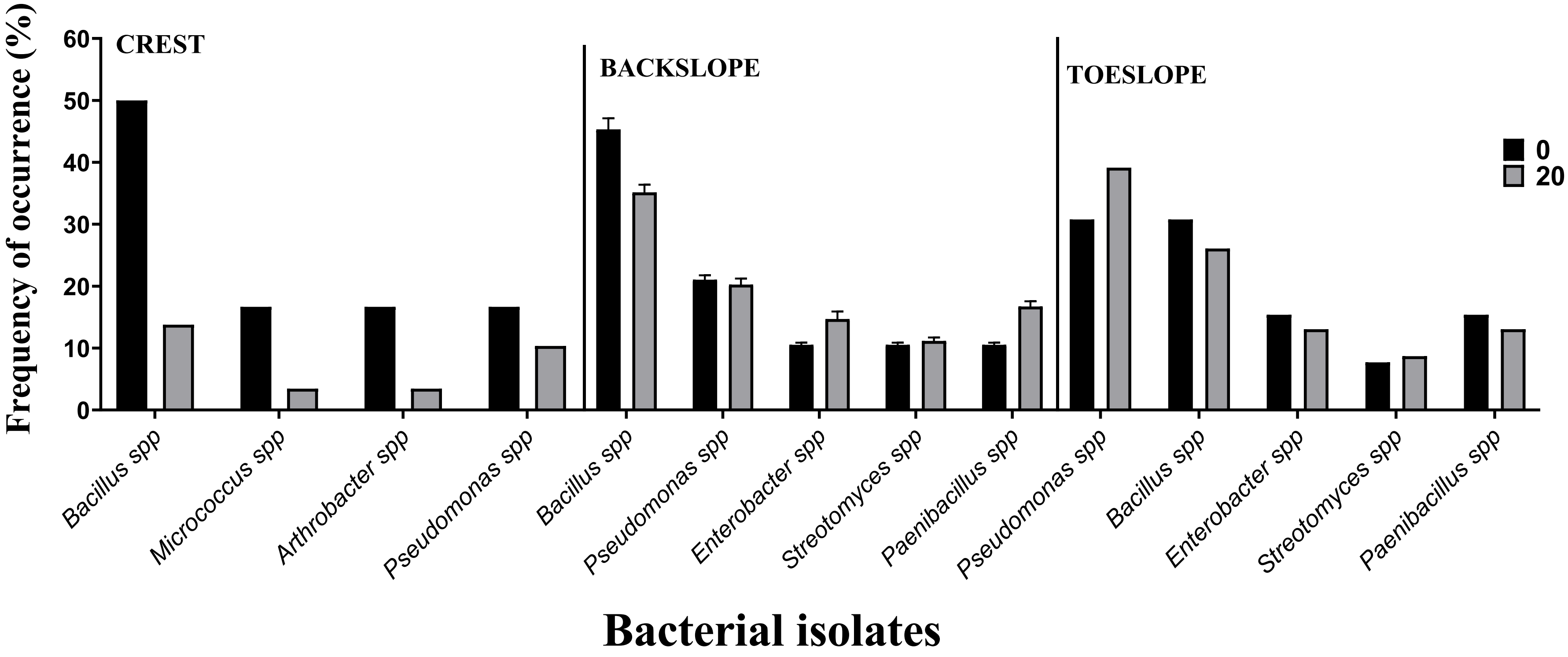


Figure 2: Frequency of occurrence (%) of dominant bacterial taxa in crest, backslope, and toeslope soils under 0 and 20 t ha^{-1} poultry-manure compost at 8 weeks after planting.

