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Assessment of Soil Degradation and Resilience Index across Different Topographic Positions in Wukari, Taraba State, Nigeria

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Abstract

Background: Soil degradation is a major challenge to agricultural productivity, particularly in continuously cultivated landscapes.
Aims: This study assesses soil degradation and resilience across upland, midland, and lowland topographic positions in Wukari, Taraba State, Nigeria, using Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA), and weighted index assessments.
Methods: A stratified random sampling approach was employed to collect 15 composite soil samples, which were analyzed for physical, chemical, and biological indicators of degradation.
Result: Results revealed that organic matter depletion was the most severe degradation factor across all terrain positions, with the upland exhibiting the highest level of degradation. Soil permeability was also significantly degraded in the upland, likely due to higher sand content and lower microporosity. Nitrogen depletion and elevated Exchangeable Sodium Percentage (ESP) were observed across all positions, indicating widespread fertility decline. The weighted degradation index (WDI) classified all positions as moderately degraded, with the upland (WDI = 2.35) experiencing the highest degradation, followed by the midland (1.8) and lowland (1.75). The resilience index (ISR) indicated that upland soils had low resilience (ISR = 0.30), whereas midland and lowland soils were moderately resilient (0.36). To mitigate degradation, organic matter restoration, conservation tillage, and erosion control are recommended for uplands, while controlled irrigation and balanced fertilization should be prioritized for midland and lowland soils. Further research should explore long-term soil monitoring to assess the effectiveness of these strategies.

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1. Introduction

Soil degradation remains a critical challenge to agricultural productivity, particularly in regions under continuous cultivation (Awwal, 2021). In Africa, an estimated 65% of farmland is degraded, threatening over 270 million people with chronic hunger (Reuters, 2024). Key man-made contributors include land-use practices like mono-cropping and overgrazing, which deplete soil nutrients and reduce fertility, ultimately diminishing agricultural output (Pacheco, 2018). Addressing this issue requires a thorough assessment of soil degradation and resilience to guide sustainable land management and agricultural planning.

Land degradation is characterized by declining soil productivity, reduced fertility, biodiversity loss, and the overall deterioration of natural resources (Olaniyi and Abioye, 2023). Degraded soils exhibit suboptimal quality, limiting their ability to support crop production and essential ecosystem functions. In contrast, soil resilience—the capacity to resist or recover from degradation—serves as a key indicator of long-term sustainability. In Nigeria, particularly in Wukari, Taraba State, terrain variations influence soil degradation susceptibility. For instance, steeper slopes accelerate runoff, causing surface erosion that depletes upland soil fertility while enriching lowland areas (Awwal *et al.,* 2022). Combined with intensive cultivation, these processes progressively degrade soil quality, necessitating a systematic assessment of degradation patterns to support effective land management (Maniyunda *et al.,* 2020).

Various methodologies have been used to quantify soil degradation, with the Global Assessment of Soil Degradation (GLASOD, 1998) identifying key indicators such as bulk density, hydraulic conductivity, and essential chemical properties, including nitrogen, phosphorus, potassium, exchangeable sodium percentage (ESP), and organic matter content. These indicators have been widely adopted in land degradation assessments by researchers such as Senjobi & Ogunkunle (2011), Ibrahim & Idoga (2013), Zuni & Jaiyeoba (2015), Maniyunda *et al.* (2020) and Awwal *et al.* (2020). However, deriving a comprehensive degradation index that accurately represents the influence and interactions of these indicators remains a challenge.

Multivariate statistical techniques, particularly Principal Component Analysis (PCA) and cluster analysis, have proven effective in classifying and interpreting complex relationships among soil properties. For instance, Onoyima & Okibe (2021) used these methods to assess soil quality in the floodplain of River Kaduna, Nigeria, reducing data dimensionality and identifying key indicators of soil health. Similarly, Awe *et al.* (2021) applied multivariate and geostatistical analyses to investigate soil property variations and crop yield relationships in Ado Ekiti, Nigeria, demonstrating their utility in soil assessment.

