Application of Nutrient Index and Multivariate Analysis for Soil Fertility Assessment of Rice Farms in Okigwe, Southeastern Nigeria

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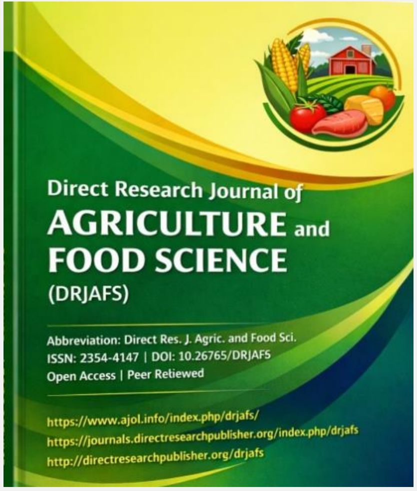
ABSTRACT

Soil fertility decline remains a major constraint to sustainable rice production in southeastern Nigeria, largely due to continuous cultivation and poor nutrient management practices. This study evaluated the nutrient status of selected rice farm soils in Okigwe area of Imo State using the nutrient index (NI) approach, alongside multivariate statistical techniques. Surface soil samples (0–15 cm) were collected from ten rice farms and analyzed for physical and chemical properties using standard procedures. Results showed that the soils were predominantly sandy, with sand content ranging from 45.2% to 68.4% (mean = 54.5%), while clay and silt contents varied widely between 5.6–41.6% (mean = 22.2%) and 6.0–48.0% (mean = 23.3%), respectively, indicating considerable spatial variability. Soil pH ranged from 4.60 to 5.96 (mean = 5.46), classifying the soils as slightly to moderately acidic. Available phosphorus ranged from 2.18 to 16.25 mg kg^{-1} (mean = 6.41 mg kg^{-1}), while total nitrogen varied from 0.60 to 3.10 g kg^{-1} (mean = 1.21 g kg^{-1}), both indicating low to moderate nutrient status. Organic carbon content ranged from 7.9 to 36.3 g kg^{-1} (mean = 14.31 g kg^{-1}). Exchangeable Ca, Mg, K, and Na ranged from 2.0–5.6, 1.2–2.8, 0.11–0.29, and 0.05–0.21 cmol kg^{-1}, respectively. Cation exchange capacity (CEC) varied from 4.83 to 10.54 cmol kg^{-1} (mean = 6.28 cmol kg^{-1}), while base saturation ranged from 71.3% to 86.9% (mean = 79.77%). Nutrient index values indicated low fertility status for pH (1.0), total nitrogen (1.6), available phosphorus (1.1), and CEC (1.1), while organic carbon (2.1), calcium (2.1), potassium (1.7), and sodium (1.8) were in the medium category, and magnesium (3.0) and base saturation (2.5) were high. Principal component analysis extracted five components explaining 90.19% of total variance, with soil fertility (37.27%) and soil acidity (19.85%) as dominant factors. Strong positive correlations were observed between organic matter and total nitrogen (r = 0.99), available phosphorus (r = 0.93), calcium (r = 0.90), and CEC (r = 0.83), highlighting the central role of organic matter in nutrient dynamics. The study concludes that although the soils are moderately fertile, acidity, low nitrogen and phosphorus, and low CEC are major constraints to rice productivity. Liming, integrated nutrient management, and site-specific fertilizer application are recommended to enhance soil fertility and sustain rice production in the area.

Keywords: *Soil fertility, nutrient index, rice soils, soil acidity, Okigwe, nutrient management.*



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INTRODUCTION

Soil fertility is a central determinant of agroecosystem productivity, particularly in intensively cultivated smallholder systems of sub-Saharan Africa, where food demand continues to rise under conditions of declining soil quality. It describes the capacity of soil to supply essential plant nutrients in adequate amounts, proportions, and temporal availability to sustain crop growth. It is governed by complex interactions among soil chemical, physical, and biological properties as well as external management inputs. In tropical environments, soil fertility is highly dynamic due to rapid organic matter turnover, intense weathering, and nutrient leaching, which collectively contribute to nutrient depletion when cultivation is continuous and not matched with appropriate replenishment strategies (Akinbode *et al*., 2024; Oyun *et al*., 2025).