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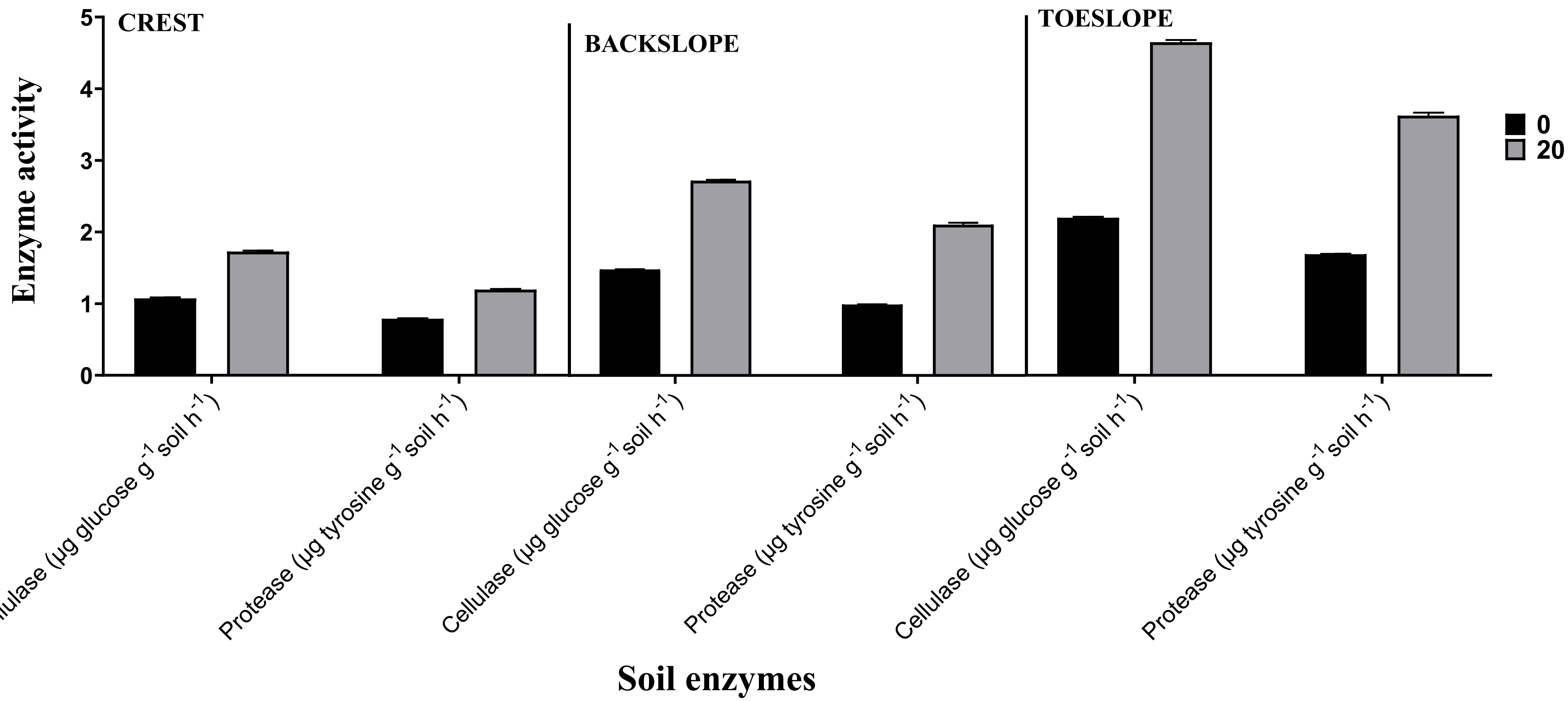

Figure 3: Cellulase and protease activities in crest, backslope, and toeslope soils receiving 0 or 20 t ha^{-1} poultry-manure compost at 8 weeks after planting.

