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SPATIAL DRIVERS OF SOIL QUALITY VARIABILITY AND IMPLICATIONS FOR REGIONAL LAND MANAGEMENT IN SOUTH-SOUTH NIGERIA

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ABSTRACT

Motives: Soil quality is a fundamental but often under-integrated component of regional land-use planning and sustainable land management in rapidly developing tropical environments. This study examines the spatial drivers of soil quality variability across selected states in the South-South region of Nigeria using multivariate and regression modelling techniques. Understanding the dominant drivers of soil quality variability is therefore essential for developing effective land-use management strategies in the region. Identifying how soil properties vary spatially and which factors control this variability can provide a scientific basis for land suitability assessment, conservation prioritization, and sustainable land-use planning.

Aim: The study aims to determine the physicochemical and textural characteristics of soils in the South-South region; evaluate interrelationships among soil quality parameters using correlation analysis; identify dominant soil quality drivers through principal component analysis; quantify the influence of selected soil properties on key soil quality indicators using multiple regression models; and to explain regional soil quality variability in relation to acidity dynamics, nutrient retention capacity, and textural composition. This study thus identifies the leading drivers controlling soil quality variability across the South-South region of Nigeria using multivariate statistical approaches including correlation analysis, principal component analysis, and regression modelling. By linking soil quality indicators with broader land management implications, the study contributes to integrating environmental assessment with spatial planning and land administration frameworks in humid tropical environments.

Results: The results indicate that soil quality variability in the South-South zone is controlled by four key interacting factors: organic matter and nitrogen dynamics, base-cation-controlled nutrient retention capacity, soil acidity regulation, and texture-mediated physical constraints. These drivers operate under humid tropical conditions characterized by intense rainfall and advanced weathering. Beyond their environmental significance, these drivers have direct relevance for regional land administration, spatial planning, and sustainable land-use management, particularly in relation to agricultural zoning,

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land suitability assessment, and land conservation policy. The study demonstrates how soil quality modelling can support evidence-based spatial decision-making and regional development strategies in humid tropical environments. The modelling framework adopted in this study demonstrates how soil quality data can be translated into spatial decision-support information for land managers and policy makers. Integrating such information into geographic information systems and land administration platforms could enhance evidence-based land management and promote sustainable land-use planning in humid tropical regions. Future studies should incorporate larger spatial datasets and more detailed sampling designs in order to improve the robustness of soil quality modelling and to better capture spatial variability across the region.

Keywords: modeling, soil quality, drivers, variability, environment, South-South region

INTRODUCTION

Soil quality is increasingly recognized as a critical environmental resource that influences land-use suitability, agricultural productivity, and sustainable land management. In many tropical regions experiencing rapid population growth and land-use transformation, soil constraints such as acidity, low nutrient retention capacity, and coarse texture directly affect agricultural productivity, infrastructure development, and long-term land sustainability. Despite its importance, soil quality information is rarely incorporated explicitly into land administration systems or spatial planning frameworks in many parts of sub-Saharan Africa, limiting the ability of planners and land managers to anticipate land degradation risks and optimize land-use allocation.

Soils are fundamental components of terrestrial ecosystems and play essential roles in supporting agricultural production, regulating water cycles, and sustaining ecosystem services. The Food and Agriculture Organization emphasizes that soils constitute a crucial enabling resource for the provision of multiple ecosystem goods and services essential to human well-being (FAO, 2015). Soil quality is therefore commonly defined as the capacity of soil to sustain plant productivity, maintain environmental quality, and support ecosystem functioning (Chandel et al., 2018; Gayan et al., 2020; Jiang et al., 2020; Sani et al., 2023). However, global evidence indicates that soil quality is declining in many regions due to land degradation, intensive land use, and unsustainable agricultural practices, posing significant challenges for food security and environmental sustainability (Adebo et al., 2020; Assefa et al., 2020; Hussain et al., 2021; Kiflu & Beyene, 2013; Laekemariam & Kibret, 2020; Zajícová & Chuman, 2019).

