NJSS 35(2) 2026: 12-24 DOI: 10.67042/njss.2026.xxxxxxxxx

Nigerian Journal of Soil Science

Original Research

Spatial Multi-Criteria Evaluation of Land Suitability for Rainfed Cowpea (*Vigna unguiculata L.*) Production in Kambriwa, Kaugama LGA, Nigeria

Alkasim Abdulkadir*, Mohammed Juji Magaji, Bassam Lawan Abdurahman, Salihu Ahmad Pantami

Department of Soil Science, Faculty of Agriculture, Bayero University Kano, P.M.B 3011, Nigeria.

***Corresponding Author Details:**
Email: alkasimabdulkadir0878@gmail.com
Orcid Id: 0009-0001-7248-285X

Keywords:
Cowpea, Geographic Information System, Multi-Criteria Decision Analysis, Analytical Hierarchy Process, Fertility Limitations; Land-use planning.

Manuscript History:
Submitted: 08th August 2026
Accepted: 16th August 2026
Published:

Abstract

Improving cowpea productivity in the semi-arid Sudan Savanna requires spatially explicit information on land resources to support agricultural planning and soil management. This study evaluated the suitability of land for rainfed cowpea (*Vigna unguiculata* (L.) Walp.) production in Kambriwa, Kaugama Local Government Area, Jigawa State, Nigeria, using a Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA). Fifty-six geo-referenced surface soil samples (0–30 cm) were collected and analyzed for selected physico-chemical properties. Continuous spatial distribution maps of the soil properties were generated through spatial interpolation and evaluated using cross-validation, while slope, topographic wetness index (TWI), rainfall, and temperature were incorporated from digital elevation and climatic datasets. The evaluation criteria were standardized using a suitability framework informed by FAO land-evaluation principles, crop-specific requirements, and established soil-fertility classifications, and weighted using the Analytical Hierarchy Process (AHP). The suitability analysis showed that sand (94.25%), soil pH (82.96%), exchangeable potassium (71.31%), slope (99.99%), TWI (97.35%), rainfall and temperature (100%), were predominantly highly suitable for rainfed cowpea cultivation. Conversely, available phosphorus and cation exchange capacity represented the limiting factors, with 29.65% and 19.50% of the study area classified as not suitable, respectively, while nitrogen was largely moderately suitable (75.12%). The final overlayed land suitability classified 132.49 ha (12.08%) as highly suitable (S1), 927.09 ha (84.52%) as moderately suitable (S2), and 37.31 ha (3.40%) as marginally suitable (S3), with no areas falling within the not suitable (N) class. The findings indicate that the study area has substantial potential for rainfed cowpea production, although strategic phosphorus fertilization and practices that improve soil nutrient retention may help address identified soil fertility limitations. The study demonstrates the applicability of GIS-based spatial MCDA for spatially informed land-use planning in semi-arid environments, while the interpretation of the resulting suitability classes should consider uncertainties associated with soil-property prediction and spatial interpolation.

1. Introduction

Land suitability evaluation provides a scientific basis for determining the capacity of land to support a specified crop under defined management conditions. It involves matching the characteristics and qualities of land, including soil, climate, topography, drainage and fertility, with the requirements of a particular crop (FAO, 1976). Such evaluation is increasingly important in semi-arid agricultural environments where population pressure, continuous cultivation, nutrient depletion and climatic variability place considerable pressure on soil resources. By identifying areas with different degrees of suitability and the factors limiting production, land evaluation can support more efficient land-use planning and sustainable soil management (FAO, 2007).

The Sudan Savanna of northwestern Nigeria is an important agricultural zone, but its production potential is constrained by the inherent characteristics of its soils and prevailing climatic conditions. Many soils in the region are dominated by coarse-textured materials and have relatively low organic matter and nutrient-retention capacity, making them susceptible to nutrient depletion and declining productivity under continuous cultivation (Esu, 2010). Prolonged cultivation without adequate nutrient replenishment has contributed to nutrient mining and soil fertility decline across the West African savannas (Bationo *et alet al*., 2007). Consequently, agricultural planning based on generalized land-use recommendations may not adequately account for the spatial variability of soil and environmental conditions.

Cowpea (*Vigna unguiculata L. Walp*.) is particularly important in these environments because of its adaptation to relatively dry conditions, nutritional value and contribution to soil fertility in cereal-legume production systems. As a legume, cowpea forms a symbiotic association with rhizobia and contributes biologically fixed nitrogen to agricultural systems. Nevertheless, its adaptation to low-rainfall environments does not eliminate the influence of soil and landscape conditions on productivity. Soil fertility, phosphorus availability, TWI and moisture conditions can influence crop growth, nodulation and yield (Singh *et alet al*., 2003). The identification of areas that satisfy the major ecological and edaphic requirements of cowpea is therefore important for improving production efficiency and supporting sustainable land management.

Conventional land suitability assessment has traditionally relied on qualitative matching of land characteristics with crop requirements. Although useful, such approaches may become restrictive when several environmental variables need to be evaluated simultaneously. Geographic Information Systems (GIS) have expanded the capacity for spatial land evaluation by enabling the integration, analysis and visualization of heterogeneous environmental datasets within a common geographic framework (Malczewski, 2004). Multi-Criteria Decision Analysis (MCDA) further provides a structured means of combining multiple criteria according to their relative importance in determining land suitability.

Among MCDA techniques, the Analytical Hierarchy Process (AHP) provides a systematic procedure for establishing the relative priorities of decision criteria through pairwise comparison (Saaty, 2008). When integrated with GIS, AHP allows soil, climatic and topographic variables to be weighted and combined spatially to produce composite suitability maps. Such GIS-based approaches have been applied successfully in agricultural land evaluation and provide useful decision-support information for crop planning and resource management (Elsheikh *et alet al*., 2013).

Despite the growing application of GIS and multi-criteria approaches to agricultural land evaluation, detailed spatial information on cowpea suitability remains limited in parts of the Sudan Savanna of Nigeria, particularly in Jigawa State. Kambriwa, in Kaugama Local Government Area, is an important agricultural landscape where crop production is influenced by spatial differences in soil properties, fertility status, TWI and terrain. The absence of detailed spatial suitability information limits the ability of farmers, extension personnel and land managers to distinguish areas with different production potentials and to target appropriate soil-management interventions.

A GIS-based multi-criteria evaluation therefore provides an opportunity to move beyond generalized recommendations by integrating the principal land characteristics that influence cowpea production into a spatial decision-support framework. Such an approach can identify highly suitable areas, distinguish areas with moderate or marginal suitability, and reveal the major constraints requiring management attention. This is particularly relevant in the Sudan Savanna, where efficient allocation of soil amendments and other agricultural inputs is essential for maintaining productivity while minimizing resource degradation.

The study aimed to evaluate the spatial suitability of land for sustainable cowpea production in Kambriwa, Kaugama Local Government Area, Jigawa State, Nigeria, using Analytical Hierarchy Process (AHP) and GIS-based multi-criteria decision framework.

2. Materials and Methods

2.1 Study Area

The study was conducted in Kambriwa, Kaugama Local Government Area (LGA) of Jigawa State, northwestern Nigeria, located approximately between 12.6167°–12.6598° N and 9.8030°–9.8377° E, at an elevation of about 350–400 m above sea level. The area lies within the Hadejia–Jama'are River Basin and is characterized by predominantly flat to gently undulating terrain underlain by Quaternary sands, silts and clays of the Chad Formation (Aliyu *et alet al*., 2022; Bakari, 2014). The area falls within the Sudan Savanna and experiences a distinct wet season, generally from June to September, with mean annual rainfall of approximately 600–800 mm, followed by a prolonged dry season. Temperatures are generally high, exceeding 38 °C during the hottest months (Abubakar *et alet al*., 2024). Agriculture is the dominant land use, with cowpea and other rain-fed crops widely cultivated. These environmental conditions provide an appropriate setting for spatial evaluation of land suitability for cowpea production.