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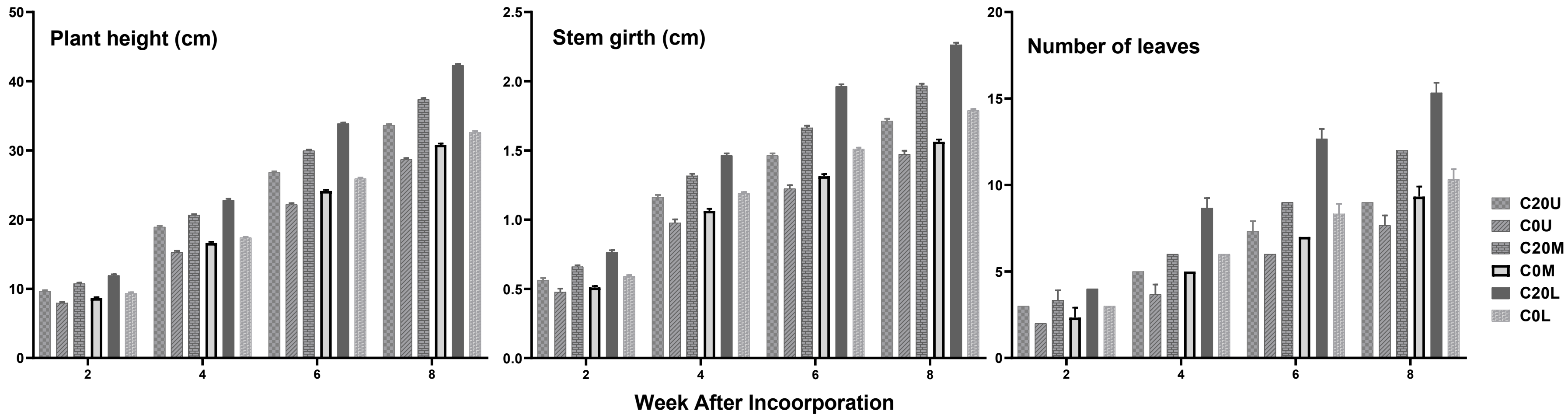

Figure 4: Temporal variation in plant height, stem girth, and number of leaves of okra under compost amendment across physiographic positions during eight weeks of growth.

C = poultry-manure-based compost, 20 = applied at 20 t ha^{-1}, 0 = control 0 t ha^{-1}, U = crest position, M = backslope position, L = toeslope position