Numerous studies have examined soil quality changes resulting from different land-use practices using various indicators and analytical approaches (Amoakwah, 2021; Bünemann et al., 2018; Doğan & Gülser, 2019; Ezeaku, 2015; Islam & Weil, 2000; Kaur et al., 2021; Kongor et al., 2019; Mulat et al., 2021; Mulyono et al., 2019; Nath et al., 2021; Nguemezi et al., 2020; Sefati et al., 2019; Saleh et al., 2021; Silvianingsih et al., 2021). While these studies have improved understanding of soil quality dynamics, relatively few have explicitly linked soil quality indicators with spatial planning and land administration processes.

In the context of regional development, soil quality can be viewed as a form of spatial capital influencing land valuation, agricultural suitability, and land-use decision-making. Integrating soil quality information into land administration systems and spatial planning frameworks can therefore improve evidence-based decision-making related to land-use zoning, agricultural land protection, and sustainable land management (Dorosh et al., 2024; Enemark, 2014; Williamson et al., 2010).

The South-South geopolitical zone of Nigeria represents a humid tropical environment characterized by high rainfall, intense weathering, and diverse geomorphic settings. The region supports dense populations and intensive land-use systems but faces persistent soil constraints including acidity, nutrient depletion, and limited nutrient retention capacity.

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These conditions contribute to spatial variability in soil quality and present challenges for sustainable land management and regional development planning.

Understanding the dominant drivers of soil quality variability is therefore essential for developing effective land-use management strategies in the region. Identifying how soil properties vary spatially and which factors control this variability can provide a scientific basis for land suitability assessment, conservation prioritization, and sustainable land-use planning.

The objective of this study is to identify the dominant drivers controlling soil quality variability across the South-South region of Nigeria using multivariate statistical approaches including correlation analysis, principal component analysis, and regression modelling. By linking soil quality indicators with broader land management implications, the study contributes to integrating environmental assessment with spatial planning and land administration frameworks in humid tropical environments.

MATERIALS AND METHODS

Study Area

The study was conducted in the South-South geopolitical region of Nigeria, comprising Akwa Ibom, Bayelsa, Cross River, Delta, Edo, and Rivers States (Figs. 1 and 2). The region lies within the humid tropical rainforest zone and is characterized

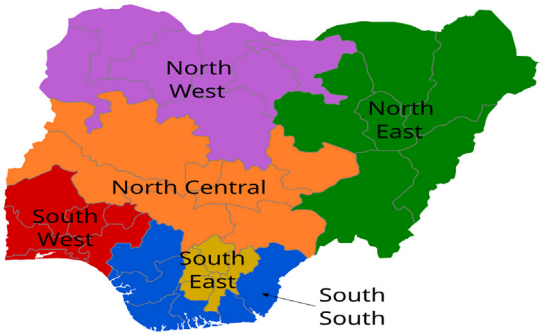


Fig. 1. Geopolitical Regions of Nigeria
Source: Wikimedia Commons.