2.2 Soil Sampling

Fifty-six (56) geo-referenced surface soil samples were collected from the approximately 1,096-ha study area using a purposive sampling approach designed to capture the observable spatial variability of the landscape and soil conditions. Sampling locations were selected based on apparent differences in terrain position and field morphological characteristics, including slope, soil colour, structure and texture. At each selected location, three soil cores were collected within close proximity using a soil auger and composited to obtain a representative sample for the sampling point while reducing the influence of small-scale spatial variability. Samples were collected from the 0–30 cm surface layer, which represents the principal cultivated soil layer and the zone directly influenced by routine agricultural management practices. Geographic coordinates of all sampling locations were recorded using a handheld Global Positioning System (GPS) receiver for subsequent spatial interpolation and suitability mapping.

2.3 Soil Sample Preparation and Analysis

The collected soil samples were air-dried under clean, shaded and well-ventilated laboratory conditions, gently disaggregated, and passed through a 2-mm stainless-steel sieve. The <2-mm fraction was retained and further finely ground to obtain a homogeneous powder for spectroscopic analysis. Selected soil physicochemical properties were estimated from mid-infrared (MIR) spectra acquired using a Bruker ALPHA II Fourier Transform Infrared (FTIR) spectrometer (Bruker Optik GmbH, Ettlingen, Germany) equipped with an Attenuated Total Reflectance (ATR) module

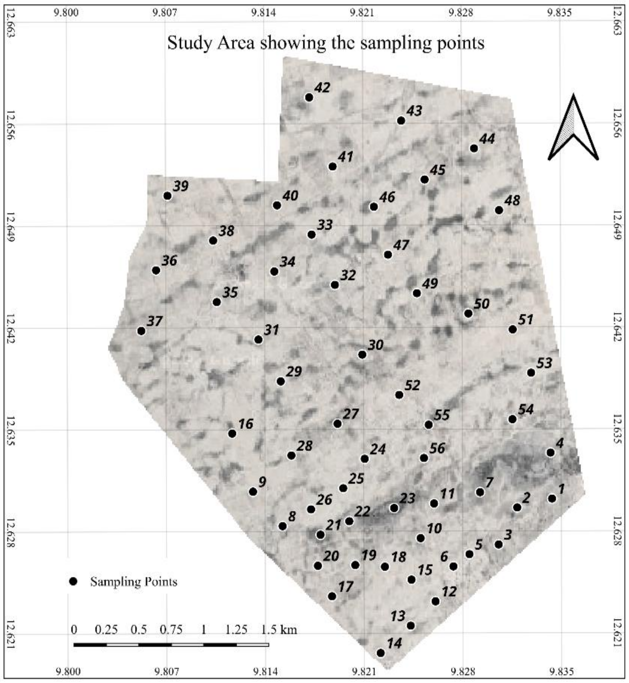

Figure 1. Study Area showing Sampling Points

at the Centre for Dryland Agriculture, Bayero University Kano. Approximately 0.5–2.0 g of the finely ground soil was placed on the ATR crystal and scanned over 4000–400 cm⁻¹ following background measurement. The spectra were processed using Bruker OPUS software through baseline correction and normalization and interpreted using calibrated multivariate spectral prediction models to estimate the selected soil properties. The predicted values were subsequently exported for statistical analysis and spatial interpolation.

2.3. Soil Sample Preparation and Analysis

The collected soil samples were air-dried under clean, shaded and well-ventilated laboratory conditions, gently disaggregated, and passed through a 2-mm stainless-steel sieve. The <2-mm fraction was retained and further finely ground to obtain a homogeneous powder for spectroscopic analysis. Selected soil physicochemical properties were estimated from mid-infrared (MIR) spectra acquired using a Bruker ALPHA II Fourier Transform Infrared (FTIR) spectrometer (Bruker Optik GmbH, Ettlingen, Germany) equipped with an Attenuated Total Reflectance (ATR) module at the Centre for Dryland Agriculture, Bayero University Kano. Approximately 0.5–2.0 g of the finely ground soil was placed on the ATR crystal and scanned over 4000–400 cm⁻¹ following background measurement. The spectra were processed using Bruker OPUS software through baseline correction and normalization and interpreted using calibrated multivariate spectral prediction models to estimate the selected soil properties. The predicted values were subsequently exported for statistical analysis and spatial interpolation.

FTIR measurements are based on the absorption of infrared radiation by molecular bonds within soil constituents. The relationship between absorbance and the concentration of an infrared-active constituent can be expressed by the Beer–Lambert relationship:

$$A = \log_{10}\left(\frac{I_0}{I}\right) = \varepsilon bc$$

where:
A = absorbance (dimensionless);
I_0 = intensity of incident infrared radiation;
I = intensity of transmitted or reflected infrared radiation;
ε = molar absorptivity coefficient;
b = optical path length (cm);
c = concentration of the absorbing component.
The recorded interferogram was transformed into an infrared spectrum through Fourier Transform processing, represented generally as:

$$F(v) = \int_{-\infty}^{+\infty} f\,(x)e^{-2\pi ivx}\,dx$$

where:
F(v) = infrared spectrum as a function of wavenumber;
f(x) = recorded interferogram;
v = wavenumber (cm⁻¹);
x = optical path difference.

These mathematical transformations enable the conversion of raw interferometric data into a high-resolution infrared spectrum, from which the calibrated spectral models predict the selected soil physicochemical properties.

The spectral information was interpreted according to the nature of the soil properties. Organic carbon and particle-size-related mineralogical characteristics have relatively stronger associations with diagnostic MIR absorption features, whereas properties such as pH, available phosphorus, exchangeable potassium and cation exchange capacity were estimated indirectly through multivariate relationships between spectral responses and reference soil properties.

2.4 Climatic and Topographic Data Processing

Slope and Topographic Wetness Index (TWI) were derived from a 30-m Copernicus Digital Elevation Model (DEM) using QGIS. The DEM was first hydrologically conditioned by filling surface depressions to facilitate continuous flow routing. Slope was derived from the DEM using the QGIS terrain-analysis slope procedure and expressed in radians for subsequent TWI calculation. TWI was generated using the SAGA Terrain Analysis–Topographic Wetness Index algorithm implemented through the QGIS Processing framework. The study-area boundary was used to define the spatial extent of the analysis, while the specific catchment area () required by the TWI algorithm represented the upslope contributing area per unit contour width. TWI was calculated as:

$$TWI = In\left(\frac{A_s}{tan\beta}\right)$$

Where:
As = Specific catchment area (unslope contributing area per unit contour width, m^2m^{-1})
B = local slope angle (in radians)

Historical climate data were obtained from WorldClim version 2.1 at approximately 30 arc-second (~1 km) spatial resolution for the 1970–2000 reference period. Monthly precipitation and mean-temperature raster layers were used to derive the climate variables required for the suitability analysis. Annual precipitation was calculated by summing the 12 monthly precipitation rasters, while annual mean temperature was calculated as the arithmetic mean of the 12 monthly mean-temperature rasters using the QGIS Raster Calculator. The resulting annual precipitation and mean-temperature layers were subsequently clipped to the Kambriwa study-area boundary and harmonized with the other suitability-factor rasters to a common coordinate reference system and spatial resolution prior to the multicriteria suitability analysis.

