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GIS-Based Multi-Criteria Evaluation of Soil Fertility Suitability in Wukari Urban, North-Eastern Nigeria

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ABSTRACT

Soil fertility suitability assessment is essential for agricultural planning and land management, particularly in urban and peri-urban environments where land use pressures are intensifying. This study developed a GIS-based Soil Fertility Suitability Index (SFSI) for the Wukari urban area in north-eastern Nigeria using a multi-criteria evaluation framework guided by principal component analysis. Five fertility indicators: total nitrogen, available phosphorus, exchangeable calcium, total exchangeable bases, and organic matter were selected based on their demonstrated significance in the study area's fertility structure. PCA-derived loadings were used as objective weights: Ca (0.305), TEB (0.301), TN (0.206), OM (0.155), and AVP (0.033). Kriged prediction surfaces were normalized to a 0–1 scale and combined via weighted linear combination. The resulting SFSI exhibited a mean of 0.329, median of 0.329, and near-symmetric distribution (IQR = 0.288–0.370). Classification using standard deviation thresholds revealed that the Moderate class occupied the largest proportion (39.02%), followed by Low (36.99%), Very Low (13.10%), High (7.88%), and Very High (3.01%). The spatial pattern was characterized by a Moderate-class matrix with localized High and Very High hotspots. Individual factor maps revealed distinct spatial patterns among criteria, with calcium and total exchangeable bases showing similar distributions consistent with their strong correlation, while available phosphorus exhibited a more fragmented pattern. The PCA-based weighting framework provides an objective, reproducible approach to fertility suitability mapping, with implications for targeted nutrient management and agricultural planning in data-scarce urban environments.

Keywords: *Soil fertility suitability, multi-criteria evaluation, GIS, principal component analysis, weighted overlay, Wukari.*

1. INTRODUCTION

Soil fertility is a critical determinant of agricultural productivity and food security, particularly in sub-Saharan Africa where smallholder farming systems dominate, and soil degradation is widespread [2, 8]. Traditional approaches to soil fertility assessment have largely focused on measuring individual nutrient concentrations or developing composite indices, often without translating these measurements into spatially explicit suitability classes useful for land use planning and agricultural decision-making [4; 5].

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Geographic Information Systems and Multi-Criteria Evaluation have emerged as powerful tools for agricultural land suitability assessment, enabling the integration of multiple soil properties into a unified decision-support framework [11; 9]. Weighted linear combination, the most widely used MCE technique, allows for the systematic combination of criteria through the application of weights that reflect their relative importance [6; 7]. However, the assignment of weights remains a persistent challenge, with many studies relying on subjective expert opinion or arbitrary scoring schemes that reduce reproducibility and scientific defensibility [3; 10].

Principal Component Analysis offers a robust alternative to subjective weighting by deriving objective weights from the covariance structure of measured soil properties [1; 12]. Variables with higher loadings on the dominant principal component exert greater influence on overall fertility variation, providing a statistically defensible basis for criterion weighting. Despite this advantage, few studies have systematically integrated PCA-derived weights into GIS-based MCE frameworks for soil fertility suitability assessment in urban agricultural landscapes.

The Wukari urban area in north-eastern Nigeria presents a relevant case for such investigation due to its heterogeneous land use patterns, evolving soil management practices, and the pressing need for evidence-based agricultural planning. This study therefore aims to develop a GIS-based Soil Fertility Suitability Index (SFSI) using PCA-derived weights and weighted linear combination techniques. Specific objectives are to: (i) identify and standardize fertility criteria based on demonstrated significance from statistical analysis, (ii) derive objective weights from PCA loadings, (iii) implement weighted overlay to generate a continuous suitability surface, (iv) classify suitability into management-relevant zones using standard deviation thresholds, (v) map individual factor distributions, and (vi) quantify spatial patterns and area distributions to inform agricultural planning.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in the Wukari urban area, located in Taraba State, north-eastern Nigeria. Wukari lies within the Guinea Savanna ecological zone, characterized by distinct wet and dry seasons with mean annual rainfall of approximately 1,200–1,400 mm. The soils are predominantly derived from basement complex rocks and are classified as Ferric Luvisols and Plinthic Lixisols, characterized by sandy textures, low organic matter content, and moderate to low cation exchange capacity. Land use is mixed, including arable agriculture, fallow lands, built-up areas, and peri-urban agricultural zones.