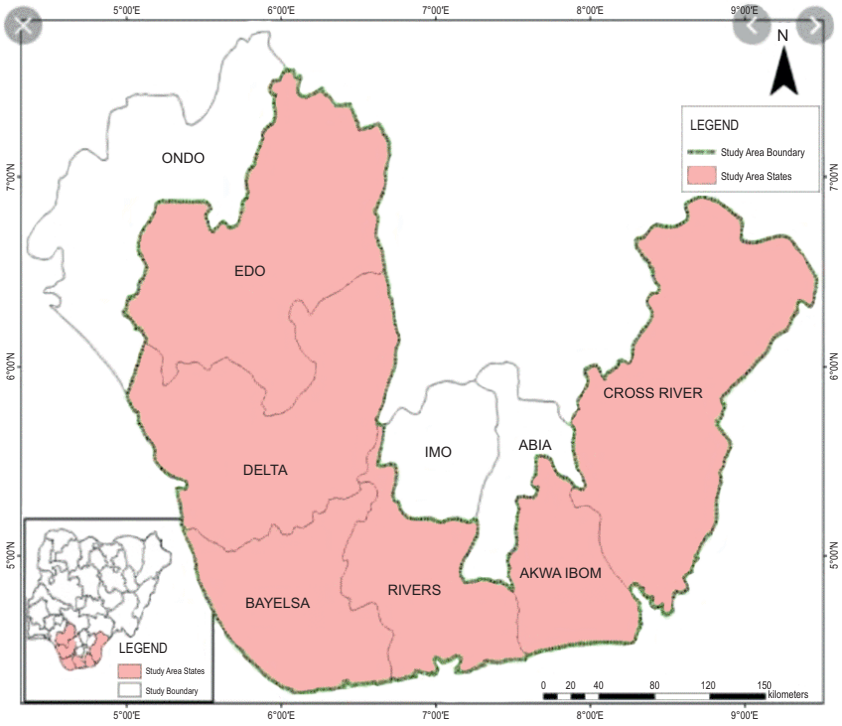


Fig. 2. Location of the South-South region in Nigeria
Source: Ukhurebor & Uzuazor (2020).

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by high annual rainfall, elevated relative humidity, and consistently high temperatures throughout the year. These climatic conditions promote intense weathering, leaching of basic cations, and soil acidification.

The soils of the South-South region are predominantly derived from coastal plain sands, alluvial deposits, and sedimentary formations, resulting in generally coarse-textured soils with variable nutrient retention capacity. Agriculture in the region is largely rain-fed, and soil degradation associated with acidity, nutrient depletion, and poor physical structure remains a major constraint to sustainable agricultural productivity. These characteristics make the region suitable for regional--scale assessment of soil quality variability and driver modeling.

Soil Sampling Strategy and Sample Representation

One composite surface soil sample (0–20 cm depth) was collected from each of the six states in the South-South geopolitical zone of Nigeria. Each composite sample was obtained by thoroughly mixing several subsamples collected from representative agricultural locations within each state in order to minimize microscale variability and capture the dominant soil conditions characteristic of each state.

Composite sampling was adopted to represent regional soil conditions rather than local plot-level variability. By integrating multiple subsamples within each state, the composite samples provide a generalized representation of prevailing soil characteristics across the broader spatial unit.

Justification of Sampling Design

The study employed a regional-scale observational design aimed at identifying broad patterns of soil quality variability across the South-South region of Nigeria. The primary objective of the study was to explore inter-state differences and identify dominant drivers of soil quality variability, rather than to characterize within-state heterogeneity.

Given this regional focus, one composite soil sample was used to represent the dominant soil conditions within each state. This approach enables preliminary comparison across the six states that constitute the South-South geopolitical zone.

However, it is important to acknowledge that the limited number of observations (n = 6) restricts the statistical robustness of multivariate analyses such as principal component analysis and regression modelling. Consequently, the results of this study should be interpreted primarily as exploratory indications of potential relationships among soil quality indicators, rather than as statistically definitive predictive models.

Despite this limitation, the analytical framework adopted in this study provides useful preliminary insights into dominant soil processes shaping soil quality variability at the regional scale and offers a foundation for future studies based on larger datasets and more detailed spatial sampling.

Laboratory Analysis of Soil Properties

All soil samples were air-dried, gently crushed, and passed through a 2-mm sieve prior to laboratory analysis. Standard analytical procedures were employed for the determination of soil physico-chemical properties.

Soil pH was measured using a glass electrode pH meter in a 1:2.5 soil-to-water suspension. Organic carbon was determined using the Walkley–Black wet oxidation method, and organic matter content was estimated by multiplying organic carbon by a conversion factor of 1.724. Total nitrogen was determined using the Kjeldahl digestion method.

Available phosphorus was extracted using the Bray-1 extraction method. Exchangeable base cations (Ca, Mg, K, and Na) were determined using 1 N ammonium acetate (NH_4OAc) extraction, while exchangeable acidity was determined using KCl extraction.

Estimated cation exchange capacity (ECEC) was calculated as the sum of exchangeable base cations and exchangeable acidity. Base saturation was computed as the proportion of exchangeable bases relative to ECEC.

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Particle size distribution (sand, silt, and clay fractions) was determined using the hydrometer method, and soil textural classes were identified using the USDA textural triangle.

Data Preparation and Standardization

Prior to statistical analysis, all soil variables were examined using descriptive statistics to evaluate their distribution and variability. Because the measured soil parameters were expressed in different units and scales, data standardization was performed to ensure comparability among variables during multivariate analysis.