Despite these advancements, few studies have integrated multivariate statistical approaches with a soil resilience framework for a comprehensive assessment of degradation. This study addresses this gap by employing ANOVA, PCA, and hierarchical clustering to evaluate soil degradation across different terrain positions in Wukari. The novelty and importance of the study lie in its development of a new Index of Soil Resilience (ISR)—a metric that combines statistical analysis with resilience-based classification to provide a holistic and decision-supportive assessment of soil degradation. The study's objectives are to determine the extent of degradation in upland, midland, and lowland soils, assess statistical variations in soil properties across these positions, and classify resilience levels to support targeted soil management strategies.

2. Methods

2.1 Study Area

The research was conducted in Wukari, Taraba State, Nigeria, a region with diverse terrain and intensive agricultural activities. It spans 9° 6' 21.60" N, 7° 49' 15.60" E to 10° 21' 28.80" N, 8° 17' 24.00" E, with an elevation ranging from 65 to 270 m (Figure 1).

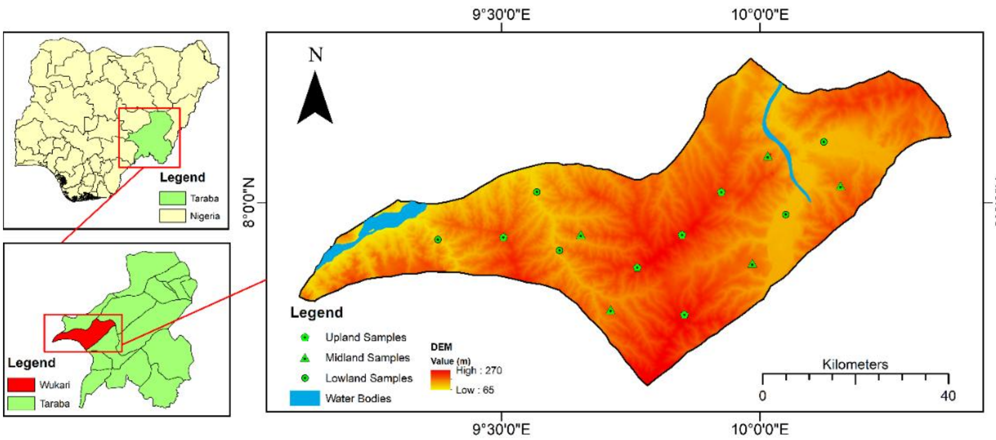

Figure 1. Digital elevation model (DEM) and spatial distribution of soil sampling points across terrain positions in Wukari, Taraba State, Nigeria.

Farmers in the region engage in continuous cultivation of important crops such as maize, cassava and rice, making it an ideal site for assessing soil quality and resilience. The study covered three terrain positions (upland, midland, and lowland) where soil samples were collected to evaluate physical, chemical, and biological properties related to degradation dynamics.

2.2 Soil Sampling, Sample Preparation and Laboratory Analysis

Prior to field sampling, terrain classification was done based on elevation and landform variations, delineating the study area into lowland (<160 m), midland (160–190 m), and upland (>190 m) positions. Then, stratified random sampling approach was employed to ensure representative coverage across terrain positions, resulting in 15 composite soil samples, with five replicates per terrain category. Disturbed and undisturbed samples were collected at a 30 cm depth to capture the cultivated layer. The collected soil samples were air-dried, sieved through a 2 mm mesh, and analyzed for key degradation indicators following standard laboratory, while bulk density (BD) and saturated hydraulic conductivity (Ks) were determined using core method (Gee & Or, 2002) and constant head permeameter method (Klute, 1986) respectively. Total nitrogen (TN) was determined using the Kjeldahl digestion method, available phosphorus (P) was extracted using the Bray-1 method for acidic soils, followed by colorimetric determination using a spectrophotometer. Exchangeable potassium (K), sodium (Na) and cation exchange capacity was extracted using 1N ammonium acetate (NH4OAc, pH 7.0), while exchangeable sodium percentage (ESP) was calculated using:

$$ESP = \frac{Na\ (cmol\ kg^{-1})}{CEC\ (cmol\ kg^{-1})} \times 100 \qquad \text{- Equation (1)}$$

Base Saturation (BS) was derived via calculation, electrical conductivity (EC) was measured in a 1:1 soil-water extract using a conductivity meter to assess salt accumulation in soil. Organic matter (OM) was estimated from organic carbon values determined by Walkley-Black wet oxidation method. These analyses were done following standard procedures as described by Uyovbisere et al. (2013).