2.2 Soil Sampling and Laboratory Analysis

A total of 70 soil samples were collected using a spatially distributed sampling design to capture intra-urban variability. Geographic coordinates were recorded using a handheld GPS receiver (WGS 1984 datum) and projected to Universal Transverse Mercator Zone 32N for spatial analysis. Following quality control screening, 50 locations with complete laboratory data and valid coordinates were retained. Laboratory analyses quantified soil reaction (pH), electrical conductivity, particle size fractions, bulk density, particle density, porosity, organic carbon, organic matter, total nitrogen, available phosphorus, exchangeable bases (Ca, Mg, K, Na), total exchangeable bases, total exchangeable acidity, effective cation exchange capacity, percent base saturation, sodium adsorption ratio, and exchangeable sodium percentage using standard methods.

2.3 Selection of Fertility Criteria

Fertility criteria for the MCE framework were selected based on demonstrated significance in the study area's soil fertility structure, as established by PCA and correlation analyses. Variables with high absolute loadings on the first principal component (PC1), which explained 31.6% of total variance, were prioritized. Additionally, variables exhibiting meaningful spatial variation in kriged prediction surfaces were retained to ensure discriminatory power in the suitability assessment.

The final set comprised five criteria: total nitrogen, available phosphorus, exchangeable calcium, total exchangeable bases, and organic matter. Calcium and TEB were included due to their dominant loadings (0.903 and 0.891, respectively) and strong correlations (r = 0.93–0.97). Total nitrogen (loading 0.609) and organic matter (loading 0.458) were selected for their contributions to nutrient cycling. Available phosphorus, despite its low loading (0.099), was retained to ensure representation of macronutrient status.

2.4 Kriging Prediction Surfaces

Spatial prediction for each selected criterion was performed using ordinary kriging, a best linear unbiased estimator that incorporates spatial autocorrelation through fitted semivariogram models.

Experimental semivariograms were computed for each variable, and theoretical models (Spherical, Exponential, Gaussian, and Stable) were fitted via weighted least squares, with model selection based on minimum residual sum of squares.

Prediction was performed at 50 m spatial resolution on a regular grid covering the Wukari urban administrative boundary. All rasters were projected in UTM Zone 32N and clipped to the study area boundary.

Model performance was evaluated using leave-one-out cross-validation. Mean prediction errors for all variables were effectively zero (ME < 0.03), confirming unbiased estimation. Root Mean Square Standardized (RMSS) values were generally close to unity (0.92–1.02), confirming reliable uncertainty estimation. Variables exhibiting high skewness, such as SAR (RMSS = 1.58) and Na (RMSS = 1.32), showed slight underestimation of variability but remained within acceptable limits. The kriging predictions were therefore considered statistically robust and suitable for use as input layers in the subsequent multi-criteria evaluation.

2.5 Criterion Weight Derivation

Weights were derived objectively from absolute PCA loadings on PC1. For each selected variable, weight was calculated as:

$$W_i = \backslash frac\{|L_i|\}\{\sum|L_i|\} \quad (1)$$

Where Wi is the weight for criterion I_i and L_i is its PC1 loading. This approach ensures that variables contributing more to the dominant fertility gradient receive proportionally greater influence in the suitability model. The resulting normalized weights are presented in Table 1.

2.6 Raster Standardization

All kriged prediction rasters were standardized to a common 0–1 scale using min-max normalization:

$$S_i = \backslash frac\{X_i - X_{\{min\}}\}\{X_{\{max\}} - X_{\{min\}}\} \quad (2)$$

Where S_t is the standardized value for criterion I, X_t is the original raster value, and $X_{\{min\}}$ and $X_{\{max\}}$ are the global minimum and maximum values across the study area. Standardization ensures that all criteria contribute proportionally to the weighted combination regardless of their original measurement scales and ranges. The standardized factor rasters were retained for spatial visualization of individual criterion distributions [Figure 3.6].