Standardization was conducted using Z-score normalization, which transforms each variable to a mean of zero and a standard deviation of one:

$$Z = X - \mu\sigma Z = \frac{X - \mu}{\sigma}Z = \sigma X - \mu \quad (1)$$

Where:

X represents the observed value of the variable
μ represents the mean value of the variable
σ represents the standard deviation

This transformation removes scale effects and ensures that variables contribute equally to correlation, principal component, and regression analyses.

Correlation Analysis

Pearson correlation analysis was performed to examine the relationships among selected soil quality indicators and to identify potential redundancy among variables. Correlation coefficients were used to assess the strength and direction of relationships among soil properties, particularly those associated with soil fertility, acidity dynamics, and nutrient retention processes. Given the limited sample size of the dataset (n = 6), correlation results were interpreted primarily in a process-based and exploratory manner, focusing on general patterns of association among variables rather than strict statistical significance testing.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was applied to identify the dominant drivers of soil quality variability in the South-South region and to reduce redundancy among correlated soil variables.

The PCA was performed using the standardized dataset and included the following soil variables:

- Organic carbon (OC)
- Total nitrogen (N)
- Soil pH
- Sand fraction
- Exchangeable calcium (Ca)
- Exchangeable magnesium (Mg)
- Estimated cation exchange capacity (ECEC)
- Exchangeable acidity (EA)
- Base saturation (BS)
- Silt fraction

The following criteria were used in the PCA procedure:

1. Data standardization using Z-score transformation.
2. Retention of components with eigenvalues greater than 1 (Kaiser criterion).
3. Identification of significant variable contributions using factor loadings ≥ |0.60|.
4. Application of Varimax orthogonal rotation to improve interpretability of the component structure.

The retained components were interpreted based on dominant soil processes represented by strongly loaded variables, including nutrient retention capacity, acidity regulation, and texture-mediated physical controls.

Because the dataset contains a limited number of observations, the PCA results are interpreted as exploratory indicators of dominant soil process domains rather than definitive statistical classifications.

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Regression Analysis and Soil Quality Driver Modelling

Multiple linear regression analysis was used to explore relationships between selected soil quality indicators and to quantify potential drivers of soil quality variability.

Based on the results of correlation analysis and PCA, three key soil indicators were selected as dependent variables representing major soil processes:

1. Organic Carbon (OC) – representing soil organic matter dynamics.
2. Estimated Cation Exchange Capacity (ECEC) – representing nutrient retention capacity.
3. Exchangeable Acidity (EA) – representing soil acidity dynamics.

Independent variables were selected based on their mechanistic relevance to soil processes and their correlation with the dependent variables. These included:

– Total nitrogen (N)
– Soil pH
– Exchangeable calcium (Ca)
– Exchangeable magnesium (Mg)
– Sand fraction (%)

Multicollinearity among predictors was assessed using the Variance Inflation Factor (VIF) and tolerance values. Predictor variables with VIF values greater than 5 were excluded or re-specified to ensure model stability.

The general form of the regression model was expressed as:

$$Y = \beta0 + \beta1X1 + \beta2X2 + \beta3X3 + \epsilonY = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \epsilonY=\beta0 +\beta1X1 + \beta2X2 + \beta3X3 + \epsilon \quad (2)$$

Where:

Y represents the dependent variable
β_0 represents the intercept
β_1–β_3 represent regression coefficients
X_1–X_3 represent predictor variables
ε represents the random error term

Because the dataset contains a limited number of observations (n = 6), the regression models are interpreted as exploratory models intended to illustrate potential relationships among soil properties rather than statistically robust predictive models.

Model Evaluation and Diagnostics

Model performance was evaluated using:

– Coefficient of determination (R^2 and adjusted R^2);
– Analysis of variance (ANOVA);
– Residual diagnostics to assess model assumptions including normality and homoscedasticity.

Due to the limited sample size, the interpretation of model performance focused primarily on explanatory consistency and process-based interpretation rather than strict statistical inference.

Statistical Software

All statistical analyses were conducted using IBM SPSS Statistics (Version 26) for regression analysis, analysis of variance (ANOVA), and model diagnostics. R statistical software (Version 4.x) was used for principal component analysis (PCA) and supplementary statistical computations.