2.3 Statistical Analysis

A one-way Analysis of Variance (ANOVA) was conducted to determine significant differences in soil properties across terrain positions. Principal Component Analysis (PCA) was applied to reduce dimensionality and identify the most influential soil properties contributing to degradation. A biplot was generated to visualize clustering patterns among soil properties. Additionally, Hierarchical Cluster Analysis (HCA) was performed to classify soil samples based on degradation characteristics. The Ward’s linkage method with Euclidean distance was employed to group similar soil properties across terrain positions, and a dendrogram was generated to illustrate clustering patterns

2.4 Determination of Soil Degradation Index

Soil degradation levels were assessed using standard indicators and criteria for land degradation assessment, following the Global Assessment of Land Degradation (GLASOD, 1998) framework. To normalize the data, soil properties were categorized into degradation classes by matching their values with predefined indicator thresholds (Table 1). Cluster Analysis (HCA) was used to group indicators with similar degradation patterns to ensure that soil properties exhibiting similar variability and response to degradation were assigned comparable weights.

Table 1. Indicators and criteria for land degradation assessment.

Indicator	Degree of Degradation			
	1	2	3	4
Physical Degradation				
Soil bulk density (Mg m^{-3})	<1.5	1.5 – 2.5	2.5 – 5	>5
Permeability (cm hr^{-1})	<1.25	1.25 – 5	5 – 10	>20
Chemical Degradation				
Content of N element N (%)	>0.13	0.13 – 0.10	0.10 – 0.08	>0.08
Content of phosphorus element (mg kg^{-1})	>8	8 – 7	7 – 6	<6
Content of potassium element (cmol kg^{-1})	>0.16	0.16 – 0.14	0.14 – 0.12	<0.12

Content of ESP (%)	<10	10 – 25	25 – 50	>50
Base saturation (%)	<2.5	2.5 – 5	5 – 10	>10
Excess salt (dS m^{-1})	<2	2 – 3	3 – 5	>5
Biological Degradation				
Content of humus in soil (%)	>2.5	2.5 – 2.0	2.0 – 1.0	>1.0

Adapted from Awwal *et al.* (2020).

The final degradation index (*WDI*) was determined by weighting soil properties based on PCA loadings and cluster groupings, and was computed using Equation (2) below:

$$Soil\ Degradation\ Index\ (WDI) = \sum_{i=1}^{n} S_i W_i \qquad \text{- Equation (2)}$$

Where S_i represents the degradation degree for each indicator, and W_i is the derived weights for each indicator. The final degradation index resulting from this formula theoretically ranges from 1.00 to 4.00, based on the possible combinations of degradation classes and their assigned weights. These ranges were not arbitrarily chosen but derived from the expected output limits of the weighted formula structure. Interpretation of the index was done using Table 2.

Table 2. Interpretation of degradation index.

WDI Range	Degradation Class	Interpretation
≤ 1.5	None to Slight	Soil is relatively stable with minimal degradation, requiring no immediate intervention.
1.51 – 2.5	Moderate	Degradation is noticeable but not severe. Some soil functions are impaired, requiring moderate conservation measures to maintain productivity.
2.51 – 3.5	Severe	Soil degradation significantly affects structure, fertility, and water retention, requiring major restoration practices.
> 3.5	Extreme	Soil is highly degraded with substantial loss of productivity and resilience. Intensive rehabilitation strategies are essential.