2.7 Weighted Linear Combination

The Soil Fertility Suitability Index was calculated as the weighted sum of standardized criteria:

$$SFSI = \sum_{\{i=1\}}^{\{n\}(W_i \times S_i)} \quad (3)$$

Where n represents the number of criteria (n = 5), W_i is the normalized PCA-derived weight, and S_i is the standardized raster for criterion ii. This linear combination was implemented using raster algebra in R (v4.3.2) with the raster package.

2.8 Suitability Classification

The continuous SFSI surface was classified into five suitability classes using standard deviation thresholds derived from the SFSI distribution.

Standard deviation classification was selected over equal interval classification because it reflects the actual data distribution and produces more balanced classes, enabling meaningful spatial interpretation. Thresholds were defined as: Very Low (below mean minus one standard deviation), Low (mean minus one standard deviation to mean), Moderate (mean to mean plus one standard deviation), High (mean plus one to two standard deviations), and Very High (above mean plus two standard deviations). Area statistics were computed by converting raster pixel counts to hectares based on 50 m resolution.

3. RESULTS

3.1 Distribution Characteristics of SFSI

The Soil Fertility Suitability Index exhibited a range of 0.085 to 0.901 across the study area, with a mean of 0.329 and a median of 0.329 (Table 2). The near-equivalence of mean and median indicates a relatively balanced distribution with minimal skewness. The interquartile range (0.288–0.370) was narrow relative to the total range, suggesting that most pixels cluster around moderate suitability values while few locations reach extremes. The 5th and 95th percentiles were 0.208 and 0.442, respectively, confirming that 90% of the study area falls within a relatively narrow suitability band (Table 3).

Table 1: PCA-derived weights for fertility criteria used in the SFSI model

Variable	PC1 Loading	Normalized Weight
Ca	0.903	0.305
TEB	0.891	0.301
TN	0.609	0.206
OM	0.458	0.155
AVP	0.099	0.033
Total	**2.960**	**1.000**

Table 2: Distribution statistics of the Soil Fertility Suitability Index (SFSI)

Statistic	Value
Minimum	0.085
Maximum	0.901
Mean	0.329
Median	0.329
1st Quartile	0.288
3rd Quartile	0.370
Interquartile Range	0.082
Standard Deviation	0.060

Table 3: Quantile summary of SFSI scores

Percentile	SFSI
5%	0.208
10%	0.243
25%	0.288
50%	0.329
75%	0.370
90%	0.403
95%	0.442

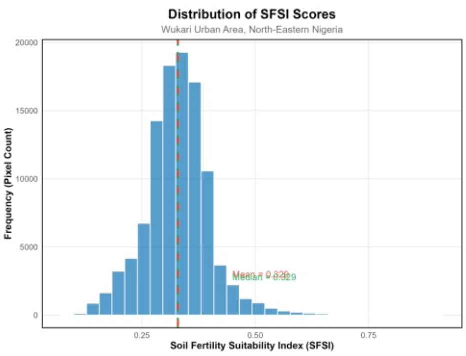

Figure 3.1 Distribution of continuous Soil Fertility Suitability Index scores across Wukari urban area, showing near-symmetric distribution with limited extreme values