RESULTS AND DATA ANALYSIS

Descriptive Statistics of Soil Quality Indicators

Table 1 presents the descriptive statistics of selected soil quality indicators in the South-South zone of Nigeria. Sand content averaged 57.71%, indicating moderately sandy soils across the region, while silt content showed considerable variability ranging from 8.12% to 34.12%. Clay content remained relatively uniform at 20% across the sampled states.

Soil pH ranged from 3.82 to 6.55, with a mean value of 5.03, indicating strongly to moderately acidic soil conditions. Available phosphorus varied between 22.40 and 68.00 mg/kg, while total nitrogen ranged from 0.098% to 0.294%. Organic carbon values ranged from 0.97% to 2.70%, with a mean of 1.62%.

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Exchangeable calcium ranged from 1.67 to 4.65 cmol(+)/kg, while magnesium ranged from 2.80 to 5.20 cmol(+)/kg. Exchangeable potassium and sodium were generally low across the region. Exchangeable acidity varied between 0.16 and 0.76 cmol(+)/kg, while estimated cation exchange capacity (ECEC) ranged from 4.81 to 8.62 cmol(+)/kg. Base saturation values were relatively high, ranging from 85% to 98%.

Table 1. Descriptive Statistics of Soil Quality Indicators in the South-South Zone of Nigeria

Variable	Mean	Mini-mum	Maxi-mum	Interpretation
Sand (%)	57.71	45.88	71.88	Moderately sandy
Silt (%)	22.12	8.12	34.12	Highly variable
Clay (%)	20.00	20.00	20.00	Uniform
Ph	5.03	3.82	6.55	Strongly–moderately acidic
P (mg/kg)	40.68	22.40	68.00	Low–moderate
N (%)	0.182	0.098	0.294	Low–moderate
OC (%)	1.62	0.97	2.70	Low–moderate
Ca (cmol/kg)	3.12	1.67	4.65	Low–moderate
Mg (cmol/kg)	3.87	2.80	5.20	Moderate
K (cmol/kg)	0.163	0.082	0.178	Low
Na (cmol/kg)	0.119	0.084	0.168	Low
EA (cmol/kg)	0.39	0.16	0.76	Moderate
ECEC (cmol/kg)	6.48	4.81	8.62	Low–moderate
BS (%)	93.8	85	98	High

Source: own elaboration based on Laboratory Tests.

Correlation Analysis of Soil Quality Indicators

The Pearson correlation matrix of selected soil quality indicators is presented in Table 2. Organic carbon showed a strong positive correlation with total nitrogen (r = 0.91) and estimated cation exchange capacity (r = 0.83). Positive relationships were also observed between organic carbon and exchangeable calcium (r = 0.71) and magnesium (r = 0.74).

Soil pH exhibited positive correlations with organic carbon (r = 0.69), nitrogen (r = 0.66), and calcium (r = 0.62). In contrast, exchangeable acidity showed strong negative correlations with pH (r = −0.84) and base cations.

Sand content showed negative correlations with organic carbon (r = −0.77), nitrogen (r = −0.73), and ECEC (r = −0.70), indicating an inverse relationship between coarse soil texture and nutrient retention capacity.

Principal Component Analysis

The results of the principal component analysis are summarized in Table 3. Four principal components with eigenvalues greater than 1 were retained, explaining 89.93% of the total variance in the dataset.

The first principal component (PC1) explained 43.00% of the total variance and was strongly associated with organic carbon, nitrogen, calcium, magnesium, ECEC, and base saturation. The second

Table 2. Pearson Correlation Matrix of Selected Soil Quality Indicators (South-South)

Variable	OC	N	pH	Sand	Ca	Mg	ECEC	EA
OC	1.00							
N	0.91	1.00						
pH	0.69	0.66	1.00					
Sand	−0.77	−0.73	−0.54	1.00				
Ca	0.71	0.68	0.62	−0.49	1.00			
Mg	0.74	0.72	0.58	−0.46	0.86	1.00		
ECEC	0.83	0.80	0.55	−0.70	0.90	0.88	1.00	
EA	−0.68	−0.61	−0.84	0.41	−0.72	−0.69	−0.76	1.00

Source: own elaboration based on Laboratory Tests.