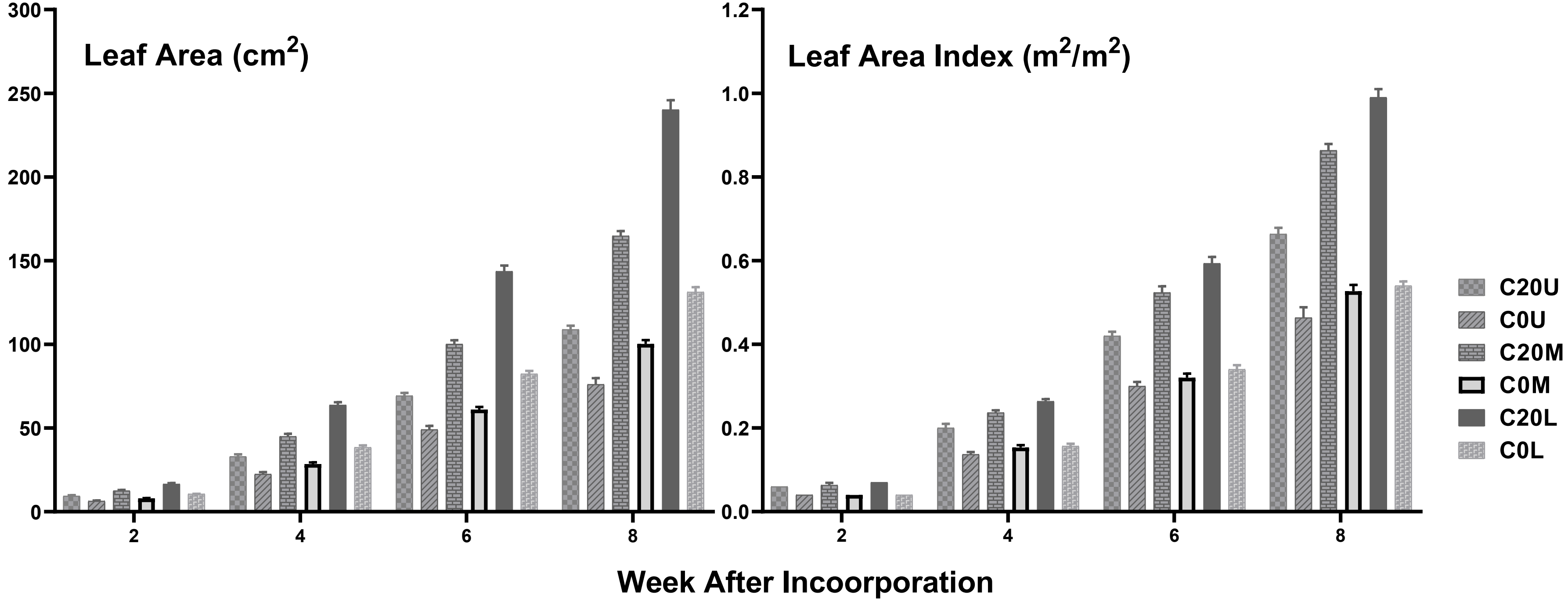

Figure 5: Temporal variation in leaf area and leaf area index of okra under compost amendment across physiographic positions during eight weeks of growth

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Relationships among hydro-environmental conditions, enzyme activity, nutrient uptake and plant growth

Pearson correlation analyses based on pooled observations collected at 8 weeks after planting (n=18) revealed strong relationships among soil moisture, moisture-derived estimates of redox potential, enzyme activities, nutrient uptake and plant growth variables (Figure 6). Soil moisture positively correlated with cellulase activity, protease activity, nutrient uptake and vegetative growth variables (r = 0.88-0.99), whereas moisture-derived estimates of redox potential were negatively associated with these parameters (r = –0.78 to –0.98). Conversely, fungal and bacterial frequencies showed weak or non-significant associations with enzyme activities, nutrient uptake and growth parameters.