2.5. Crop Requirement Matching and Suitability Rating

The suitability thresholds were compiled from crop-specific land-requirement literature and supporting soil-fertility classifications rather than from a single universal FAO threshold table. Climate and terrain criteria were interpreted according to the requirements of rainfed cowpea production, while soil chemical indicators were used as measures of soil fertility status. Where published cowpea requirements did not provide direct numerical thresholds for a particular soil property, the corresponding limits were adopted or adapted from established soil-fertility classification schemes and are identified as such. TWI was included as a terrain-derived indicator of relative potential wetness rather than as a direct measurement of soil drainage.

2.6 Analytical Hierarchy Process and Spatial Suitability Analysis

Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) was employed as a multi-criteria decision-support approach to determine the relative importance and weights of the selected soil, climatic, and topographic criteria. AHP enables multiple criteria to be systematically compared and integrated within a common decision framework (Saaty, 1980; Malczewski, 1999, 2004; Feizizadeh *et alet al*., 2013). The procedure involved four main steps: construction of the pairwise comparison matrix, normalization of the matrix, derivation of criterion weights, and consistency verification.

Step 1: Construction of the pairwise comparison matrix.

The selected criteria were compared pairwise based on researcher judgement, informed by published cowpea crop requirements, relevant soil-fertility literature, and the limiting factors identified within the study area that may constrain cowpea growth and productivity. The judgments therefore represented a literature-informed assessment of the relative importance of the criteria for rainfed cowpea production. Given the subjective nature of individual judgement in AHP weighting, the internal consistency of the pairwise comparisons was evaluated using the Consistency Ratio (CR), with CR ≤ 0.10 considered acceptable. The relative importance of the criteria was assigned using Saaty's nine-point scale, ranging from 1 (equal importance) to 9 (extreme importance) as shown in Table 2.

For a set of ‘n’ evaluation criteria, the pairwise comparison results were organized into a square n × n reciprocal matrix A, expressed as:

Table 1. Land suitability criteria, threshold ranges and suitability ratings adopted for rainfed cowpea production in Kambriwa

Parameter	Unit	Highly Suitable (S1)	Moderately Suitable (S2)	Marginally Suitable (S3)	Not Suitable (N)
Annual Rainfall	Mm	400 – 700	300 – 400	200 – 300	<200 or >700
Av. Temperature	°C	25 – 30	20- 25 or 30 – 33	18 – 20	<18 / >33
TWI (TWI)		<6	6 – 8	8 – 10	>10
Slope	%	0 – 4	4 – 8	8 – 12	>12
Sand	%	40 – 70	70 – 80	80 – 90	>90
Clay	%	15 – 25	10 – 15	5 - 10	< 5 / > 25
Organic Carbon	%	> 1.0	0.6– 1.0	0.3 – 0.6	< 0.3
Total Nitrogen	%	0.08 – 0.20	0.05 – 0.08	0 - 0.05	> 0.20 (Excessive)
Avail. P	mg/kg	> 10	7 – 10	4 – 7	< 4
Exch. K	cmol/kg	> 0.20	0.12 – 0.20	0.06 – 0.12	< 0.06
CEC	cmol/kg	> 12	8 – 12	4 - 8	< 4
Soil pH	(H_2O)	5.5 – 6.5	5.0 – 5.5 / 6.5 – 7.0	4.5 – 5.0 / 7.0 – 7.5	< 4.5 / > 7.5

Source: Adapted from FAO (1976, 1983), Dent and Young (1981), Sys *et alet al*. (1991), and UAS Bangalore (2018), with crop-specific criteria adapted to the conditions of Kambriwa. **Note:** Criteria were adapted from the cited crop-specific land-evaluation and soil-fertility literature. Thresholds that were not directly available in published cowpea requirements were adapted from established soil-fertility classifications based on their relevance to the study environment. The TWI classes were treated separately as terrain-based relative-wetness classes and should not be interpreted as direct measurements of soil drainage.

Table 2. Saaty's (1980) Nine-Point Scale of Relative Importance

Rating	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
2	Intermediate between 1 & 3	A compromise judgment between equal and moderate importance
3	Moderate importance	One criterion is slightly more important than the other
4	Intermediate between 3 & 5	A compromise judgment between moderate and strong importance
5	Strong importance	One criterion is strongly more important than the other
6	Intermediate between 5 & 7	A compromise judgment between strong and very strong importance
7	Very strong importance	Very strongly more important; demonstrated in practice
8	Intermediate between 7 & 9	A compromise judgment between very strong and extreme importance
9	Extreme importance	Highest possible order of affirmation

Source: Saaty (1980)

$$A = [a_{ij}]$$

Where:

$$a_{ij} = \frac{W_i}{W_j}$$

And reciprocal property:

$$a_{ji} = \frac{1}{a_{ij}}$$

$$a_{ii} = 1$$

Step 2: Normalization of the matrix.

The values in each column of the pairwise comparison matrix were summed, and each individual value was divided by its respective column total.

$$\sum_{i=1}^{n} a_{ij}$$

$$N_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$$

Where:

$N_{ij} = normalized\ value$

$a_{ij} = pairwise\ comparison\ value$

Step 3: Derivation of criterion weights.

The weight or priority of each criterion was obtained by calculating the average of the normalized values across each row.

$$W_i = \frac{\sum_{j=1}^{n} N_{ij}}{n}$$

Where W_i is the weight (priority) of criterion, i and n is the total number of criteria. The sum of all weights equals 1.0.

Step 4: Consistency verification.

The consistency of the pairwise judgments was evaluated using the Consistency Ratio (CR). First, the weighted sum vector was obtained by multiplying the pairwise comparison matrix by the weight vector:

The consistency vector was then calculated as:

$$(AW)_i = \sum_{j=1}^{n} a_{ij} W_j$$

Each element of the weighted sum vector was then divided by the corresponding criterion weight to obtain the λ values:

$$\lambda_i = \frac{WS_i}{W_i}$$

The maximum eigenvalue was estimated as the average of all λ_i values:

$$\lambda_{max} = \frac{\sum_{i=1}^{n} CV_i}{n}$$

The Consistency Index (CI) was subsequently calculated as:

$$C.I = \frac{\lambda\_max - n}{n - 1}$$

and the Consistency Ratio was determined as:

$$C.R = \frac{C.I}{R.I}$$

The appropriate Random Consistency Index (RI) was selected according to the number of criteria in the pairwise comparison matrix, as presented in Table 3. A CR ≤ 0.10 was considered acceptable, indicating that the pairwise judgments were sufficiently consistent for use in the suitability analysis (Saaty, 1980). All AHP calculations were performed in Microsoft Excel 2019.