2.5 Determination of Soil Resilience Index

Since soil resilience is the ability of soil to resist and recover from degradation, the index-based approach used to measure its magnitude on different terrain positions is shown in Equation (3):

$$Index\ of\ Soil\ Resilience\ (ISR) = \frac{1}{1+WDI} \qquad \text{- Equation (3)}$$

Where *WDI* is the final degradation score, which was weighted based on key indicators. The ISR values range from 0.20 to 0.50, reflecting the inverse relationship with degradation levels. These theoretical limits were derived directly from the mathematical behavior of Equation (3) applied to the WDI range. This formulation provides a standardized and interpretable scale of resilience across terrain positions, as summarized in Table 3.

Table 3. Interpretation of ISR values

ISR Range	Soil Resilience Category	Interpretation
0.45 - 0.50	Highly Resilient	Soil resists degradation well, functions are stable.
0.30 - 0.44	Moderately Resilient	Soil shows some degradation but can still recover.
0.22 - 0.29	Low Resilience	Degradation is affecting productivity, slow recovery.
0.20 - 0.21	Extremely Degraded	Severe degradation, minimal resilience, major soil function loss.

3. Results and Discussion

3.1 Soil Properties on Different Terrain Positions

The analysis of soil properties across different terrain positions revealed significant variations, with key differences in textural composition, bulk density, permeability, and nutrient content (Table 3). Mean sand content was significantly higher in upland (73.26%) and midland (71.20%) soils compared to lowland (60.08%), while silt and clay contents followed an inverse pattern. The observed textural differences align with natural sediment deposition processes, where finer particles tend to accumulate in lowland areas due to downslope movement and alluvial deposition (Jimoh *et al.,* 2017; Awwal & Maniyunda, 2023). These variations influenced bulk density, with lowland soils exhibiting significantly lower BD (1.31 Mg m^{-3}) compared to upland and midland positions (1.41 and 1.43 Mg m^{-3}, respectively). The lower BD in lowland soils may be attributed to higher organic matter accumulation, which enhances soil structure and porosity (Lardy *et al.,* 2022).

Soil permeability (Ks) followed the trend of upland > midland > lowland, with upland soils exhibiting the highest permeability (5.56 cm hr^{-1}), likely due to their higher sand content and lower clay fraction (Upadhyay & Raghubanshi, 2020). Conversely, lowland soils had the lowest permeability (2.10 cm hr^{-1}), consistent with their higher silt and clay content, which reduces infiltration and increases water retention. This suggests that lowland soils may be more prone to waterlogging, which could impact growth and microbial activity for certain crops (Tsui *et al.,* 2004).

Soil fertility indicators such as content of nitrogen (TN), phosphorus (Av. P), and potassium (Ex. K) concentrations varied significantly across terrain positions, with lowland soils consistently exhibiting higher values than upland and midland soils. Interestingly, base saturation (BS) and exchangeable sodium percentage (ESP) did not show significant differences (NS) across terrain positions, suggesting that cation exchange dynamics are relatively stable across the landscape, possibly due to similar parent material composition and long-term cultivation practices (Havlin, 2005). The organic matter content (OM) was significantly higher in lowland soils (16.64 g kg^{-1}) compared to midland (11.43 g kg^{-1}) and upland (9.41 g kg^{-1}) soils. The higher OM in lowland soils is likely due to enhanced moisture retention, which supports microbial decomposition and organic matter accumulation (Jakšić *et al.,* 2021).

Table 3. Variation of soil properties across terrain positions in Wukari.

Soil Properties	Units	Upland	Midland	Lowland	LOS
Sand	%	73.26^a	71.20^a	60.08^b	**
Silt	%	19.28^c	24.12^b	29.72^a	*
Clay	%	7.45^b	4.67^c	9.33^c	**
Soil Bulk Density	Mg m^{-3}	1.41^b	1.43^b	1.31^a	*
Permeability	cm hr^{-1}	5.56^a	4.53^a	2.10^b	*
Nitrogen	g kg^{-1}	0.56^b	0.53^b	0.71^a	*
Phosphorus	mg kg^{-1}	6.84^b	8.27^b	17.07^a	***
Potassium	cmol kg^{-1}	0.10^b	0.14^b	0.28^a	*
Base Saturation	%	80.29	79.46	77.89	NS
ESP	dS m^{-1}	0.11	0.11	0.10	NS
Humus Content (OM)	g kg^{-1}	9.41^c	11.43^b	16.64^a	*