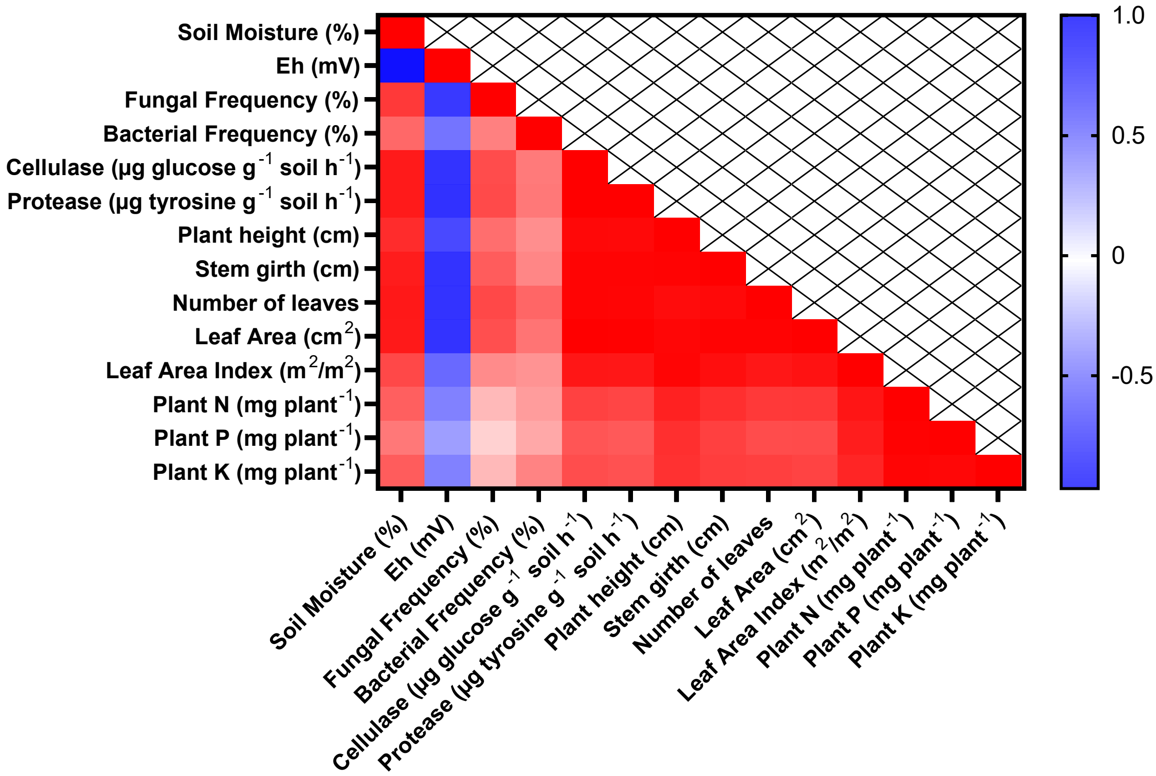

Figure 6: Pearson correlation heat map showing relationships among soil moisture, moisture-derived redox potential, enzyme activities, nutrient uptake and vegetative growth parameters based on pooled observations collected at 8 weeks after planting (n = 18).

Correlation coefficients ranged from -1 to +1, where dark blue indicates strong negative correlations, white indicates no correlation, and dark red indicates strong positive correlations.

Discussion

Compost maturation and quality of the organic amendment

The temporal changes observed during composting indicate successful aerobic decomposition and the production of a stable, mature poultry-manure-based compost. The rapid temperature increase during the early stages of composting reflects intense microbial degradation of readily available organic substrates, while the subsequent decline toward ambient temperature indicates progression into the curing phase. Similar thermophilic patterns have been reported during poultry manure composting and are widely recognised as indicators of effective organic matter decomposition (Papale et al., 2021; Wang et al., 2024). The progressive decline in organic carbon, coupled with increases in total nitrogen and available phosphorus, resulted in a marked reduction in the C: N ratio from 17.4 to 6.4, confirming compost stabilisation and maturity (Jakubus, 2020; Ouali et al., 2025). Apparent reductions in extractable heavy metal concentrations were observed throughout composting, possibly due to immobilisation within humified organic fractions, adsorption onto newly formed organo-mineral complexes, and changes in compost mass during decomposition. The apparent decrease in extractable heavy metal concentrations and increase in exchangeable Ca, Mg, K and Na further enhanced compost quality. These changes are consistent with nutrient concentration through organic matter degradation, humification processes and metal immobilisation mechanisms that improve the agronomic value of composted materials (Okoro et al., 2025).

Physiographic influences on soil moisture and estimated redox conditions

Physiographic position strongly influenced soil moisture dynamics throughout the study. Moisture content consistently followed the pattern toeslope > backslope > crest, reflecting the redistribution and accumulation of water along the landscape gradient (Omokaro, 2023; Okebalama et al., 2025). Compost application further increased moisture retention across all positions, likely due to improvements in soil aggregation, porosity and water-holding capacity, as reported for organic-amended soils (Rasa et al., 2024; Tao et al., 2024). Estimated redox potential exhibited an inverse relationship with soil moisture, with lower moisture-derived estimates of Eh values occurring in wetter soils and under compost application. Although redox potential was estimated from moisture-based models rather than measured directly, the observed patterns are consistent with established relationships between soil water status, aeration and oxygen availability (Dorau et al., 2018; Husson, 2013). These findings suggest that physiographic position influences the hydro-environmental conditions under which soil biological and biochemical processes occur.