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component (PC2) explained 23.43% of the variance and was dominated by soil pH and exchangeable acidity. The third component (PC3) explained 15.07% of the variance and was associated primarily with soil texture variables.

Table 3. Eigenvalues and Percentage Variance Explained by Principal Components

Principal Component	Eigenvalue	Variance (%)	Cumulative (%)
PC1	6.02	43.00	43.00
PC2	3.28	23.43	66.43
PC3	2.11	15.07	81.50
PC4	1.18	8.43	89.93

Source: own elaboration based on Laboratory Tests.

The rotated component matrix (Table 4) indicates that PC1 represents a soil fertility and nutrient retention component, PC2 represents an acidity regulation component, and PC3 reflects texture-related physical properties.

Table 4. Rotated Component Matrix (Varimax Rotation)

Variable	PC1 (Fertility / Retention)	PC2 (Acidity)	PC3 (Texture)
OC	0.85	0.20	−0.17
N	0.82	0.24	−0.19
Ca	0.87	−0.12	0.11
Mg	0.84	−0.15	0.13
ECEC	0.90	−0.08	0.10
BS	0.77	−0.22	0.14
pH	0.21	0.86	−0.09
EA	−0.25	−0.83	0.12
Sand	−0.32	0.10	−0.85
Silt	0.30	−0.07	0.82

Source: own elaboration based on Laboratory Tests.

Regression Analysis for Organic Carbon

The multiple regression model for organic carbon is presented in Table 5. Total nitrogen showed a strong positive relationship with organic carbon (β = 0.69), while sand content exhibited a negative effect (β = −0.63). Soil pH showed a comparatively weaker positive influence on organic carbon variability.

Table 5. Multiple Regression Model for Organic Carbon (OC)
Dependent Variable: Organic Carbon

Predictor	B	Std. Error	Beta	t
Constant	−0.73	0.49	–	−1.49
Nitrogen (N)	3.01	1.05	0.69	2.87
Sand (%)	−0.016	0.005	−0.63	−3.12
pH	0.10	0.06	0.30	1.61

Source: own elaboration based on Laboratory Tests.

The ANOVA results for the regression model (Table 6) indicate that the selected predictors explain a substantial proportion of the variability in organic carbon across the study area.

Table 6. ANOVA for Organic Carbon Regression Model

Source	SS	df	MS	F
Regression	2.01	3	0.67	10.04
Residual	0.27	2	0.14	
Total	2.28	5		

Source: own elaboration based on statistical model.

Regression Analysis for Estimated Cation Exchange Capacity (ECEC)

The regression model for ECEC is presented in Table 7. Exchangeable calcium showed the strongest positive influence on ECEC (β = 0.66), followed by magnesium (β = 0.57) and organic carbon (β = 0.39).

Table 7. Multiple Regression Model for ECEC
Dependent Variable: ECEC

Predictor	B	Std. Error	Beta	t
Constant	0.98	2.64	—	0.37
Calcium (Ca)	1.09	0.35	0.66	3.11
Magnesium (Mg)	0.79	0.30	0.57	2.63
Organic Carbon (OC)	0.88	0.44	0.39	2.00

Source: own elaboration based on statistical model.

The ANOVA results (Table 8) indicate that the regression model explains a large proportion of the variability in nutrient retention capacity across the region.

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Table 8. ANOVA for ECEC Regression Model

Source	SS	df	MS	F
Regression	14.72	3	4.91	7.86
Residual	1.25	2	0.63	
Total	15.97	5		

Source: own elaboration based on statistical model.

Regression Analysis for Exchangeable Acidity

The regression model for exchangeable acidity is presented in Table 9. Soil pH showed a strong negative relationship with exchangeable acidity (β = −0.73), while exchangeable calcium also showed a negative influence (β = −0.62).

The ANOVA results (Table 10) indicate that the regression model explains most of the variability in exchangeable acidity within the dataset.

Table 9. Multiple Regression Model for Exchangeable Acidity (EA)

Dependent Variable: Exchangeable Acidity

Predictor	B	Std. Error	Beta	t
Constant	0.69	0.24	—	2.88
pH	−0.088	0.028	−0.73	−3.14
Calcium (Ca)	−0.027	0.010	−0.62	−2.70

Source: own elaboration based on statistical model.