3.2 Multivariate Analysis of Soil Properties

The Principal Component Analysis (PCA) results provide insight into the contribution of soil properties to variability across terrain positions. The first three principal components (PCs) collectively explain 99% of the total variance, with PC1 (74%) capturing the majority of the variation, followed by PC2 (19%), while PC3 (5%) accounts for a minimal portion of variability (Table 4). In the PC1, the dominant soil properties included OM (0.326), TN (0.324), silt (0.303), clay (0.260) and av. P (0.275). These variables positively contribute to PC1, indicating that fertility-related factors and finer soil fractions (silt, clay) drive the primary differentiation of soil properties. The strongly negative loadings such as sand (-0.333), Ks (-0.324), BD (-0.318) and BS (-0.317) confirms that low-fertility status are usually associated with higher values of these properties. Additionally, permeability (Ks) is negatively associated with these variables, suggesting that coarser soils with higher Ks tend to have lower nutrient retention (Awwal, 2021).

The PC2 loadings suggests that it captures sodium-related soil chemical variability, with ESP having the strongest positive loading (0.568), followed by clay content (0.398). A strong negative loading was also recorded for exchangeable K (-0.319). This suggests that potassium dynamics are inversely related to sodium accumulation. This may indicate cation exchange competition, where higher ESP leads to lower exchangeable K availability. This phenomenon is consistent with the reports of Yang *et al.* (2024). The strongest negative loading in PC3 was ex. P (-0.931). This near-exclusive contribution of K to PC3 suggests that PC3 primarily reflects variations in potassium availability, which does not significantly impact the broader variability captured by PC1 and PC2. The PCA biplot (Figure 2) illustrates the spatial distribution of soil samples from different terrain positions based on PCs 1 and 2.

Table 4. Principal component analysis (PCA) loadings and soil property variability.

Variable	**PC1**	**PC2**	**PC3**
Position	0.297	-0.288	0.148
BD	-0.318	-0.181	-0.051
Ks	-0.324	0.153	-0.106
TN	0.324	0.155	-0.014
Av. P	0.275	0.352	-0.106
Ex. K	0.161	-0.319	-0.931
ESP	0.15	0.568	-0.152
BS	-0.317	0.189	-0.128
OM	0.326	-0.143	0.085
Sand	-0.333	0.061	-0.079
Silt	0.303	-0.264	0.146
Clay	0.260	0.398	-0.104
Eigenvalue	8.13	2.19	0.59
Proportion	0.74	0.19	0.05
Cumulative	0.74	0.94	0.99