In Nigeria, particularly within rain-fed agricultural systems, soil fertility decline has emerged as a major biophysical constraint to crop production, with significant implications for food security and rural livelihoods. Rice (Oryza sativa L.), being a strategic staple crop, is increasingly cultivated in both upland and lowland ecologies to meet rising consumption demands. However, long-term rice cultivation without balanced nutrient inputs has been associated with progressive depletion of macronutrients, deterioration of soil organic carbon, and increasing nutrient imbalance, thereby reducing system productivity and resilience (Adelana *et al*., 2022). In southeastern Nigeria, including the Okigwe agro ecological zone of Imo State, rice production systems are characterized by marked spatial heterogeneity arising from variations in parent material, topography, hydrology, and land management practices. This heterogeneity results in highly variable soil fertility conditions, which complicate uniform fertilizer recommendations and often leads to suboptimal nutrient use efficiency (Nwawuike, 2024). Traditional soil fertility evaluation approaches typically rely on univariate assessments of individual soil parameters such as pH, organic matter, total nitrogen, available phosphorus, and exchangeable bases. While these indicators are important, they do not adequately represent the interactive and multicollinearity nature of soil systems, where nutrient availability is controlled by coupled physicochemical processes. Consequently, there has been a paradigm shift toward integrated soil fertility assessment frameworks that combine composite indices with multivariate statistical techniques to better characterize soil quality and identify dominant controlling factors. The nutrient index approach provides a semi-quantitative classification of soil fertility status by aggregating key nutrient concentrations into interpretable fertility classes (low, medium, high), thereby facilitating agronomic decision-making and spatial comparison across landscapes (Ojobor *et al*., 2021). However, its interpretative strength is enhanced when combined with multivariate statistical tools such as principal component analysis (PCA), factor analysis, and cluster analysis, which reduce data dimensionality, minimize redundancy among correlated variables, and extract latent structures governing soil variability (Awe *et al*., 2020). Despite the increasing recognition of these integrated analytical approaches in soil science, their application in many rice-producing environments in southeastern Nigeria remains limited. In Okigwe, fertilizer management practices are still largely generalized, with minimal incorporation of site-specific soil information. This often results in inefficient nutrient management, characterized by either under-application or over-application of fertilizers, both of which have negative consequences including reduced economic returns, soil nutrient imbalance, and potential environmental degradation. Furthermore, continuous cultivation without systematic soil monitoring exacerbates nutrient mining and organic matter depletion, thereby threatening the long-term sustainability of rice-based production systems (Okafor *et al*., 2025).

Given the complexity and spatial variability of rice agroecosystems in Okigwe, there is a clear need for robust, data-driven soil fertility assessment frameworks that integrate nutrient index evaluation with multivariate statistical analysis. Such an integrated approach not only provides a comprehensive diagnosis of soil fertility constraints but also enables the identification of key limiting nutrients and dominant soil quality indicators driving productivity variations. This is critical for developing site-specific nutrient management strategies that enhance nutrient use efficiency, improve crop yield stability, and support sustainable intensification of rice production systems in the region. Therefore, this study applies nutrient index methodology in combination with multivariate statistical techniques to evaluate the soil fertility status of rice farms in Okigwe, southeastern Nigeria. The study further seeks to identify principal soil factors controlling fertility variation and to provide a scientific basis for precision-based nutrient management interventions aimed at improving rice productivity and sustaining soil health in the agro ecological zone.

MATERIALS AND METHOD

Description of Study Area

Soil sampling was conducted within rice-growing fields in Okigwe, Imo State, Southeastern Nigeria, a humid tropical agro ecological zone characterized by high rainfall, intensive land use, and spatially variable soil conditions (Figure 1). Geographically, it is located between latitudes 5^{o} 18' and 5^{o} 34' N and longitudes 7^{o} 15'