Normality Assessment and Geostatistical Interpolation

Prior to spatial interpolation, the distribution of the measured soil properties was assessed using skewness and kurtosis to determine whether data transformation was required. Where necessary, appropriate transformation was applied before spatial analysis. Global Moran's I was subsequently used to assess the presence and strength of spatial autocorrelation

Table 3. Random Consistency Index (RI) Values by Matrix Size (Saaty, 1980)

N	1	2	3	4	5	6	7	8	9	10	11	12
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54

among the soil properties. Based on the observed spatial dependence and the objective of generating continuous spatial surfaces for the study area, Inverse Distance Weighting (IDW) was employed as the spatial interpolation technique (Li & Heap, 2011). IDW estimates values at unsampled locations based on the values of nearby sampled locations, with closer observations receiving greater influence than those farther away. The interpolated surfaces were subsequently used as input layers for the GIS-based land suitability evaluation. The IDW estimator is expressed as:

$$Z(x_0) = \frac{\sum_{i=1}^{n} w_i(x_i)}{\sum_{i=1}^{n} w_i}$$

$$w_i = \frac{1}{d_i^p}$$

Where:
wi= weight
di= distance
p= power parameter
The IDW interpolation was performed in ArcGIS version 10.4.1 using the Geostatistical Analyst extension

Standardization and Weighted Overlay Analysis

The interpolated soil-property maps, together with the climatic and topographic criteria, were standardized according to their respective crop suitability requirements. Each criterion was assigned a suitability score based on its degree of suitability for cowpea production.
The standardized criterion maps were then integrated using the AHP-derived weights through a weighted linear combination:

$$SI = (w_1 r_1) + (w_2 r_2) + (w_3 r_3) + \cdots + (w_n r_n)$$

Subject to the normalization condition:

$$\sum_{i=1}^{n} wi = 1$$

Where:
SI = composite suitability index
wi = weight assigned to criterion i derived from the analytic hierarchy process (AHP)
ri = standardized suitability score of criteria i at a raster cell
n = total number of evaluation criteria

The resulting suitability index maps were reclassified according to the adopted FAO land suitability classes (Table 4), thereby producing the final suitability maps for sorghum, cowpea, and sesame. All spatial interpolation, raster processing, reclassification, and weighted overlay operations were performed in QGIS.

Table 4. FAO Land Suitability Classification Scheme

Suitability Class	Score Range	Description
S1 (Highly Suitable)	≥ 80%	Land can Produce 80% or more of the maximum attainable yield. Limitations are minor.
S2 (Moderately Suitable)	60% - 80%	Land produces 60 – 80% of the maximum yield. Moderate limitations reduce productivity or require extra inputs.
S3 (Marginally Suitable)	40% - 60%	Land produce 40 – 60% of the maximum yield. Severe limitations reduce benefits to level that are only marginally justified by input.
N1 (Currently Not Suitable)	<40%	Land currently has limitations that cannot be corrected without prohibitive inputs, but it is not permanently unsuited.
N (Permanently Not Suitable)	0%	Land has severe limitations that preclude any successful use for the given purpose.

Source: Adapted from FAO (1976)

3. Result

3.1 Descriptive Statistics of Selected Soil Physicochemical Properties

The descriptive statistics of the selected soil physicochemical properties from the 56 sampled locations are presented in Table 5. Sand content ranged from 43.335 to 79.119%, with a mean of 61.562% and a coefficient of variation (CV) of 15.797%, indicating relatively low variability across the study area. Silt content ranged from 0.240 to 44.956%, with a mean of 18.284% and a CV of 68.125%, indicating high variability. Clay content ranged from 8.525 to 33.389%, with a mean of 20.154% and a CV of 35.065%, reflecting moderate variability in its distribution.

Soil pH ranged from 5.47 to 6.93, with a mean of 6.144 and a CV of 7.227%, indicating relatively low variability and generally slightly acidic to near-neutral soil conditions. Organic carbon ranged from 0.281 to 1.597%, with a mean of 0.888% and a CV of 43.131%, indicating substantial variability among sampling locations. Total nitrogen ranged from 0.0211 to 0.0899%, with a mean of 0.0579% and a CV of 37.997%, also indicating considerable variability. Available phosphorus ranged from 0.117 to 10.089 mg kg^{-1}, with a mean of 5.324 mg kg^{-1} and the highest CV among the principal suitability-related soil fertility variables (56.931%), indicating pronounced spatial variability in phosphorus status.

Exchangeable potassium ranged from 0.0901 to 0.4076 cmol kg^{-1}, with a mean of 0.249 cmol kg^{-1} and a CV of 37.911%, indicating considerable highly variability. Exchangeable calcium ranged from 0.967 to 5.739 cmol kg⁻¹, with a mean of 3.331 cmol kg⁻¹ and a CV of 39.930%. Exchangeable magnesium ranged from 0.352 to 3.869 cmol kg⁻¹, with a mean of 0.873 cmol kg⁻¹ and a CV of 36.042%. Exchangeable sodium ranged from 0.051 to 0.273 cmol kg⁻¹, with a mean of 0.093 cmol kg⁻¹ and a CV of 27.093%, indicating comparatively moderate variability. Cation exchange capacity (CEC) ranged from 2.169 to 6.862 cmol kg⁻¹, with a mean of 4.734 cmol kg⁻¹ and a CV of 26.827%, indicating moderate variability in the nutrient-retention capacity of the soils.

The skewness values indicated that most of the soil properties were approximately symmetrically distributed, with only slight departures from symmetry. However, exchangeable magnesium showed pronounced positive skewness (1.592), while exchangeable sodium exhibited moderate positive skewness (0.725). Most variables had negative kurtosis values, indicating relatively flat distributions, whereas exchangeable magnesium showed a markedly positive kurtosis (14.891), suggesting a distribution influenced by a small number of relatively high observations.

Table 5. Soil physical and Chemical Properties Analysis of the Study Area

Parameter	Mean	Minimum	Maximum	Variance	S.D	CV	Skewness	Kurtosis
Sand (%)	61.562	43.335	79.119	94.571	9.725	15.797	-0.132	-0.949
Silt (%)	18.284	0.24	44.956	155.133	12.456	68.125	0.26	-1.228
Clay (%)	20.154	8.525	33.389	49.948	7.067	35.065	0.131	-0.912
pH (1:1)	6.144	5.47	6.93	0.198	0.444	7.227	0.244	-1.187
O.C (%)	0.888	0.2807	1.597	0.146	0.383	43.131	0.280	-1.071
N (%)	0.0579	0.0211	0.0899	0.0003	0.022	37.997	-0.125	-1.467
P (mg/kg)	5.324	0.117	10.089	9.187	3.031	56.931	-0.131	-1.162
K^+ (Cmol/kg)	0.249	0.0901	0.4076	0.009	0.0944	37.911	0.056	-1.052
Ca^{2+} (Cmol/kg)	3.331	0.9668	5.739	1.788	1.33	39.93	0.048	-1.068
Mg^{2+} (Cmol/kg)	0.873	0.3522	3.869	0.099	0.315	36.042	1.592	14.891
Na^+ (Cmol/kg)	0.093	0.0508	0.273	0.001	0.0256	27.093	0.725	3.463
CEC (Cmol/kg)	4.734	2.169	6.862	1.613	1.270	26.827	-0.181	-0.75

3.2 AHP-Derived Criterion Weights and Consistency for Cowpea Suitability

The AHP criteria weight results for cowpea land suitability are presented in Table 6. Soil pH received the highest criterion weight (18.24%), followed by available phosphorus (15.58%) and TWI (12.94%), indicating their greater relative influence on the suitability assessment. Organic carbon (10.46%), cation exchange capacity (9.38%), clay content (8.96%), and total nitrogen (8.42%) contributed moderately to the overall suitability index. Sand (5.67%), rainfall (3.01%), slope (2.78%), and temperature (2.68%) received comparatively lower weights, while exchangeable potassium had the lowest weight (1.88%).

The consistency assessment showed a maximum eigenvalue (λmax) of 12.797, a Consistency Index (CI) of 0.072, and a Consistency Ratio (CR) of 0.049 (Table 7). The CR was below the recommended threshold of 0.10, indicating that the pairwise judgments were sufficiently consistent and that the derived criterion weights were suitable for use in the cowpea land suitability assessment (Saaty, 1980).