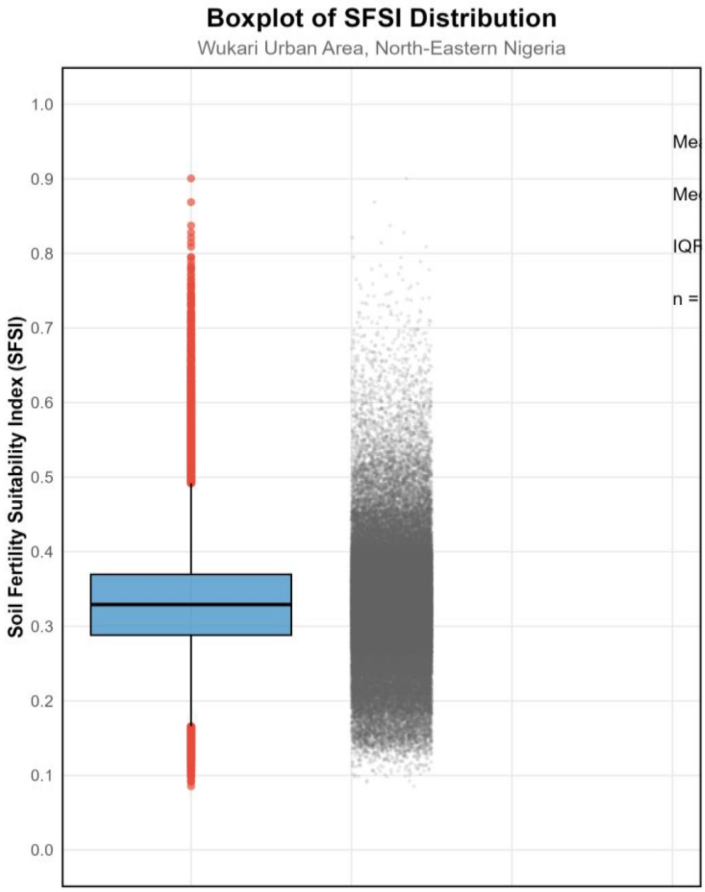

Figure 3.2: Boxplot showing SFSI distribution with narrow interquartile range and limited outliers

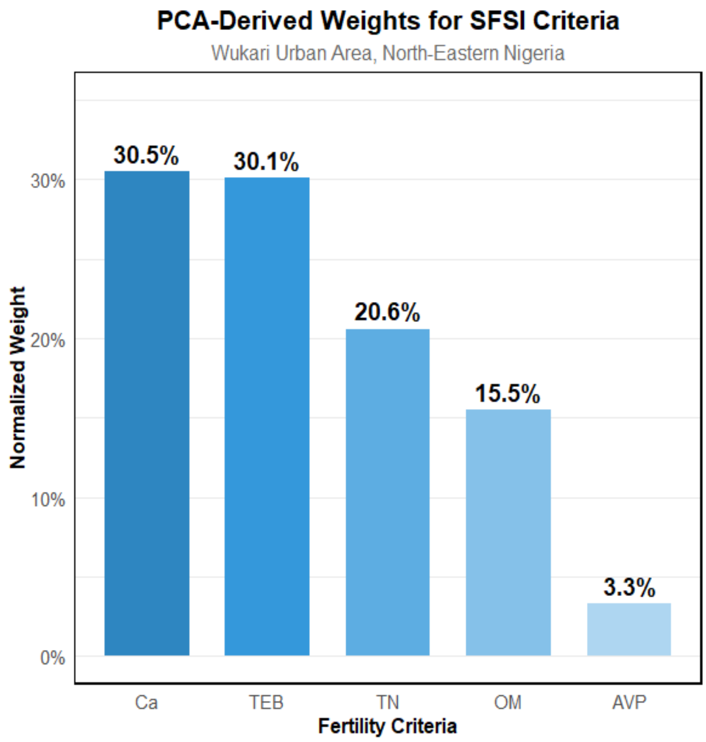

Figure 3.3: PCA Weight Contribution Chart: Normalized PCA-derived weights for each fertility criterion, showing dominant influence of Ca (30.5%) and TEB (30.1%) on the SFSI model.

3.2 Spatial Patterns of Individual Fertility Criteria (Factor Maps)

The standardized factor maps (Figure 3.3) reveal the spatial distribution of the five fertility criteria before their combination into the SFSI. Calcium and total exchangeable bases exhibited broadly similar spatial patterns, characterized by moderate spatial continuity across the study area. This similarity is consistent with their strong correlation (r = 0.93) and joint dominance in the PCA structure. Total nitrogen and organic matter showed moderate spatial correspondence, reflecting the organic–nitrogen coupling observed in the correlation analysis (r = 0.79). Available phosphorus displayed a more fragmented and spatially discontinuous pattern, consistent with its independence from exchange-complex dynamics and weak association with the dominant fertility gradient.