Table 10. ANOVA for Exchangeable Acidity Regression Model

Source	SS	df	MS	F
Regression	0.091	2	0.046	8.42
Residual	0.011	3	0.004	
Total	0.102	5		

Source: own elaboration based on statistical model.

DISCUSSION

Overview of Soil Quality Variability in the South-South Zone

This study examined the dominant drivers of soil quality variability in the South-South zone of Nigeria using a regional-scale modelling framework combining descriptive statistics, correlation analysis, principal component analysis (PCA), and regression modelling. The results demonstrate that soil quality variability in the region is governed by interacting physical, chemical, and biological processes rather than by isolated soil properties.

The soils of the South-South zone are typical of humid tropical coastal environments characterized by high rainfall, intense weathering, and substantial leaching of basic cations. These conditions often result in acidic soils with relatively low nutrient retention capacity. Similar soil characteristics have been reported for tropical soils in other parts of West Africa and humid tropical regions worldwide (Lal, 2015; Prathibha & Kuligod, 2020). The modelling results of this study provide additional quantitative insight into how these environmental conditions interact to shape soil quality variability across the region.

Influence of Soil Texture on Soil Quality Variability

Soil texture emerged as a fundamental physical control on soil quality variability in the South-South zone. The soils were moderately sandy with considerable variability in silt content and relatively uniform clay fractions. The strong negative correlations between sand content and organic carbon, nitrogen, and estimated cation exchange capacity indicate that coarse soil texture limits the accumulation and stabilization of organic matter and reduces nutrient retention capacity.

In humid tropical environments, sandy soils promote rapid drainage and enhance nutrient leaching, thereby reducing the residence time of nutrients in the soil system. Previous studies have similarly reported that coarse-textured soils in tropical coastal regions are particularly susceptible to nutrient depletion and organic matter loss (Six et al., 2002; Wiesmeier et al., 2019). The identification of texture as a distinct principal component confirms that particle size distribution provides the physical framework that regulates chemical and biological soil processes.

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Fig. 3. Conceptual framework linking soil quality indicators, dominant drivers, and land administration decision-making for regional land management
Source: own elaboration.

Organic Matter and Nitrogen Dynamics

Organic carbon and total nitrogen exhibited strong positive correlations and dominant loadings within the fertility-related principal component, highlighting the close coupling of carbon and nitrogen cycling processes. Regression analysis further confirmed that nitrogen availability was the strongest predictor of organic carbon variability across the South-South zone.

This close relationship reflects the fact that nitrogen in tropical soils is largely stored in organic

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Fig. 4. Interplay of soil quality and other key components of the environment and society
Source: Pérez-Rendón (2020).

forms and released through microbial mineralization processes (Lehmann & Kleber, 2015). Under warm and humid climatic conditions typical of the South-South region, microbial activity is generally high, which accelerates the decomposition of organic matter and limits long-term carbon accumulation (Gerke, 2022). Consequently, spatial differences in organic matter inputs, decomposition rates, and nutrient cycling processes play a critical role in shaping soil quality patterns across the region.

Nutrient Retention Capacity and Exchangeable Base Status

Estimated cation exchange capacity (ECEC) emerged as an important indicator of soil quality variability. Regression modelling demonstrated that exchangeable calcium and magnesium were the dominant predictors of ECEC, while organic carbon provided an additional but comparatively smaller contribution.

In highly weathered tropical soils dominated by low-activity clay minerals, cation exchange capacity is often controlled more strongly by organic matter and exchangeable base cations than by clay mineralogy alone (Aprile & Lorandi, 2012). The relatively low ECEC values observed in the South-South zone therefore reflect the combined effects of coarse soil texture, advanced weathering, and limited organic matter accumulation.

The strong influence of calcium and magnesium indicates that base cation availability plays a central role in regulating nutrient retention capacity in the region. Continuous leaching under high rainfall conditions may reduce base cation concentrations, thereby increasing the vulnerability of soils to nutrient depletion.

Soil Acidity Dynamics

Soil acidity emerged as another major driver of soil quality variability in the South-South zone. Strong negative relationships were observed between soil pH and exchangeable acidity, and regression analysis confirmed soil pH as the primary regulator of exchangeable acidity dynamics.