Table 6. AHP-derived Criteria weights

Parameter	Criteria Weight	Percentage (%)	Rank
Rainfall	0.0301	3.01	9
Temp	0.0268	2.68	11
TWI	0.1294	12.94	3
Slope	0.0278	2.78	10
Clay	0.0896	8.96	6
Sand	0.0567	5.67	8
Avail.P	0.1558	15.58	2
OC	0.1046	10.46	4
CEC	0.0938	9.38	5
N	0.0842	8.42	7
pH	0.1824	18.24	1
K	0.0188	1.88	12
Total	**1**	**100**	

Table 7. Consistency Statistics for the AHP Pairwise Comparison Matrix for Cowpea Production

Criteria	Rain	Temp	TWI	Slope	Clay	Sand	P	OC	CEC	N	pH	K
WSV	0.38	0.33	1.67	0.35	1.16	0.74	2.01	1.36	1.21	1.08	2.33	0.24
ɣ	12.69	12.43	12.93	12.44	12.97	13.01	12.93	12.99	12.93	12.86	12.81	12.58
Max	12.79											
CI	0.072											
CR	0.049 (acceptable)											

WSV = weighted sum vector, ɣ= Consistency measure, CI = Consistency index, CR = Consistency Ratio

3.3 Spatial Autocorrelation and Validation of Soil Property Interpolation

Global spatial autocorrelation of soil properties

Global Moran's I was used to assess the spatial autocorrelation of the soil properties selected for spatial analysis (Table 7). The Moran's I values ranged from −0.0361 for available phosphorus to 0.0264 for soil pH. None of the evaluated soil properties showed statistically significant global spatial autocorrelation ($p < 0.05$). This indicates that the sampled soil properties did not exhibit significant global clustering or dispersion at the spatial scale assessed.

Although Global Moran's I did not indicate statistically significant global spatial autocorrelation, this does not preclude local spatial variation within the study area. IDW was therefore employed based on the spatial sampling configuration and the need to generate continuous surfaces for suitability analysis. The performance of the resulting interpolated surfaces was subsequently assessed through cross-validation using ME, MAE, RMSE, and relative RMSE.

Table 7. Global Moran's I of Selected Soil Properties

Parameter	Moran's 1	P. value
OC	-0.0124	0.671
pH	0.0264	0.1115
Sand	0.0157	0.2237
Silt	-0.020302	0.5081
Clay	−0.0059	0.5665
N	−0.0112	0.8458
P	−0.0361	0.9282
K	−0.0268	0.8578
CEC	-0.0117	0.6614

Cross-validation of IDW-interpolated soil properties

The predictive performance of IDW interpolation was assessed using cross-validation based on Mean Error (ME), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and relative RMSE (Table 3.5). The ME values were close to zero for all interpolated properties, ranging from −0.0493 for clay to 0.00052 for pH, indicating limited systematic bias in the interpolated estimates. RMSE values ranged from 0.0201 for total nitrogen to 10.171 for sand, while relative RMSE ranged from 25.8% for exchangeable potassium to 31.9% for available phosphorus. Exchangeable potassium showed the lowest relative RMSE (25.8%), whereas available phosphorus showed the highest (31.9%). Overall, the cross-validation results indicate moderate predictive performance of the IDW surfaces, with relatively small systematic errors across the evaluated soil properties.

Table 8. Cross-validation of the IDW interpolation method for selected soil properties

Parameter	ME	MAE	RMSE	Relative RMSE (%)
Sand	0.031	8.4249	10.171	28.4
Clay	-0.0493	6.441	7.7157	31.0
pH	0.00052	0.3831	0.4488	30.7
OC	0.00053	0.327	0.3886	29.6
N	1.4×10^{-5}	0.0167	0.02014	29.3
Avail. P	-0.00179	2.6437	3.1831	31.9
Exch. K	0.0004	0.0674	0.082	25.8
CEC	-0.00403	1.207	1.492	31.8

ME = Mean Error, MAE = Mean Absolute Error, RMSE = Root Mean Square Error,

3.4 Suitability Classification of Individual Criteria use for Cowpea Production

Table 9 shows the area coverage and percentage distribution of the suitability classes for the selected parameters used in the land suitability evaluation for cowpea production in the study area. Percentage sand indicates that 1,034.76 ha (94.25%) of the study area was classified as highly suitable (S1), while 62.13 ha (5.75%) was moderately suitable (S2). No area was classified as either marginally suitable (S3) or not suitable (N). Percentage clay indicates that 874.87 ha (79.70%) of the study area was highly suitable (S1), 83.87 ha (7.65%) was moderately suitable (S2), and 0.17 ha (0.01%) was marginally suitable (S3). However, 138.49 ha (12.64%) was classified as not suitable (N).

Soil organic carbon (OC) indicates that 433.81 ha (39.51%) was highly suitable (S1), while 460.24 ha (41.99%) was moderately suitable (S2). In addition, 195.10 ha (17.80%) was marginally suitable (S3), whereas only 7.75 ha (0.70%) was not suitable (N). Soil pH indicates that 910.18 ha (82.96%) of the study area was highly suitable (S1), while 186.71 ha (17.04%) was moderately suitable (S2). No area was classified as either marginally suitable (S3) or not suitable (N).

Total nitrogen (N) indicates that only 15.16 ha (1.38%) was highly suitable (S1), while 823.81 ha (75.12%) was moderately suitable (S2). The remaining 257.89 ha (23.50%) was marginally suitable (S3), with no area classified as not suitable (N). Available phosphorus (P) indicates that only 0.11 ha (0.01%) of the study area was highly suitable (S1), while 180.02 ha (16.43%) was moderately suitable (S2). In addition, 590.81 ha (53.91%) was marginally suitable (S3), whereas 325.95 ha (29.65%) was not suitable (N). Exchangeable potassium (K) indicates that 781.58 ha (71.31%) was highly suitable (S1), 269.35 ha (24.58%) was moderately suitable (S2), and 45.96 ha (4.11%) was marginally suitable (S3). No area was classified as not suitable (N).