The factor maps also reveal that areas of elevated calcium and TEB did not always coincide with elevated nitrogen or organic matter, indicating that the different criteria capture complementary dimensions of fertility. This spatial heterogeneity underscores the importance of a multi-criteria approach: a location may possess favorable exchange capacity yet have limited nitrogen availability, or vice versa. The factor maps therefore provide diagnostic insight into which specific criteria are driving the overall suitability classification.

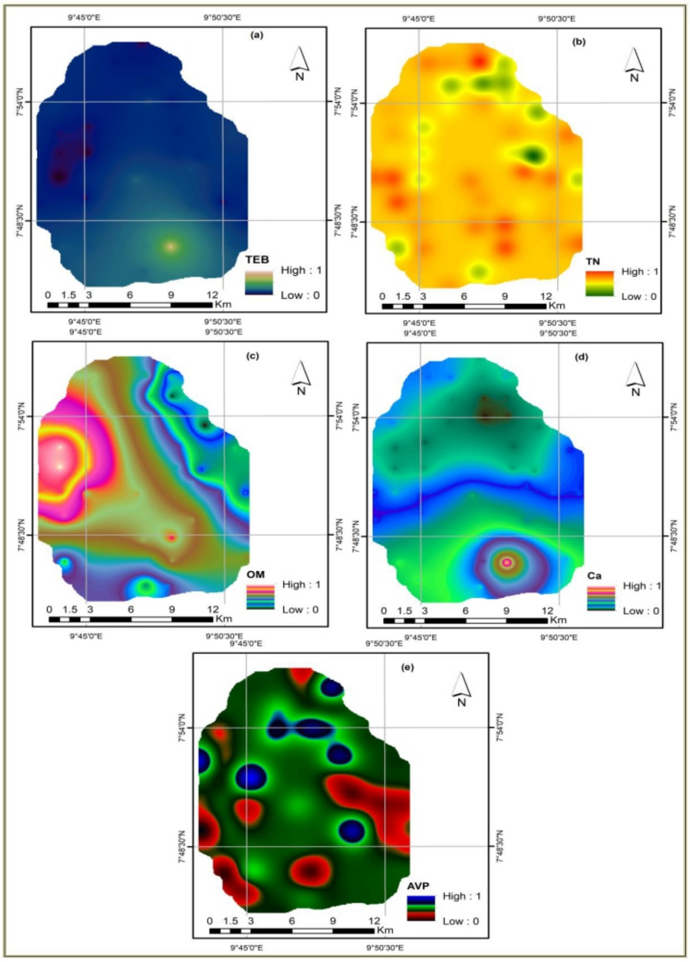

Figure 3.4: [Standardized Factor Maps (a–e)]: Spatial distribution of standardized fertility criteria across Wukari urban area: (a) Total Exchangeable Bases, (b) Total Nitrogen, (c) Organic Matter, (d) Exchangeable Calcium and (e) Available Phosphorus. All rasters are normalized to a 0–1 scale using min-max standardization.

3.3 Suitability Class Distribution

The spatial configuration of classes (Figure 3.5) revealed a gradient from Very Low to Very High rather than a binary pattern. The Moderate class, being the largest, formed the matrix within which higher and lower suitability patches were embedded. High and Very High classes occurred as localized hotspots, consistent with the exchange-complex dominance identified in the weighting structure. Very Low areas were spatially distributed rather than concentrated, suggesting that severe fertility limitations are not confined to a single geomorphic domain. Classification using standard deviation thresholds, derived from the SFSI distribution (mean = 0.329, SD = 0.060), revealed a balanced distribution of suitability classes (Table 4). The Moderate class was the largest, occupying 10,307.5 ha (39.02% of the study area), followed by Low at 9,770.75 ha (36.99%). Very Low covered 3,461 ha (13.10%), while High and Very High classes occupied 2,081 ha (7.88%) and 794 ha (3.01%), respectively.