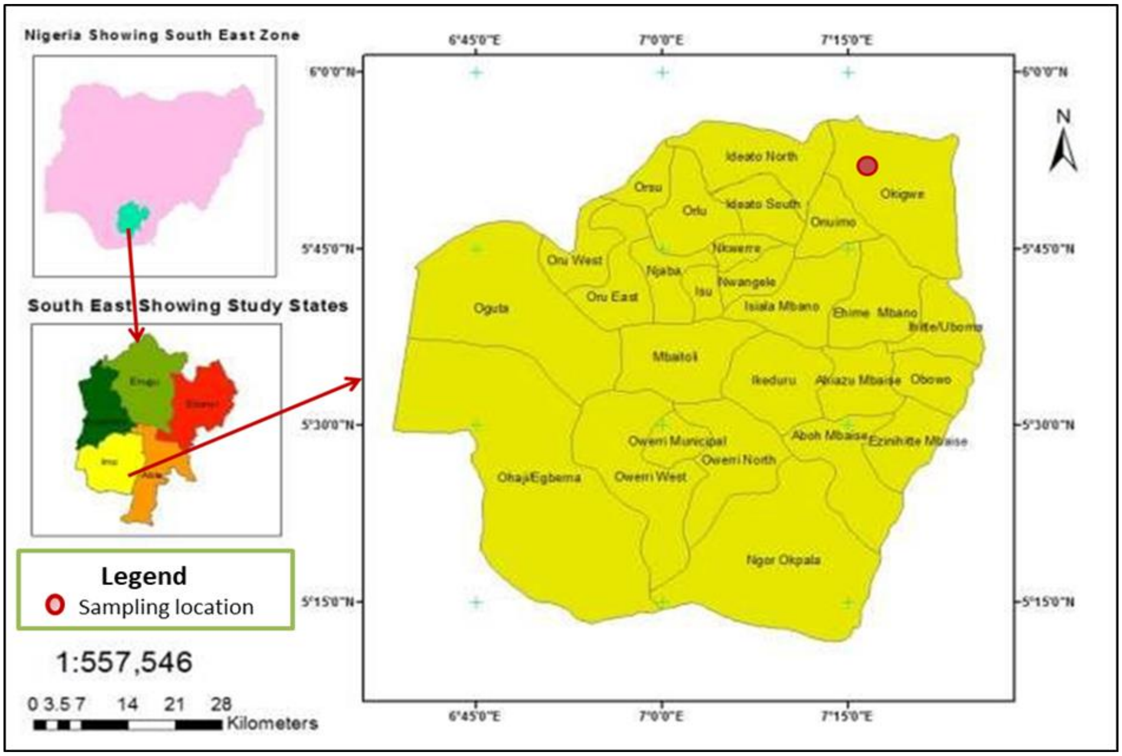

Figure 1: Map showing the study location

and 7^{o} 26' E (Iwuji *et al*., 2022). The study area occupies a landmass of about 360 km^{2} (NBS, 2006). The area supports both upland and lowland rice systems, where soil fertility status is strongly influenced by topography, flooding regime, and management intensity (Nwawuike, 2024). A reconnaissance survey was first carried out to identify representative rice farms, after which a stratified random sampling design was adopted to capture variability across different rice production environments. Stratification was based on landform position and cropping intensity to ensure adequate representation of soil heterogeneity, which is critical for fertility assessment in tropical agroecosystems (Akinbode *et al*., 2024).

Soil Sampling and Preparation

Soil samples were collected from the 0–20 cm depth, representing the plough layer and the most biologically active zone for nutrient cycling and plant uptake. Ten farms were selected at random and from each farm soil samples were collected at the beginning, medium and the end of each farm. Samples from each farm were bulked to get one composite sample. In all ten (10) composite samples were collected which was air-dried, gently crushed, and sieved through a 2 mm mesh prior to laboratory analysis, following standard soil analytical procedures (Oyun *et al*., 2025).

Laboratory Analysis

Soil physicochemical properties relevant to fertility assessment were determined using standard methods. Soil pH was measured in a 1:2.5 soil-to-water suspension using a calibrated pH meter. Soil organic carbon (SOC) was determined using the Walkley–Black wet oxidation method, and organic matter was estimated using the conversion factor of 1.724. Total nitrogen was analyzed using the Kjeldahl digestion method. Available phosphorus was extracted using the Bray-1 method and quantified spectrophotometrically. Exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) was extracted using neutral ammonium acetate (1N, pH 7.0) and measured using atomic absorption spectrophotometry or flame photometry, while CEC was determined by neutral ammonium acetate procedure buffered at pH 7.0 (Thomas, 1982). Particle size distribution was determined using the hydrometer method (Adelana *et al*., 2022).

Soil fertility Assessment

Soil fertility status was evaluated using the Nutrient Index (NI) approach, which provides a composite classification of soil nutrient status into low, medium, and high categories. This method is widely used for simplifying nutrient evaluation in agricultural soils and supporting

Table 1: The soil physical properties of the selected rice farms in the study location.

Locations	Sand	Clay	Silt	Textural class
		%		
Site 1	55.2	6.8	38.0	Sandy loam
Site 2	49.2	5.6	45.0	Sandy loam
Site 3	55.2	6.4	38.4	Sandy loam
Site 4	45.2	6.8	48.0	Sandy loam
Site 5	53.2	22.8	24.0	Sandy clay loam
Site 6	68.4	25.6	6.0	Sandy clay loam
Site 7	50.8	41.2	8.0	Sandy clay
Site 8	52.4	41.6	6.0	Sandy clay
Site 9	68.4	25.6	6.0	Sandy clay loam
Site 10	46.0	40.0	14.0	Sandy clay
Mean	54.5	22.2	23.3	-
STD	8.12	15.19	17.46	
%CV	14.93	68.31	74.81	-

fertilizer recommendations (Ojobor *et al*., 2021). The nutrient index was computed using the expression:

$$NI = \frac{(1XNL) + (2XNM) + (3XNH)}{TNS}$$

Where; NL, NM, and NH represent the number of samples in low, medium, and high fertility classes, respectively, and TNS is the total number of samples analyzed. Nutrient index values will be interpreted as: <1.67 (low fertility), 1.67–2.33 (moderate fertility), and >2.33 (high fertility). This classification provides a rapid diagnostic tool for identifying nutrient limitations across the study area (Delsouz *et al*., 2017).