Occurrence patterns of dominant microbial taxa and enzyme-mediated nutrient transformations

Compost amendment increased the frequency with which fungal and bacterial taxa were isolated, suggesting a broader distribution of decomposer organisms in amended soils. The dominance of fungal genera such as *Aspergillus, Penicillium, Trichoderma and Rhizopus*, together with bacterial genera including *Bacillus, Pseudomonas* and *Streptomyces*, agrees with previous reports identifying these organisms as important decomposers and contributors to nutrient cycling in organically amended soils (Chauhan et al., 2023; Chen et al., 2023). However, microbial frequency showed weak and non-significant relationships with nutrient uptake and plant growth variables. In contrast, cellulase and protease activities exhibited strong positive associations with soil moisture, nutrient uptake and vegetative growth parameters.

These findings suggest that enzyme activity was more closely associated with nutrient transformations than microbial frequency of occurrence. Cellulase facilitates the decomposition of cellulose-rich organic materials and contributes to carbon turnover, while protease promotes the breakdown of organic nitrogen compounds into plant-available forms (Zhang et al., 2018; Solangi et al., 2024). The higher enzyme activities observed in compost-amended backslope and toeslope soils suggest that favourable moisture conditions may have enhanced microbial functioning and nutrient mineralisation. Therefore, the results support the view that enzyme-mediated processes appear to represent an important mechanism linking compost application with nutrient availability. Temporal trends in microbial occurrence and enzyme activities observed during crop growth generally paralleled the patterns recorded at 8 WAP (data not shown)

Nutrient uptake and vegetative growth responses

The enhanced biochemical activity observed in compost-amended soils translated into significant improvements in nutrient acquisition and vegetative growth of okra. Compost application increased N, P and K uptake across all physiographic positions, indicating improved nutrient availability and utilisation. Similar responses have been reported following the application of poultry-manure-based composts and other organic amendments in tropical cropping systems (Frimpong et al., 2017; Adekiya et al., 2020; Okole et al., 2025). Increased nutrient uptake was accompanied by improvements in plant height, stem girth, leaf number, leaf area and leaf area index, demonstrating the positive influence of compost on plant development.

The magnitude of these responses varied across the physiographic gradient, with backslope and toeslope soils generally outperforming crest soils. This pattern is likely attributable to greater moisture availability, enhanced nutrient diffusion and more favourable conditions for microbial and enzymatic activity in lower landscape positions (Rahman & Thomas, 2021; Liu et al., 2023). The findings therefore demonstrate that physiographic position modifies the efficiency with which compost-derived nutrients are transformed into plant biomass.

Integrated relationships among soil moisture, enzyme activity and crop performance

Correlation analysis based on pooled observations suggested that soil moisture and associated hydro-environmental conditions were closely linked with enzyme activity, nutrient uptake and vegetative growth variables. The strong relationships between enzyme activities and plant performance support the proposition that enzyme-mediated nutrient transformations constituted an important pathway through which compost enhanced crop growth. However, because redox potential was derived from moisture-based predictive models, the observed relationships involving Eh should be interpreted as indicative of coordinated moisture-associated biochemical responses rather than direct evidence of redox regulation.

The weak correlations observed between microbial frequency and plant growth further indicate that microbial occurrence alone is insufficient to explain variations in crop performance. Instead, the results suggest a coordinated soil-plant system in which physiographic position influences soil moisture status, moisture availability was associated with higher enzyme activity and nutrient transformations, and these processes collectively enhance nutrient uptake and plant growth. This interpretation is consistent with contemporary understanding of soil biological functioning in heterogeneous landscapes (Bhanwaria et al., 2022; Chen et al., 2024).

Study limitations and implications

Certain limitations should be considered when interpreting the findings of this study. Redox potential was estimated using moisture-based regression models rather than measured directly using platinum electrodes; therefore, the reported Eh values should be regarded as indicators of relative hydro-environmental conditions rather than direct electrochemical measurements. In addition, intermediate nutrient pools such as ammonium, nitrate and soluble phosphorus were not quantified, limiting direct assessment of specific nutrient transformation pathways. Future studies incorporating direct redox measurements, nutrient flux monitoring, microbial functional analyses and metagenomics or quantitative PCR approaches would provide greater mechanistic understanding of the interactions among physiography, compost amendment and soil biochemical processes.