Table 4: SFSI class area summary using standard deviation classification

Class	Pixel Count	Area (ha)	Percentage
Very Low	13,844	3,461.00	13.10
Low	39,083	9,770.75	36.99
Moderate	41,230	10,307.50	39.02
High	8,324	2,081.00	7.88
Very High	3,176	794.00	3.01
Total	**105,657**	**26,414.25**	**100**

3.4 Quantile Structure and Spatial Patterns

Quantile analysis (Table 3) confirmed the narrow concentration of SFSI scores. The 10th and 90th percentiles were 0.243 and 0.403, respectively, indicating that 80% of the study area falls within a 0.160-unit range. The 25th and 75th percentiles (0.288 and 0.370) show that half the area is concentrated within a 0.082-unit band. This narrow interquartile range, combined with the class distribution, indicates that fertility suitability in Wukari is remarkably uniform across the majority of the landscape, with only localized patches departing from this central tendency.

Spatially, High and Very High pixels occurred as localized clusters rather than forming broad contiguous zones, suggesting that extremely favorable soil conditions are rare and spatially fragmented. These hotspots likely correspond to areas with elevated exchange capacity and calcium enrichment, consistent with the dominance of Ca and TEB weights in the model (61% combined).

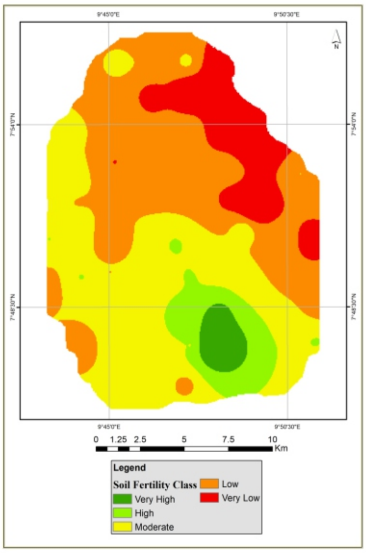

Figure 3.5: Spatial distribution of Soil Fertility Suitability Index classes across Wukari urban area using standard deviation classification, showing Moderate class dominance (39.02%) and localized High/Very High hotspots.