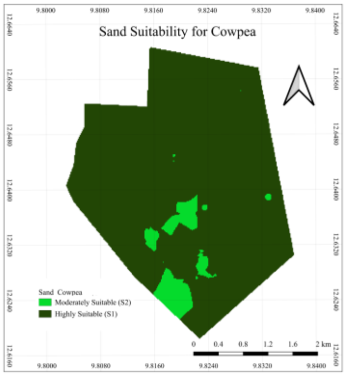

Figure 2. Sand Suitability Class Map for Cowpea

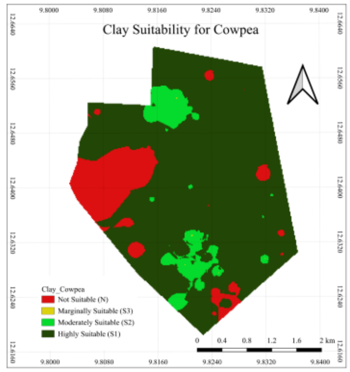

Figure 3. Clay Suitability Class Map for Cowpea

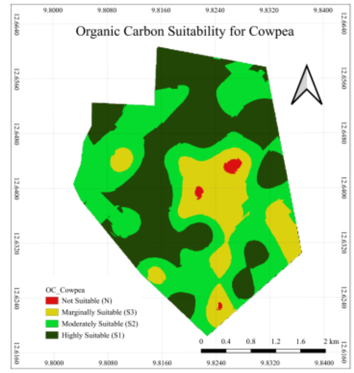

Figure 4. % Organic Carbon Suitability Class Map for Cowpea

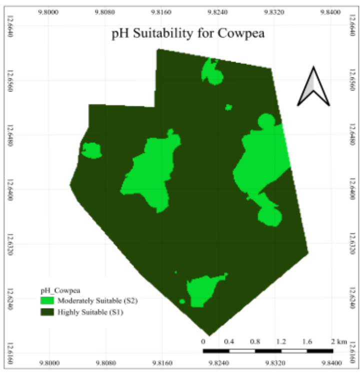

Figure 5. pH Suitability Class Map for Cowpea

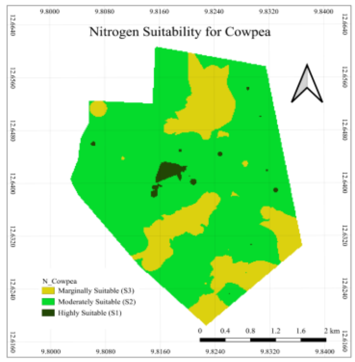

Figure 6. % Total Nitrogen Suitability Class Map for Cowpea

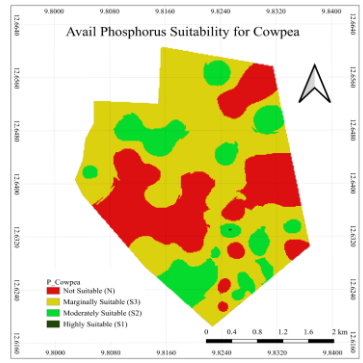

Figure 7. Avail. Phosphorus Suitability Class Map for Cowpea

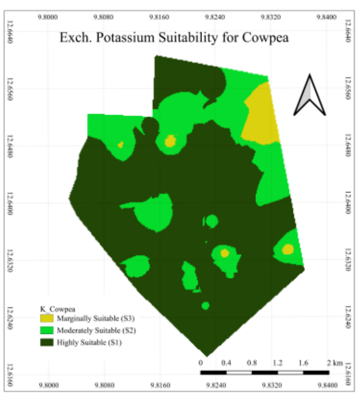

Figure 8. Exch. Potassium Suitability Class Map for Cowpea

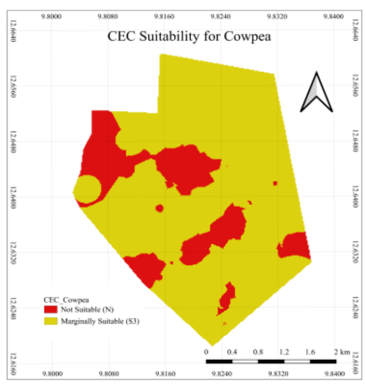

Figure 9. Cation Exchange Capacity Suitability Class Map for Cowpea

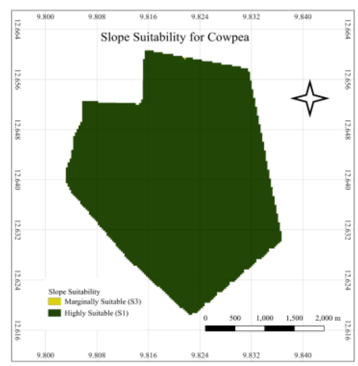

Figure 10. Slope Suitability Class Map for Cowpea

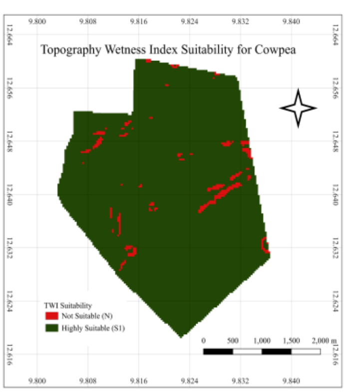

Figure 11. TWI Suitability Class Map for Cowpea

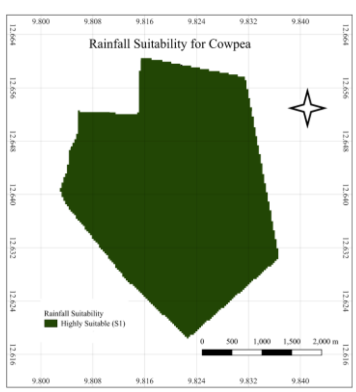

Figure 12. Rainfall Suitability Class Map for Cowpea

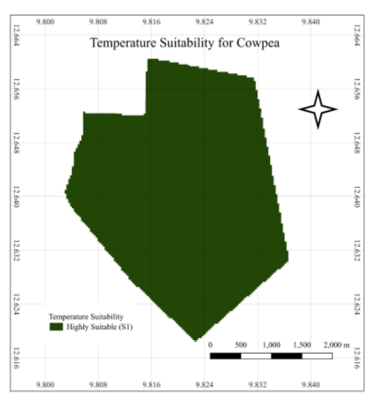

Figure 13. Temperature Suitability Class Map for Cowpea

Table 9. Suitability Classes for Cowpea in the Study Area

Suitability Classes	Sand		Clay		OC		pH	
	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)
Suitable (S1)	1034.76	94.25	874.87	79.70	433.81	39.51	910.18	82.96
Moderately Suitable (S2)	62.13	5.75	83.87	7.65	460.24	41.99	186.71	17.04
Marginally Suitable (S3)	0	0.00	0.17	0.01	195.10	17.80	0	0.000
Not Suitable (N)	0	0.00	138.49	12.64	7.745	0.70	0	0.00
Total	1096.89	100	1096.89	100	1096.89	100	1096.89	100

Suitability Classes	N		P		K		CEC	
	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)
Suitable (S1)	15.16	1.38	0.11	0.01	781.58	71.31	0	0
Moderately Suitable (S2)	823.81	75.12	180.02	16.43	269.35	24.58	0	0
Marginally Suitable (S3)	257.89	23.50	590.81	53.91	45.96	4.11	882.39	80.5
Not Suitable (N)	0	0.00	325.95	29.65	0	0.00	214.50	19.50
Total	1096.89	100	1096.89	100	1096.89	100	1096.89	100

Suitability Classes	Slope		TWI		Rainfall		Temperature	
	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)
Suitable (S1)	1096.36	99.99	1067.46	97.35	1096.89	100	1096.89	100
Moderately Suitable (S2)	0.53	0.001	0	0.00	0	0.00	0	0.00
Marginally Suitable (S3)	0	0.00	0	0.00	0	0.00	0	0.00
Not Suitable (N)	0	0.00	29.43	2.65	0	0.00	0	0.00
Total	1096.89	100	1096.89	100	1096.89	100	1096.89	100

Cation exchange capacity (CEC) indicates that no part of the study area was classified as either highly suitable (S1) or moderately suitable (S2). Instead, 882.39 ha (80.50%) was marginally suitable (S3), while 214.50 ha (19.50%) was not suitable (N).

Slope indicates that 1,096.36 ha (99.99%) of the study area was highly suitable (S1), while only 0.53 ha (0.01%) was moderately suitable (S2). No area was classified as either marginally suitable (S3) or not suitable (N). TWI indicates that 1,067.46 ha (97.35%) was highly suitable (S1), whereas 29.43 ha (2.65%) was not suitable (N). No area was classified as moderately suitable (S2) or marginally suitable (S3). Both rainfall and temperature indicate that the entire study area, covering 1,096.89 ha (100%), was classified as highly suitable (S1).