Statistical Analysis

Multivariate statistical techniques were applied to complement the nutrient index approach by evaluating relationships among soil properties and identifying key factors controlling fertility variability. Data were standardized using z-score transformation after normality testing. Principal Component Analysis (PCA) was performed for dimensionality reduction, extracting components with eigenvalues > 1 (Kaiser's criterion), while Varimax rotation improved interpretability and loadings ≥ 0.5 were considered significant (Awe *et al*., 2020). Hierarchical Cluster Analysis (Ward's method, Euclidean distance) grouped sampling sites into homogeneous fertility classes for delineating management zones in precision agriculture. Pearson correlation analysis was used to determine relationships among soil properties and nutrient dynamics (Adelana *et al*., 2022). All analyses were conducted using SPSS version 26.0. The integrated approach of nutrient index and multivariate analysis provides a robust framework for identifying soil fertility constraints and supporting sustainable rice production in Okigwe agroecosystems.

RESULTS AND DISCUSSION

Soil Physical Properties of the Selected Rice Farms

Soil particle size distribution across the selected rice farms showed marked spatial variability in sand, silt, and clay fractions, resulting in sandy loam, sandy clay loam, and sandy clay textures (Table 1). Sand content ranged from 45.2% to 68.4% (mean 54.5% ± 8.12), indicating generally coarse-textured soils with high infiltration, low water-holding capacity, and potential nutrient leaching risks (Brady & Weil, 2016; Osinuga *et al*., 2020). Silt ranged from 6.0% to 48.0% (mean 23.3% ± 17.46), reflecting strong spatial heterogeneity and contributing to improved moisture and nutrient retention in higher-silt sites (González *et al*., 2023). Clay varied from 5.6% to 41.6% (mean 22.2% ± 15.19), with higher values enhancing water retention and flood stability essential for rice production (Zhang *et al*., 2024). Soils were classified as sandy loam (Sites 1–4), sandy clay loam (Sites 5–6, 9), and sandy clay (Sites 7–8, 10). In all, sandy loam dominance suggests moderate constraints for rice cultivation, whereas clay-enriched soils are more favorable for water and nutrient retention. High coefficients of variation indicate strong spatial heterogeneity, supporting the need for site-specific nutrient and water management under precision agriculture systems.

Soil Chemical Properties of the Selected Rice Farms

The chemical properties of soils across the ten rice farms showed notable spatial variability, indicating differences in fertility status (Table 2). Soils were generally moderately acidic, with pH ranging from 4.60 to 5.96 (mean 5.46 ± 0.36), reflecting typical tropical conditions and potential constraints on nutrient availability, particularly phosphorus, due to increased fixation and possible Al toxicity (Brady & Weil, 2016; Zhang *et al*.,

Table 2: The soil chemical properties of the selected rice farms in the study location

Site No.	pH	Avail P	Total N	OC	Ca	Mg	K	Na	H^+	Al^{3+}	CEC	BS
	(H_2O)	mgkg-1	gkg-1			Cmolkg-1			Cmolkg-1		Cmolkg-1	%
Site 1	5.63	9.63	1.30	15.9	2.8	2.0	0.18	0.09	0.8	1.0	6.87	73.7
Site 2	5.44	6.36	1.13	13.1	2.6	1.6	0.27	0.16	0.3	0.8	5.73	80.5
Site 3	5.51	5.86	1.00	12.3	3.2	1.2	0.11	0.15	0.3	0.4	5.36	86.9
Site 4	5.26	5.63	1.25	14.5	2.4	1.6	0.12	0.19	0.5	0.8	5.61	76.8
Site 5	5.31	16.25	3.10	36.3	5.6	2.8	0.23	0.11	0.7	1.1	10.54	82.9
Site 6	5.65	3.76	0.90	10.5	2.0	1.2	0.15	0.13	0.6	0.8	4.88	71.3
Site 7	5.60	3.07	0.92	10.9	2.6	1.6	0.11	0.05	0.3	0.4	5.06	86.1
Site 8	4.60	4.25	0.96	11.2	2.4	1.2	0.23	0.10	0.3	0.6	4.83	81.3
Site 9	5.65	7.12	0.90	10.5	3.2	2.8	0.16	0.12	0.4	1.3	7.98	78.6
Site 10	5.96	2.18	0.60	7.9	2.6	1.6	0.29	0.21	0.5	0.7	5.90	79.6
Mean	5.46	6.41	1.21	14.31	2.94	1.76	0.19	0.13	0.47	0.79	6.28	79.77
STD	0.36	4.07	0.69	8.05	1.00	0.60	0.07	0.05	0.18	0.29	1.79	4.97
%CV	6.62	63.54	57.60	56.25	34.10	34.22	35.88	36.60	38.91	36.52	28.44	6.23