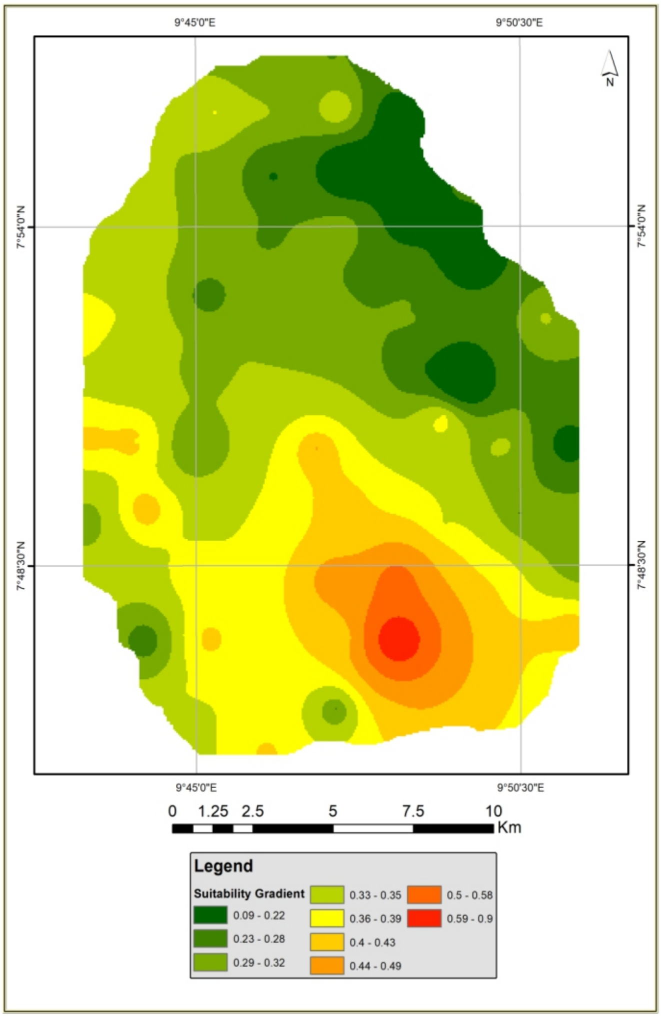

Figure 3.6: Continuous SFSI surface across Wukari urban area showing gradual suitability gradients and localized hotspots. Values range from 0.085 (lowest suitability) to 0.901 (highest suitability)

4. DISCUSSION

4.1 Fertility Suitability Constraints in Wukari

The standard deviation classification reveals that the Moderate class dominates (39.02%), followed closely by Low (36.99%), with Very Low (13.10%), High (7.88%), and Very High (3.01%) occupying smaller proportions. This distribution indicates that while fertility resources are present across much of the landscape, the simultaneous optimization of all evaluated fertility criteria is spatially limited. The Moderate class dominance suggests that most areas meet some but not all criteria for high suitability.

The Very Low class (13.10%) represents areas with significant fertility limitations requiring priority intervention. These areas likely correspond to sandy, nutrient-depleted soils with low organic matter and limited exchange capacity. The High (7.88%) and Very High (3.01%) classes, while small in extent, represent the most promising agricultural lands in the study area. Their spatial fragmentation indicates that high agricultural suitability is not governed by broad pedogenic processes but by localized factors—possibly micro-topography, land use history, or localized anthropogenic inputs.

4.2 Exchange-Complex Dominance in Suitability Patterns

The weighting structure (Ca 30.5%, TEB 30.1%) reflects the fundamental chemical architecture of Wukari soils identified in the PCA.

The dominance of exchange-complex variables in the SFSI confirms that calcium availability and cation reserve capacity are the primary chemical constraints governing suitability patterns. This finding is consistent with soils derived from basement complex rocks, which typically exhibit low weatherable minerals and limited cation reserves [2; 12].

Areas classified as High or Very High suitability likely correspond to locations with elevated exchangeable Ca and TEB, possibly reflecting parent material heterogeneity or localized organic amendments. The limited influence of available phosphorus (3.3%) in the suitability model, despite its agronomic importance, reflects its weak association with the dominant fertility gradient as established by PCA. This does not diminish phosphorus's importance for crop production but rather indicates that phosphorus availability varies independently of exchange-complex chemistry. Consequently, phosphorus management should be considered separately from overall fertility suitability assessment.

4.3 Factor Map Insights

The standardized factor maps (Figure 3.4) provide additional diagnostic value by revealing the spatial patterns of individual criteria. The similar distributions of calcium and TEB confirm that these variables are functionally redundant in the fertility system; a finding consistent with their near-perfect correlation (r = 0.97). The moderate correspondence between TN and OM reflects their coupled biogeochemical cycling, while the fragmented pattern of AVP indicates that phosphorus availability is controlled by processes distinct from the exchange complex, such as fixation reactions or management history [6; 11].

The factor maps also highlight an important limitation of the weighted linear combination approach: a pixel may achieve Moderate suitability through different combinations of criterion scores. For example, one area may have high Ca and TEB but low TN, while another may have moderate Ca and moderate TN. The SFSI does not distinguish between these scenarios, which is a limitation of the additive model. This reinforces the need for site-specific management informed by both the overall SFSI and the underlying factor maps.

4.4 Spatial Heterogeneity and Management Implications

The spatial fragmentation of High and Very High classes has important implications for agricultural management. The patchiness suggests that blanket fertilizer recommendations would be inefficient, as they would over-apply nutrients to areas with limited response potential while under-supplying localized hotspots. Instead, site-specific management strategies should prioritize the limited High and Very High areas for intensive cultivation, while Moderate and Low areas may require targeted amendments, particularly organic matter addition and calcium supplementation to improve suitability [3; 10].