3.4 Final Land Suitability for Cowpea Production

The final distribution of the suitability classes based on FAO classification for cowpea production in the study area following the integration of the selected parameters using the GIS-based weighted overlay approach is presented in Table 3.7. The result indicates that 927.09 ha (84.52 %) of the study area was classified as moderately suitable (S2), followed by 132.49 ha (12.08 %) classified as highly suitable (S1) and 37.31 ha (3.4 %) as marginally suitable (S3), none of the study area was classified as either currently not suitable (N1) or permanently not suitable (N2) for Cowpea production.

Table 10. Final Suitability Class for Cowpea in the Study Area

Suitability Class	Cowpea	
	Area (ha)	%
Highly Suitable (S1)	132.49	12.08
Moderately Suitable (S2)	927.09	84.52
Marginally Suitable (S3)	37.31	3.4
Currently Not Suitable (N1)	0	0.00
Permanently Not Suitable (N2)	0	0.00
Total	**1096.89**	**100**

4. Discussion

4.1 Analytical Hierarchy Process (AHP) for Cowpea Land Suitability Evaluation

The AHP weighting indicates that soil chemical conditions and landscape wetness were more influential in the suitability assessment than the climatic and topographic factors. The prominence of soil pH is agronomically reasonable because pH regulates nutrient availability and soil biological processes, including those associated with biological nitrogen fixation. Recent evidence also indicates that soil pH and other physicochemical properties can influence nitrogen-fixing microbial communities and N fixation processes (Yang *et alet al.*, 2022).

Available phosphorus was also given substantial importance because P availability is closely associated with root development, nutrient acquisition and the functioning of

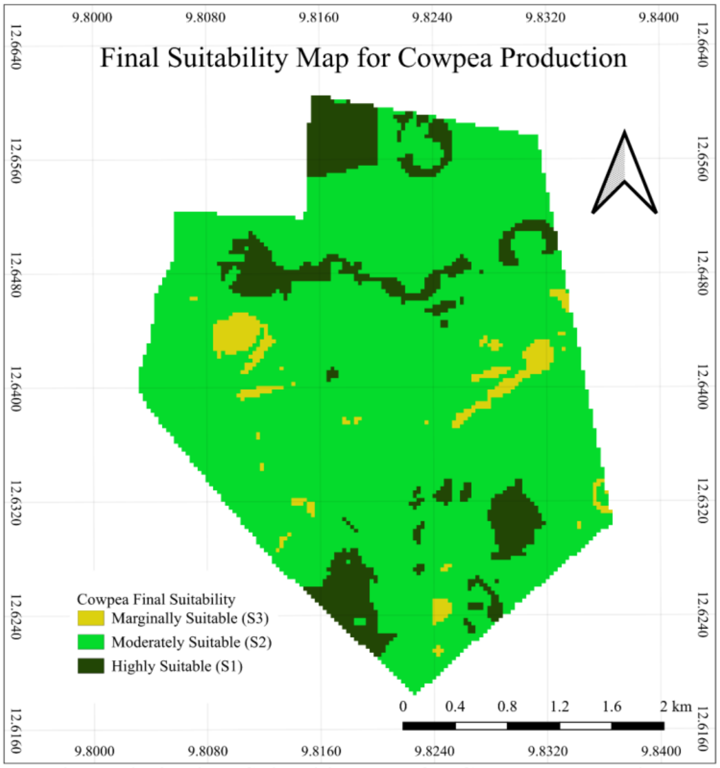

Figure 14. Final Suitability Map for Cowpea Production

legume-based production systems. Evidence from the West African Sahel shows that phosphorus deficiency can represent a stronger production constraint than rainfall in nutrient-depleted farming systems, reinforcing the importance of P management in semi-arid cropping environments (Bado *et alet al*., 2022).

The relatively high importance assigned to TWI reflects its use as an indicator of relative landscape wetness and potential moisture accumulation, rather than direct soil drainage. This distinction is important because TWI is influenced by DEM resolution and the flow-routing algorithm, and its relationship with actual soil moisture can be modest (Riihimäki *et alet al*., 2021). Similar findings have demonstrated that TWI performance can vary considerably with DEM preparation and algorithm selection (Winzeler *et alet al*., 2022). Thus, the TWI weight should be interpreted as representing the potential influence of landscape wetness on cowpea suitability rather than as a direct measure of drainage.

The intermediate weighting of organic carbon, CEC, clay and total nitrogen reflects their supporting roles in soil fertility, nutrient retention and the physical environment of the root zone. These properties are particularly relevant in semi-arid systems where nutrient depletion can constrain crop productivity. Recent work from the Sahel similarly emphasizes integrated nutrient management, including mineral fertilizers, organic inputs and crop diversification, for maintaining soil fertility and productivity (Bado *et alet al*.,

The comparatively lower importance assigned to rainfall, temperature, slope and exchangeable K reflects their relative limiting influence within the study area, rather than indicating that they are agronomically unimportant. Because AHP weights represent relative priorities among criteria, a criterion may receive a lower weight where its spatial conditions are generally favourable or less restrictive. The weighting should therefore be understood as context-specific and literature-informed, rather than as universal importance coefficients for cowpea production.

The consistency ratio (CR) of 0.049 indicates that the pairwise comparisons used to derive the criterion weights were acceptably consistent. The value was below the 0.10 threshold recommended for AHP applications, indicating that the judgments used in assigning relative importance to the criteria were logically coherent and sufficiently reliable for subsequent weighted-overlay analysis (Saaty, 1980). Therefore, the derived criterion weights provide a consistent basis for integrating the standardized suitability layers and generating the final cowpea land suitability map.

4.2 Distribution of Suitability Classes for Cowpea Production

The distribution of individual suitability classes indicates that the study area generally provides favourable conditions for cowpea production, with the principal limitations arising from soil fertility rather than climate or terrain. The favourable pH and exchangeable K conditions suggest that widespread correction of soil reaction or K deficiency is unlikely to be a priority.

Available P and CEC represent the more important fertility constraints. Phosphorus is particularly important for cowpea because it supports root development, nodulation, energy transfer and biological N fixation. studies in savanna soils have demonstrated improved cowpea performance where P is combined with appropriate inoculation and nutrient management (Emmanuel *et alet al*., 2020). Accordingly, S2 and S3 areas limited by P should receive targeted, soil-test-based P fertilization, with rhizobia inoculation considered where appropriate.

The less favourable CEC, OC and N conditions indicate a need to improve nutrient retention and soil fertility. Integrated nutrient management, including appropriate mineral fertilizers, organic-resource management and crop diversification, has been shown to address nutrient depletion and improve productivity in the West African Sahel (Bado *et alet al*., 2022). For S2 and S3 areas, retention of crop residues, suitable organic amendments, crop rotation and balanced fertilization are therefore recommended.

The favourable TWI classes indicate generally low potential wetness limitation; however, TWI should be interpreted as an indicator of relative landscape wetness rather than direct soil drainage, because its performance depends on DEM resolution and flow-routing methods (Riihimäki *et alet al*., 2021). Overall, management should therefore be limitation-specific, prioritizing P correction and improvement of soil nutrient-retention capacity rather than applying uniform interventions across the study area.

5. Conclusion and Recommendation

5.1 Conclusion

This study applied a GIS-based multi-criteria evaluation integrated with the Analytical Hierarchy Process (AHP) to assess the spatial suitability of land for cowpea production in Kambriwa, Kaugama LGA, Jigawa State. The assessment identified soil pH, available phosphorus, and topographic wetness index (TWI) as relatively influential criteria within the adopted weighting framework, while the individual suitability assessment indicated generally favourable climatic, topographic, and selected soil conditions across much of the study area.