Table 3: Rotated component loadings and communalities of 16 physical and chemical, properties on significant principal components (PCs) for rice fields of the Okigwe region of Imo State

Soil Characteristics	PC1	PC2	PC3	PC4	PC5
Eigenvalue	7.53	2.89	2.36	1.52	1.09
% of Variance	44.29	17.00	13.88	8.93	6.42
Cumulative percent	44.29	61.29	75.17	84.10	90.52
Factor loading					
Avail P	0.967	-0.158	0.048	-0.131	-0.038
CEC	0.956	0.004	-0.131	0.130	0.206
OM	0.911	-0.348	0.002	-0.035	-0.119
OC	0.911	-0.348	-0.003	-0.036	-0.119
TN	0.908	-0.348	-0.011	-0.046	-0.133
Ca2+	0.874	-0.362	-0.163	0.070	0.214
Mg2+	0.825	0.189	-0.229	0.094	0.328
TEA	0.784	0.597	0.074	0.053	-0.094
Al3+	0.723	0.576	-0.018	0.102	0.021
H+	0.659	0.460	0.194	-0.035	-0.245
BS	-0.077	-0.849	-0.255	0.036	0.436
Sand	0.116	0.620	-0.460	-0.413	0.080
Silt	0.177	-.0264	0.907	-0.203	0.060
Clay	-0.266	-0.027	-0.798	0.454	-0.112
Na+	-0.152	0.122	0.675	0.501	0.169
K+	0.187	-0.002	0.082	0.876	-0.209
pH	-0.015	0.495	0.141	0.115	0.703

Extraction Method: Principal Component Analysis.
Highly weighted loadings are presented in bold italic type.

2024). Available phosphorus (2.18–16.25 mg kg^{-1}; mean 6.41 ± 4.07 mg kg^{-1}) and total nitrogen (0.60–3.10 g kg^{-1}; mean 1.21 ± 0.69 g kg^{-1}) were generally low, indicating widespread nutrient limitations likely driven by leaching and P fixation in acidic soils (González *et al*., 2023). Organic carbon varied widely (7.9–36.3 g kg^{-1}), reflecting differences in organic matter inputs, with higher values improving soil quality and nutrient cycling. Exchangeable Ca (2.0–5.6 cmol kg^{-1}) and Mg (1.2–2.8 cmol kg^{-1}) were moderate, while K was low (0.11–0.29 cmol kg^{-1}), suggesting potential K limitation. Exchangeable acidity (H^+: 0.3–0.8 cmol kg^{-1}; Al^{3+}: 0.4–1.3 cmol kg^{-1}) indicated possible aluminum toxicity risks in more acidic sites. Cation exchange capacity was low to moderate (4.83–10.54 cmol kg^{-1}), limiting nutrient retention, although base saturation remained relatively high (71.3–86.9%). In summary, the soils are moderately acidic with low to moderate fertility status, characterized by N and P deficiencies, variable organic carbon, limited nutrient retention capacity, and localized Al toxicity. The high spatial variability underscores the need for site-specific soil management, including liming, organic amendments, and balanced NPK fertilization to improve rice productivity and sustain soil fertility in the study area (Osinuga *et al*., 2020; González *et al*., 2023; Zhang *et al*., 2024).

Grouping soil quality indicators as a determinant for major soil fertility constraints: Principal component analysis (PCA)

Principal Component Analysis (PCA) was applied to reduce dataset dimensionality and identify key factors controlling soil variability. Five principal components (PCs) with eigenvalues > 1 were extracted, explaining 90.52% of total variance, indicating strong model adequacy (Jolliffe & Cadima, 2016; González *et al*., 2023) (Table 3). PC1 (44.29%) was the dominant factor,