Contribution to knowledge

This study provides empirical evidence that physiographic position mediates compost effectiveness through its influence on soil moisture status and associated biochemical processes. By integrating moisture dynamics, enzyme activity, nutrient uptake and plant growth responses within a single experimental framework, the study advances understanding of soil-plant-microbe interactions across tropical toposequences and supports the development of landscape-specific organic amendment strategies.

Conclusion and Recommendations

Poultry-manure-based compost significantly improved soil moisture retention, biochemical functioning, nutrient uptake and vegetative growth of okra across contrasting physiographic positions. Compost amendment enhanced cellulase and protease activities, increased N, P and K uptake, and improved post-harvest soil fertility, demonstrating its potential as an effective organic amendment for sustainable crop production. Physiographic position strongly influenced the magnitude of these responses, with backslope and toeslope soils consistently outperforming crest soils due to their more favourable moisture and moisture-associated hydro-environmental conditions. Correlation analyses further revealed that enzyme activity was more closely associated with nutrient uptake and plant growth than microbial frequency, highlighting the importance of functional microbial processes in nutrient cycling. Overall, the findings suggest a physiography-associated continuum linking soil moisture, enzyme activity, nutrient uptake and crop performance. Integrating landscape variability into organic amendment management can therefore improve nutrient use efficiency and productivity in tropical agroecosystems.

Therefore, the study recommends the following:

i. Compost management strategies in tropical savanna soils may benefit from considering landscape position because response magnitude varies significantly across crest, backslope and toeslope environments.
ii. Higher compost rates, supplemental irrigation or moisture-conservation practices such as mulching should be considered for crest positions where moisture limitations reduce amendment effectiveness, especially under field conditions.
iii. Soil moisture and enzyme activities may serve as useful indicators for evaluating nutrient cycling efficiency in research and advisory programmes.
iv. Poultry-manure composting may provide a promising option for improving soil quality and reducing dependence on inorganic fertilisers in tropical savanna production systems, although field-scale validation is recommended.
v. Future studies should directly measure redox potential and quantify mineral nitrogen fractions (NH_4^+ and NO_3^-), soluble phosphorus and microbial functional genes to improve understanding of the mechanisms governing nutrient transformations across physiographic gradients.

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Declaration

Ethics approval and consent to participate

This study did not involve human participants, human data, or animals. Okra (*Abelmoschus esculentus* L. Moench) seeds were purchased from a certified agricultural input supplier in Ilorin, Nigeria. Soil samples were collected from the University of Ilorin Teaching and Research Farm with institutional approval for research purposes. No additional permits or licenses were required because no wild, protected, endangered or regulated plant species were collected. All procedures complied with relevant institutional and national guidelines.

Consent for publication

Not applicable

Availability of data and materials

All data generated or analysed during this study are included in this manuscript. Additional information related to the datasets used and analysed during the current study is available from the corresponding author upon reasonable request.

Clinical trial number

Not applicable

Competing interests

The authors declare that there are no competing interests, financial or non-financial, that could have influenced the work reported in this manuscript.

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Authors' contributions

Yahaya James Ukwumonu and Fawole Oluyemisi Bolajoko conceived and designed the study. Yahaya James Ukwumonu, Olasupo Hammed Alabi, and Ikuoponiyi Damilola Abigael experimented. Yahaya James Ukwumonu performed data analysis and drafted the manuscript. Yahaya James Ukwumonu, Fawole Oluyemisi Bolajoko, Isiaka Kareem, and Oni Femi Emmanuel reviewed and approved the final manuscript.

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Supplementary Files

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