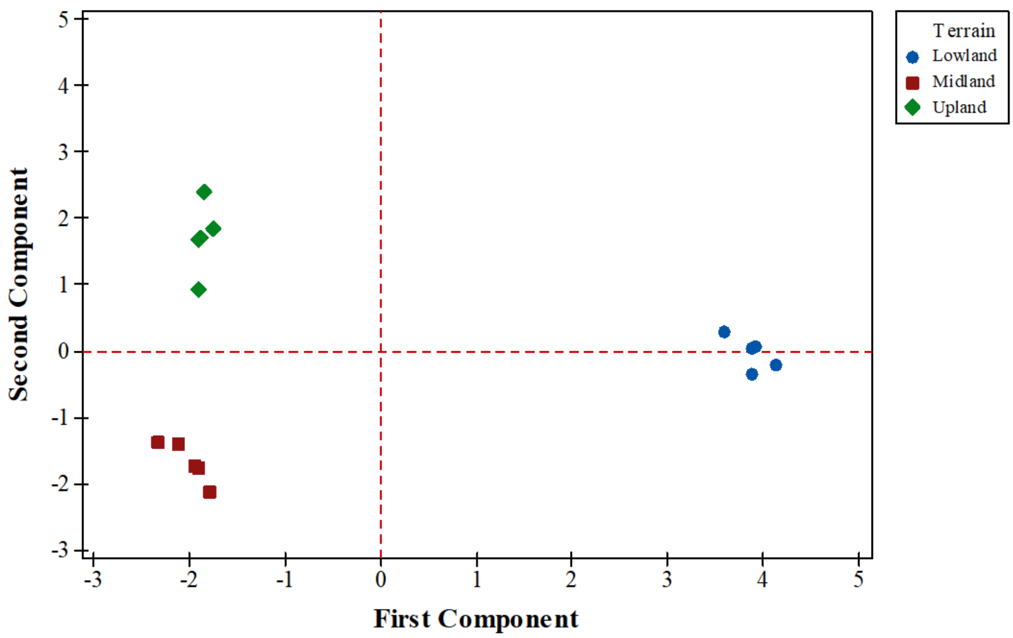

Figure 2. Principal Component Analysis (PCA) biplot showing the spatial separation of soil samples across different topographic positions (Lowland, Midland, and Upland) based on key soil degradation and resilience indicators. The clustering of points indicates distinct soil property patterns associated with each terrain category.

The clustering pattern observed suggests distinct soil property variations across terrain positions, emphasising the influence of topography on soil characteristics. Samples from the lowland terrain position cluster positively along the first principal component (PC1), suggesting that these soils share similar characteristics, likely influenced by depositional processes and prolonged water retention. Conversely, upland samples are positioned positively along PC2, implying well-defined soil attributes likely influenced by erosion, organic matter depletion, and reduced moisture retention, while the midland samples are negatively associated with PC1 and PC2, indicating unique soil properties distinct from both lowland and upland terrains, hinting that the midland soils may exhibit transitional characteristics due to moderate elevation and drainage. This corroborates findings of Jimoh (2015) and Awwal (2021) who reported transitional properties in middle slope positions. The clustering pattern of soil properties confirm that topography significantly affected soil variability, reflecting differences in texture, nutrient distribution, and water dynamics, suggesting terrain-specific soil management strategies to enhance productivity and mitigate degradation risks.

3.3 Hierarchical Cluster Analysis of Soil Properties for Degradation Assessment

The hierarchical cluster analysis (HCA) dendrogram (Figure 3) illustrates the similarity relationships among selected soil properties, aiding in understanding their potential interactions and influence on soil degradation. The vertical axis represents similarity levels, with variables merging at lower levels exhibiting greater similarity, while those joining at higher levels are more distinct (Carroll *et al.,* 2015). In this study, clustering soil properties helps identify interrelationship between key indicators of degradation,

Bulk density, Ks, BS, and sand content form a closely related group, likely driven by physical soil structure and porosity-related properties. High BD, for instance, has been linked to reduced infiltration and increased runoff, exacerbating soil degradation (Lal, 2015). Similarly, Ks and BS are critical in determining soil permeability and cation retention, which affect soil resilience against degradation processes (Weil & Brady, 2017).

The second cluster is subdivided into two distinct sub-clusters. The first sub-cluster, consisting of TN, av. P, clay, and ESP, highlights a strong linkage between soil fertility and degradation-related chemical properties. Previous studies have established that declines in nitrogen and phosphorus levels, coupled with high ESP, contribute to soil structural instability and fertility decline in degraded landscapes (Blanco-Canqui & Lal, 2010). The second sub-cluster, consisting of ex. K, OM, and silt, likely represents soil fertility components more associated with organic matter content and fine-textured fractions. The role of OM in maintaining soil structure and nutrient availability has been extensively documented (Six *et al.,* 2002), with its depletion often serving as an early indicator of degradation.

Identification of strongly correlated variables provides a basis for selecting representative indicators in future monitoring and modelling efforts. Furthermore, the hierarchical clustering results provide a structured basis for assigning weights to soil degradation indicators. Variables within the same cluster exhibit strong interrelationships, and weights are distributed proportionally based on their influence on soil degradation. The three identified clusters represent physical properties, fertility and degradation indicators, and organic matter-related properties, each contributing differently to overall soil health. Given that physical properties (Cluster 1) and soil fertility indicators (Cluster 2) are key drivers of soil structure and degradation, they are assigned higher proportions (0.40 and 0.35, respectively). Organic matter and texture-related properties (Cluster 3) are crucial for nutrient cycling and stability but play a relatively lesser role, so they are assigned 0.25 of the total weight. Within each cluster, weights are distributed based on the relative importance of individual variables, and were multiplied by the normalized degradation scores to achieve the final soil degradation index, ensuring that more influential properties have a greater impact on the overall assessment.