Available phosphorus and cation exchange capacity emerged as the principal soil-related limitations, contributing to the predominance of moderately suitable areas. These limitations suggest that general soil fertility interventions, particularly phosphorus management and organic matter improvement, may help address some of the constraints associated with the S2 and S3 classes. However, such recommendations should be interpreted as broad management implications rather than site-specific prescriptions.

The resulting suitability map provides a spatial representation of the relative suitability of the study area based on the selected criteria and their adopted weights. Given the absence of comprehensive uncertainty estimates for the FTIR-derived soil-property predictions and AHP weight variability, the suitability classes should be interpreted as decision-support information rather than definitive boundaries of production potential.

5.2 Recommendation

Based on the identified suitability limitations, management efforts should prioritize improving phosphorus availability through appropriate phosphorus fertilization and efficient fertilizer placement, particularly in areas where phosphorus was identified as a major constraint. The incorporation of well-decomposed organic materials should also be encouraged to improve soil organic matter, nutrient retention, and soil condition, especially in moderately and marginally suitable areas. Where low cation exchange capacity is a limitation, the use of organic amendments and practices that increase soil organic matter may help improve nutrient-retention capacity. Farmers should also adopt integrated soil fertility management, combining appropriate mineral fertilizers with locally available organic resources and good crop-residue management. Because the suitability maps are subject to uncertainties associated with soil-property estimation, spatial interpolation, and criterion weighting, the mapped suitability classes should be regarded as decision-support information rather than precise field-level prescriptions. Further field validation and uncertainty assessment are recommended before implementing location-specific land-use or fertilizer recommendations.

5.3 Limitations

The selected soil properties were estimated from MIR spectra, but independent laboratory calibration and validation statistics for the individual prediction models were not available because the relevant calibration information was not accessible to the study. As a result, the uncertainty associated with the initial spectral estimates could not be fully quantified. The IDW surfaces were nevertheless evaluated using cross-validation through ME, MAE, RMSE, and relative RMSE, providing an empirical assessment of their predictive performance. However, uncertainty from the spectral estimation stage could not be propagated through the interpolation and subsequent suitability analysis. The AHP weights were also based on literature-informed crop requirements and identified limiting factors and, although the consistency assessment was satisfactory, they necessarily involve an element of researcher judgement. In addition, TWI was interpreted as an indicator of relative potential wetness rather than direct soil drainage. Therefore, the final suitability classes are best regarded as relative spatial decision-support information rather than precise field-level prescriptions. Future studies should strengthen the assessment through independent spectral validation, uncertainty propagation, and AHP sensitivity analysis.

References

Abubakar, K., Abaje, I. B., and Tukur, R. (2024). Rainfall and temperature dynamics in the context of climate change in the Sudan Savanna ecological zone of Katsina State, Nigeria. *FUDMA Journal of Earth and Environmental Sciences*, 1(2), 82–98.

Aliyu, M., Nuhu, O. I., Saminu, A. I., Azare, I. M., Abdurkadir, M., and Abdu, N. (2022). Pedogeochemical assessment of wetland soils in Hadejia-Jama'are river basin in the Nigerian Sahel savanna. *EQA – International Journal of Environmental Quality*, 51, 13–19.

Bado, B. V., Bationo, A., Whitbread, A., Tabo, R., and Manzo, M. L. S. (2022). Improving the productivity of millet based cropping systems in the West African Sahel: Experiences from a long-term experiment in Niger. Agriculture, Ecosystems and Environment, 335, 107992.

Bakari, A. (2014). An investigation of the physical and mineralogical characteristics of the quaternary formation of the Chad Basin, Nigeria. *International Journal of Scientific and Technology Research*, 3(8), 92–96.

Bationo, A., Ntare, B. R., Tarawali, S. A., and Tabo, R. (2002). production in the semiarid tropics. Challenges and opportunities for enhancing sustainable cowpea production, 301.

Bationo, A., Waswa, B., Kihara, J., and Kimetu, J. (2007). Advances in integrated soil fertility management in sub-Saharan Africa: Challenges and opportunities. *Nutrient Cycling in Agroecosystems, 76*(1), 2–17.

Dent, D., and Young, A. (1981). *Soil Survey and Land Evaluation*. George Allen and Unwin, London.

Elsheikh, R., Mohamed Shariff, A. R., Amiri, F., Ahmad, N. B., Balasundram, S. K., and Soom, M. A. M. (2013). Agriculture land suitability evaluator (ALSE): A decision and planning support tool for tropical and subtropical crops. *Computers and Electronics in Agriculture, 93*, 98–110.

Emmanuel, O. C., Akintola, O. A., Tetteh, F. M., and Babalola, O. O. (2020). Combined application of inoculant, phosphorus and potassium enhances cowpea yield in savanna soils. Agronomy, 11(1), 15.

Esu, I. E. (2010). *Soil characterization, classification and survey*. HEBN Publishers Plc.

FAO. (1976). A framework for land evaluation. Soils Bulletin 32. Food and Agriculture Organization of the United Nations.

FAO. (1983). *Guidelines: Land evaluation for rainfed agriculture* (Soils Bulletin No. 52). Food and Agriculture Organization of the United Nations.

FAO. (2007). Land evaluation: Towards a revised framework. Land and Water Discussion Paper 6. Food and Agriculture Organization of the United Nations.

Feizizadeh, B., and Blaschke, T. (2013). Land suitability analysis for Tabriz County, Iran: A multi-criteria evaluation approach using GIS. *Journal of Environmental Planning and Management, 56*(1), 1–23.

Li, J., and Heap, A. D. (2011). A review of comparative studies of spatial interpolation methods in environmental sciences: Performance and impact factors. *Ecological Informatics*, *6*(3-4), 228-241.

Malczewski, J. (1999). GIS and multicriteria decision analysis. John Wiley and Sons.

Malczewski, J. (2004). GIS-based land-use suitability analysis: A critical overview. *Progress in Planning*, 62(1), 3–65.

Riihimäki, H., Kemppinen, J., Kopecký, M., and Luoto, M. (2021). Topographic wetness index as a proxy for soil moisture: the importance of flow-routing algorithm and grid resolution. Water Resources Research, 57(10), e2021WR029871.

Saaty, T. L. (1980). *The Analytic Hierarchy Process: Planning, priority setting, resource allocation*. McGraw-Hill.

Singh, B. B., Ajeigbe, H. A., Tarawali, S. A., Fernandez-Rivera, S., and Abubakar, M. (2003). Improving the production and utilization of cowpea as food and fodder. *Field Crops Research, 84*(1–2), 169–177.

Sys, C., Van Ranst, E., and Debaveye, J. (1991). *Land evaluation: Part I, Principles in land evaluation and crop production calculations*. Agricultural Publications No. 7. General Administration for Development Cooperation.

University of Agricultural Sciences (UAS) Bangalore. (2018). *Soil fertility and crop production guidelines*. UAS Publications.

Winzeler, H. E., Owens, P. R., Read, Q. D., Libohova, Z., Ashworth, A., and Sauer, T. (2022). Topographic wetness index as a proxy for soil moisture in a hillslope catena: flow algorithms and map generalization. Land, 11(11), 2018.

Yang, Z., Chen, X., Hou, J., Liu, H., and Tan, W. (2022). Soil texture and pH exhibit important effects on biological nitrogen fixation in paddy soil. Applied Soil Ecology, 178, 104571.