The Very High class (3.01%, 794 ha) represents the most favorable agricultural lands in Wukari. These areas warrant priority for conservation and sustainable intensification. The Very Low class (13.10%, 3,461 ha) requires attention to avoid further degradation through appropriate soil conservation measures and targeted fertility restoration.

4.5 Methodological Contribution and Data-Driven Weighting

The use of PCA-derived weights represents the primary methodological contribution of this study.

By deriving weights from the covariance structure of measured soil properties, rather than expert opinion or arbitrary scoring, the SFSI is statistically defensible and objectively reproducible. This addresses a persistent criticism of MCE studies: the subjectivity of weight assignment and provides a replicable framework for fertility suitability assessment in data-scarce environments [9; 1].

The adoption of standard deviation classification, rather than equal interval, further strengthens the methodological rigor. Standard deviation thresholds reflect the actual data distribution and produce classes that are statistically meaningful, enabling more reliable spatial interpretation. The inclusion of factor maps (Figure 3.4) adds transparency by allowing readers to visualize the individual criterion distributions underlying the composite SFSI.

4.6 Implications for Agricultural Planning

The findings have direct implications for agricultural planning in Wukari. First, the limited extent of High and Very High suitability (10.89% combined) suggests that priority should be given to protecting and enhancing these rare zones through conservation agriculture and organic matter management. Second, the widespread Moderate and Low suitability (76.01% combined) indicates that most agricultural lands would require significant investment to achieve productive potential. Third, the spatial fragmentation of High zones suggests that dispersed small-scale interventions may be more effective than large-scale uniform approaches. Fourth, the factor maps provide diagnostic information to guide location-specific interventions based on which criteria are most limiting.

5. CONCLUSION

This study developed a GIS-based Soil Fertility Suitability Index for the Wukari urban area using a multi-criteria evaluation framework guided by PCA-derived weights. The key findings are:

I) Balanced suitability distribution. Standard deviation classification revealed that the Moderate class dominates (39.02%), followed by Low (36.99%), Very Low (13.10%), High (7.88%), and Very High (3.01%). This represents a more nuanced pattern than the equal interval approach, which artificially compressed 84.97% into the Low class.

ii) Exchange-complex governance. Calcium (30.5%) and total exchangeable bases (30.1%) dominated the suitability model, confirming that cation reserve capacity is the primary chemical constraint governing suitability patterns in Wukari.

iii) Spatial fragmentation. High and Very High classes occurred as localized hotspots rather than contiguous areas, reflecting localized fertility hotspots rather than broad pedogenic transitions.

iv) Factor map insights. Individual criterion distributions revealed similar spatial patterns for Ca and TEB (consistent with their strong correlation), moderate correspondence between TN and OM, and a fragmented pattern for AVP, confirming its independence from exchange-complex dynamics.

v) Methodological contribution. The PCA-derived weighting framework provides an objective, reproducible approach to fertility suitability assessment, reducing the subjectivity inherent in expert-based weighting schemes. The adoption of standard deviation classification and inclusion of factor maps further strengthen the methodological rigor.

The Very High class (3.01%, 794 ha) represents the most favorable agricultural lands in Wukari and should be prioritized for conservation.

The Very Low class (13.10%, 3,461 ha) requires priority intervention to avoid further degradation. The widespread Moderate and Low classes (76.01% combined) indicate that most agricultural lands would benefit from targeted organic amendments and exchange-complex enhancement.

Recommendations for Further Research

Future work should integrate socioeconomic criteria (e.g., market access, infrastructure, labor availability) with the biophysical suitability assessment to produce a comprehensive agricultural land evaluation framework. Incorporating land use and land cover data could refine suitability classification by accounting for current agricultural activities. Temporal monitoring of fertility suitability would elucidate the impacts of urbanization on soil quality and inform adaptive management strategies. Finally, validation of suitability classes against crop yield data would strengthen the practical applicability of the SFSI for agricultural planning.

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Declaration of competing interests

The authors declare no competing interests.

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