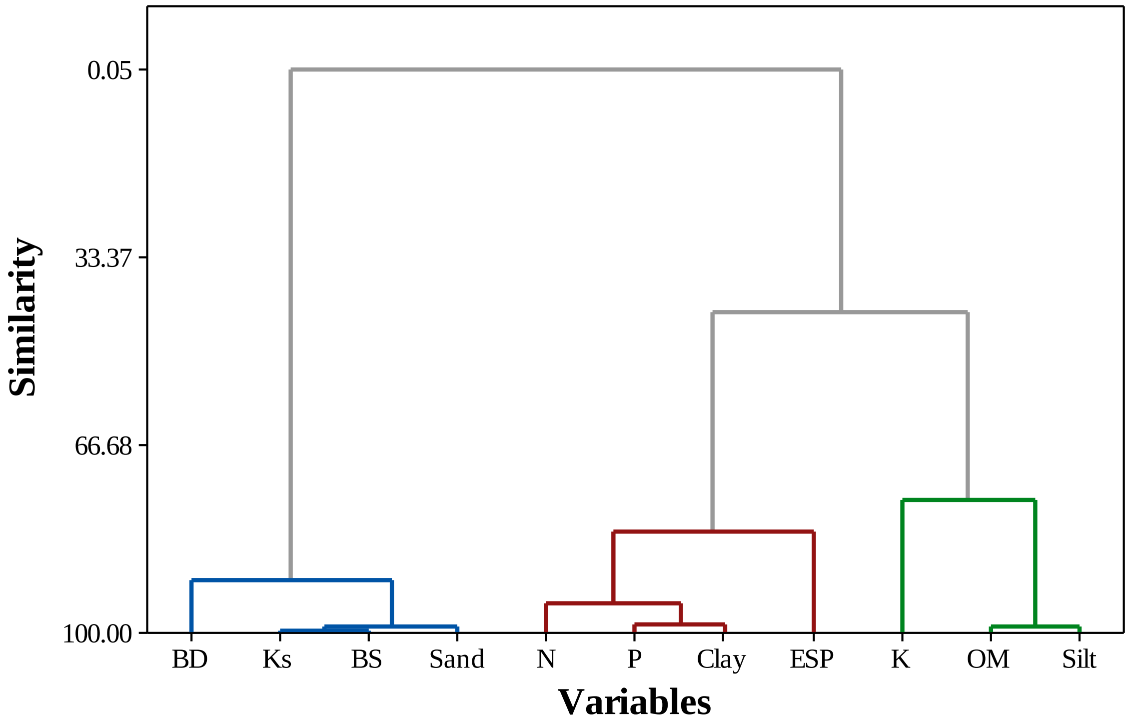

Figure 3. Hierarchical Cluster Analysis (HCA) dendrogram showing similar groupings among soil degradation indicators based on their response patterns. Variables clustered at lower similarity levels (e.g., BD, Ks, BS, Sand) indicate stronger interrelationships, aiding in the weighting and integration of indicators for the soil degradation index.

3.4 Soil Degradation and Resilience Rates

The most degraded soil property across all terrain positions is organic matter content, with the highest degradation observed in the upland compared to the midland and lowland. This pattern is common in tropical environments due to higher decomposition rates, intensive land use, and erosion-prone conditions in upland soils (Lal, 2003). Studies by Basak *et al.* (2022) in tropical agroecosystems also confirm that organic matter depletion is accelerated in well-drained upland soils due to reduced biomass return and increased oxidation.