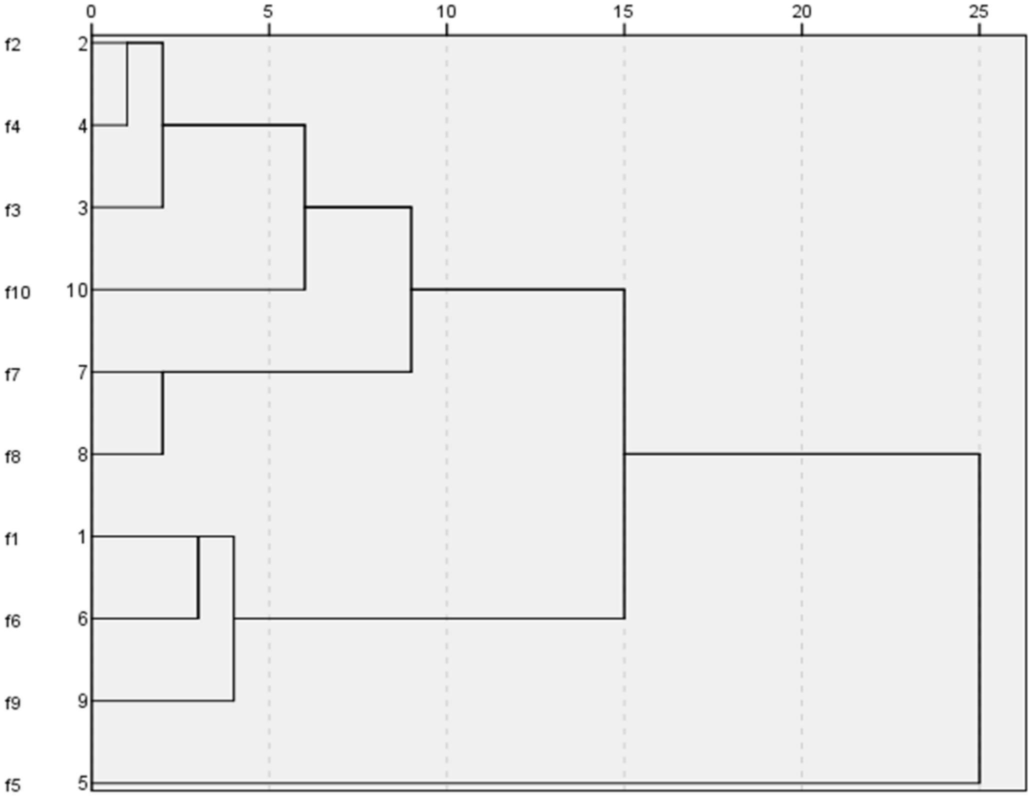

Figure 2: Grouping of sites for its similarity in fertility using hierarchical cluster analysis (HCA)

followed by PC2 (17.00%), PC3 (13.88%), PC4 (8.93%), and PC5 (6.42%). The first three PCs accounted for 75.17% of the variance, capturing the major soil processes. PC1 showed strong positive loadings for available P, CEC, organic matter, organic carbon, total N, Ca, Mg, and exchangeable acidity (Al^{3+} and H^+), representing a combined fertility–acidity factor driven by organic matter and nutrient retention in acidic conditions. PC2 was associated with TEA, Al^{3+}, H^+, sand, and negative loading for base saturation, indicating an acidity–leaching factor influenced by soil texture. PC3 was defined by silt (positive) and clay (negative), representing soil texture variability with implications for Na^+ distribution and water–nutrient dynamics. PC4 was dominated by K^+ (with contributions from Na^+ and clay), indicating a potassium-controlled fertility factor influenced by finer particles. PC5 was characterized by pH and base-related properties (base saturation and Mg), representing soil reaction dynamics.

Overall, PCA indicates that soil variability is governed by five key controls: organic matter–driven fertility (PC1), acidity and leaching processes (PC2), texture (PC3), potassium distribution (PC4), and soil reaction (PC5). The dominance of PC1 highlights organic matter and nutrient status as primary fertility drivers, while PC2 and PC3 emphasize the roles of acidity and texture. These findings support integrated soil management strategies involving organic amendments, liming, and balanced NPK fertilization to improve soil productivity in the study area (Brady & Weil, 2016; Zhang *et al*., 2024).

Hierarchical cluster analysis (HCA)

Hierarchical Cluster Analysis (HCA) using Ward's linkage and Euclidean distance grouped the ten sampling sites based on similarities in soil physicochemical properties, with linkage distances indicating degrees of dissimilarity (González *et al*., 2023). Three main clusters were identified. Cluster I comprised Sites 2, 4, and 3, with Sites 2 and 4 showing the highest similarity and Site 3 joining at a slightly higher distance, indicating comparable soil fertility status and chemical properties likely influenced by similar management or parent material. Cluster II included Sites 10, 7, and 8, where Sites 7 and 8 were most similar, and Site 10 merged at a moderate distance, reflecting moderately similar soils characterized by comparable texture, acidity, and nutrient status (Figure 2). Cluster III consisted of Sites 1, 6, 9, and 5. Sites 1 and 6 formed a close subgroup, later joined by Site 9, while Site 5 was the most distinct, clustering at the highest linkage distance. This indicates a unique, higher-fertility soil condition at Site 5, consistent with elevated organic carbon, nitrogen, phosphorus, and CEC observed in earlier analyses. Overall, the dendrogram reveals strong