Acidification processes are common in humid tropical soils where prolonged leaching removes base cations and increases hydrogen ion activity in the soil solution (Wu et al., 2023; Wu et al., 2024). The relatively acidic conditions observed in this study are therefore consistent with the environmental characteristics of the South-South region.

Exchangeable calcium also showed a significant negative relationship with exchangeable acidity, indicating the buffering role of base cations in moderating soil acidity. Similar buffering effects have been reported in other tropical soil systems where calcium availability reduces the dominance of acidic cations on exchange sites (Hinsinger et al., 2011).

Integration of PCA and Regression Results

The PCA results identified three major components controlling soil quality variability: chemical fertility and nutrient retention, soil acidity dynamics, and texture-related physical controls. These components

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provided a conceptual framework for interpreting the regression models.

The strong agreement between PCA loadings and regression coefficients suggests that soil quality variability in the South-South zone is structured by coherent soil processes rather than by random variation. The integration of multivariate analysis and regression modelling therefore provides a robust analytical approach for identifying dominant soil quality drivers in data-limited environments.

Implications for Land Administration and Spatial Planning

The identification of dominant soil quality drivers has important implications for land administration, spatial planning, and sustainable land management in the South-South region of Nigeria. Areas characterized by coarse-textured soils and low nutrient retention capacity may require specific soil management practices to maintain agricultural productivity.

Similarly, zones exhibiting strong soil acidity constraints may benefit from soil amendment strategies such as liming and organic matter management. Incorporating soil quality information into land-use planning frameworks can therefore improve land suitability assessments, guide agricultural zoning decisions, and support sustainable regional development strategies.

More broadly, the modelling framework adopted in this study demonstrates how soil quality data can be translated into spatial decision-support information for land managers and policy makers. Integrating such information into geographic information systems and land administration platforms could enhance evidence-based land management and promote sustainable land-use planning in humid tropical regions.

Study Limitations

This study was based on six composite soil samples representing the states of the South-South region of Nigeria. While this sampling design allows exploratory regional comparison, the limited sample size restricts the statistical robustness of multivariate analyses.

Future studies incorporating larger spatial datasets and more detailed sampling strategies would allow more robust modelling of soil quality drivers and improve the ability to capture within-region variability.

CONCLUSIONS

This study investigated the dominant drivers of soil quality variability in the South-South zone of Nigeria using a regional-scale modelling framework integrating descriptive statistics, correlation analysis, principal component analysis (PCA), and multiple regression modelling. The results demonstrate that soil quality variability across the region is governed by a limited number of interacting physical and chemical soil processes.

Organic carbon and total nitrogen exhibited strong coupling, reflecting the central role of organic matter dynamics in regulating soil fertility. Regression modelling confirmed nitrogen availability as the most influential predictor of organic carbon variability, highlighting the importance of biological processes in soil quality regulation.

Estimated cation exchange capacity (ECEC) showed relatively low to moderate values and was primarily controlled by exchangeable calcium and magnesium, with organic carbon providing an additional contribution. These results indicate that nutrient retention capacity in the region is largely governed by base cation availability rather than clay mineral content.

Soil acidity emerged as another important driver of soil quality variability. Strong negative relationships between soil pH and exchangeable acidity were observed, with regression analysis confirming soil pH as the primary regulator of acidity dynamics. Exchangeable calcium also played an important buffering role by reducing acidity levels.

Overall, the results indicate that soil quality variability in the South-South zone is controlled

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by four key interacting factors: organic matter and nitrogen dynamics, base-cation-controlled nutrient retention capacity, soil acidity regulation, and texture-mediated physical constraints. These drivers operate under humid tropical conditions characterized by intense rainfall and advanced weathering.

Beyond their environmental significance, these findings have important implications for land administration and spatial planning. Identifying dominant soil quality drivers provides a scientific basis for incorporating soil constraints into land-use zoning, land suitability classification, and sustainable agricultural land management strategies.

Future studies should incorporate larger spatial datasets and more detailed sampling designs in order to improve the robustness of soil quality modelling and to better capture spatial variability across the region.

Although the study provides useful insights into regional soil quality drivers, future research incorporating larger datasets and finer spatial sampling would improve model robustness and regional applicability.

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