Soil permeability follows as the next most degraded property, particularly in upland soils. This is largely explained by the higher sand content and lower fine-sized particles, which reduce microporosity and promote increased leaching (Hillel, 1998). Reduced permeability in these soils exacerbates surface runoff, leading to nutrient loss and further degradation (Blanco-Canqui & Lal, 2010).

Soil nitrogen content and ESP were consistently degraded across different terrain positions. The depletion of nitrogen in the upland, midland, and lowland can be attributed to continuous cropping, limited organic inputs, and leaching losses (Awwal, 2021). Similarly, the relatively high degradation of ESP across all positions suggests persistent issues with soil sodicity, which negatively affects soil structure and hydraulic properties, further reinforcing degradation patterns (Qadir *et al.*, 2006).

The weighted degradation index confirms that upland soils (2.35) are the most degraded, followed by midland (1.8) and lowland (1.75). This aligns with previous findings indicating that upland landscapes are more susceptible to degradation due to erosion, organic matter loss, and lower moisture retention (Weil & Brady, 2017). In contrast, the resilience index is lowest in the upland (0.30) and higher in the midland and lowland (0.36). This suggests that midland and lowland soils retain better recovery potential, likely due to finer soil texture, higher organic matter retention, and periodic sediment deposition (Schwilch *et al.*, 2011). However, the overall moderate resilience of these soils indicates that without sustainable management interventions, long-term productivity may still decline.

These findings underscore the need for terrain-specific soil conservation strategies. In the uplands, organic matter management, conservation tillage, and agroforestry systems could enhance resilience. Meanwhile, in midland and lowland soils, controlled irrigation, nutrient balancing, and erosion control should be prioritized to maintain soil functionality and prevent further degradation (Lal, 2015).

Table 4. Soil degradation and resilience indices across terrain positions in Wukari.

Soil Properties	Upland	Midland	Lowland
Physical Degradation			
Soil Bulk Density	0.2	0.2	0.2
Permeability	0.5	0.3	0.3
Chemical Degradation			
Nitrogen	0.2	0.2	0.2
Phosphorus	0.1	0.1	0.1
Potassium	0.2	0.1	0.1
Base Saturation	0.1	0.1	0.1
ESP	0.3	0.3	0.3
Biological Degradation			
Humus Content	1.0	0.8	0.8
Weighted Degradation Index	2.35	1.8	1.75
Class	Moderate	Moderate	Moderate
Index of Soil Resilience	0.30	0.36	0.36
Category	Low Resilience	Moderately Resilient	Moderately Resilient

4. Conclusions

This study assessed soil degradation and resilience across upland, midland, and lowland terrain positions in Wukari, Taraba State, using HCA, PCA, and weighted index approaches. HCA grouped soil properties based on their interrelationships, correctly clustering BD, Ks, sand content, and BS together, while TN, P, ESP, and clay formed a separate group, and OM, ex. K, and silt were classified distinctly. These clusters highlight organic matter's central role in soil stability and fertility.

The PCA identified OM, TN, P, and ESP as the most significant contributors to degradation, explaining 74% of total variance. Soils with high sand content, low permeability, and reduced OM exhibited the highest degradation risks. The WDI classified all positions as moderately degraded, with upland (2.35) most affected, followed by midland (1.8) and lowland (1.75). Organic matter loss was the dominant factor, especially in uplands due to higher erosion and lower biomass return. Nitrogen depletion and ESP accumulation were consistent across all terrain positions, indicating widespread fertility decline.

The ISR indicated low resilience in upland soils (0.30), while midland and lowland soils were moderately resilient (0.36). Upland soils are more vulnerable to degradation due to erosion and OM depletion, whereas midland and lowland soils retain better recovery potential due to finer texture and moisture retention. To enhance soil quality and resilience, organic matter restoration, erosion control, and conservation tillage should be prioritized, especially in the context of increasing climate variability.

While this study offers valuable insight at the local scale, its implementation is currently limited to a single site. Future research should expand to multiple agroecological zones or landscapes to validate the robustness of the Index of Soil Resilience (ISR) and degradation indicators across broader contexts. This scale-up remains a challenge due to resource and logistical constraints, but it is essential for generalizing findings and informing regional or national land management policies.

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