Table 4: The relationship between soil nutrients

	pH	**Sand**	**Silt**	**Clay**	**OM**	**TEA**	**Al3+**	**H+**	**TN**	**Ca2+**	**Mg2+**	**K+**	**Na+**	**CEC**	**BS**	**Avail P**
pH	1															
Sand	0.18	1														
Silt	-0.01	-0.50*	1													
Clay	-0.08	0.04	-0.89**	1												
OM	-0.21	-0.10	0.23	-0.21	1											
TEA	0.21	0.36	0.04	-0.24	0.50*	1										
Al3+	0.14	0.43	-0.02	-0.21	0.40	0.93**	1									
H+	0.27	0.15	0.13	-0.23	0.52*	0.82**	0.56*	1								
TN	-0.24	-0.09	0.22	-0.21	0.99**	0.50*	0.41	0.50*	1							
Ca2+	-0.05	-0.01	0.08	-0.09	0.90**	0.43	0.41	0.34	0.90**	1						
Mg2+	0.18	0.24	-0.07	-0.05	0.60	0.75*	0.83**	0.41	0.60*	0.72*	1					
K+	-0.04	-0.31	-0.05	0.22	0.14	0.20	0.24	0.10	0.13	0.17	0.13	1				
Na+	0.24	-0.33	0.40	-0.28	-0.19	0.00	0.02	-0.03	-0.20	-0.17	-0.19	0.34	1			
CEC	0.09	0.14	0.04	-0.12	0.83**	0.74*	0.74*	0.53*	0.82**	0.91**	0.92**	0.23	-0.12	1		
BS	-0.18	-0.38	0.01	0.19	0.15	-0.62*	-0.51*	-0.62*	0.15	0.38	-0.01	-0.07	-0.18	0.06	1	
Avail P	-0.14	0.08	0.29	-0.38	0.93**	0.66*	0.60*	0.57*	0.93**	0.88**	0.73*	0.12	-0.23	0.90**	0.04	1

**: Correlation is significant at the 0.01 level (2-tailed).

*: Correlation is significant at the 0.05 level (2-tailed).

spatial heterogeneity in soil properties across the study area. Cluster I and II represent moderately similar soils, while Cluster III includes both moderately similar and highly distinct soils. The pronounced separation of Site 5 highlights a high-fertility zone, emphasizing the influence of variable management practices, parent materials, and environmental conditions typical of tropical agroecosystems (Brady & Weil, 2016).

Relationship between Soil Nutrients

The Pearson correlation matrix (Table 4) revealed significant relationships ($p \leq 0.05$ and $p \leq 0.01$) among soil physical and chemical properties, indicating tightly coupled fertility processes consistent with PCA and HCA results (Brady & Weil, 2016; González *et al*., 2023). A strong negative correlation between silt and clay ($r = -0.89$) and between sand and silt ($r = -0.50$) reflects contrasting particle size distribution influencing soil water and nutrient dynamics. Organic matter (OM) showed the strongest positive associations with total nitrogen ($r = 0.99$), available phosphorus ($r = 0.93$), calcium ($r = 0.90$), and CEC ($r = 0.83$), indicating its central role in regulating soil fertility. TN also correlated strongly with Ca ($r = 0.90$), CEC ($r = 0.82$), and Avail P ($r = 0.93$), highlighting integrated nutrient behavior driven by OM. CEC exhibited strong relationships with Ca ($r = 0.91$), Mg ($r = 0.92$), TN ($r = 0.82$), and Avail P ($r = 0.90$), confirming its role as a key integrative fertility parameter.

Exchangeable acidity components (Al^{3+}, H^{+}, TEA) were strongly interrelated (r up to 0.93) and negatively correlated with base saturation ($r = -0.62$ to -0.51), indicating displacement of basic cations under increasing acidity. Available phosphorus correlated positively with OM ($r = 0.93$), TN ($r = 0.93$), Ca ($r = 0.88$), CEC ($r = 0.90$), and acidity parameters ($r = 0.57$–0.66), reflecting its dependence on both organic matter and soil chemical environment. Soil pH showed weak and mostly non-significant relationships, indicating that exchangeable acidity better explains nutrient dynamics in these soils. Overall, the correlations confirm that soil fertility is governed by interacting physical and chemical processes, with organic matter, CEC, and acidity components acting as key controlling factors. These findings support integrated soil fertility management involving organic amendments, liming, and balanced fertilization (Brady & Weil, 2016; Zhang *et al*., 2024).

Nutrient index value (NIV) of the study area

The nutrient index (NI) approach was used to assess overall soil fertility status by classifying parameters into low, medium, and high categories, providing a simplified interpretation for management decisions in heterogeneous agroecosystems (Brady & Weil, 2016). Soil pH recorded a low NI (1.0), indicating strong acidity and associated constraints on nutrient availability, particularly phosphorus, and increased risk of Al toxicity. Organic carbon showed a medium NI (2.1), reflecting moderate organic matter status, while total nitrogen was low (1.6), indicating widespread N deficiency typical of tropical soils due to leaching and rapid mineralization (González *et al*., 2023).

Calcium (2.1), potassium (1.7), and sodium (1.8) exhibited medium NI values, suggesting moderate availability, whereas magnesium recorded a high NI (3.0), indicating sufficiency. CEC was low (1.1), reflecting poor nutrient retention capacity, consistent with sandy texture and low organic matter. Base saturation was high (2.5), indicating dominance of exchangeable bases despite acidic conditions. Available phosphorus also showed a low NI (1.1), confirming severe P limitation due to fixation under acidic conditions (Zhang *et al*., 2024). The soils are characterized by low pH, nitrogen, phosphorus, and CEC, with moderate organic carbon and base cations, and high magnesium and base saturation. This pattern indicates

Table 5: Soil rating chart for calculating nutrient index

Soil properties	**Range**		
	Low	**Medium**	**High**
Soil pH	5.5 - 6.0	6.1 - 6.9	7.1 - 8.5
Available Phosphorus (mgkg^{-1})	<10	10 - 20	>20
Base saturation (%)	<50	50 - 80	>80
Total nitrogen (gkg-1)	<1.0	1.0 - 2.0	>2.0
Organic carbon (gkg-1)	<10	10 - 15	>15
Exchangeable cations			
Calcium (Cmolckg^{-1})	<2	2 - 5	>5
Magnesium (Cmoclkg^{-1})	<0.3	0.3 - 1.0	>1.0
Potassium (Cmolckg^{-1})	<0.15	0.15 - 0.30	>0.30
Sodium (Cmoclkg-1)	<0.1	0.1 - 0.3	>0.3
Cation exchange capacity (CEC) (Cmolckg^{-1})	<6	6 - 12	>12

Source Esu, 1992

Table 6: Nutrient index with range and remark (Ramamoorthy and Bajay, 1969)

Nutrient index	**Range**	**Remark**
I	Below 1.67	Low
II	1.67 - 2.33	Medium
III	Above 2.33	High

Table 7: Nutrient index of the soil chemical properties of the study area

Soil Parameters	**Nutrient index**	**Remark**
pH	1.0	Low
O.C	2.1	Medium
TN	1.6	Low
Ca	2.1	Medium
Mg	3.0	High
K	1.7	Medium
Na	1.8	Medium
CEC	1.1	Low
BS	2.5	High
Avail P	I.1	Low

moderate inherent fertility but strong constraints from acidity, low nutrient reserves, and poor retention capacity (Tables 5-7). The findings highlight the need for liming, nitrogen and phosphorus fertilization, and organic matter incorporation to improve nutrient retention and rice productivity under site-specific soil management strategies (Brady & Weil, 2016; González *et al*., 2023; Zhang *et al*., 2024).

Conclusion

The soils of Okigwe rice farms exhibit pronounced spatial variability in physical and chemical properties, with textures ranging from sandy loam to sandy clay. This heterogeneity, combined with coarse fractions, predisposes the soils to low water-holding capacity and nutrient leaching. Chemically, the soils are moderately acidic, with consistently low nitrogen, available phosphorus, and cation exchange capacity, alongside localized aluminum toxicity risks, collectively indicating constrained fertility despite moderate organic carbon and base saturation. Multivariate analyses (PCA and HCA) and correlation results consistently identify organic matter, soil acidity, and texture as the dominant controls of soil fertility. Organic matter plays a central role in nutrient availability and retention, while acidity and texture regulate nutrient dynamics and leaching processes. The nutrient index further confirms that low pH, N, P, and CEC are the principal fertility limitations. These findings have important implications for the research community and soil management in Okigwe. The marked spatial variability invalidates uniform management approaches and supports the adoption of site-specific soil fertility strategies. Sustainable rice production will require integrated soil fertility management, including liming to correct acidity, organic amendments to enhance nutrient retention, and balanced N and P fertilization. Furthermore, the delineation of soil variability zones provides a scientific basis for precision agriculture and targeted interventions. Finally, this study underscores the necessity for data-driven, location-specific soil management to improve productivity and sustain soil health in the region.

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