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# Agricultural Land Suitability Analysis for a Rice Cultivation Using a Fuzzy AHP and GIS in Jibia Irrigation Project Area

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## *Abstract*

Rice production plays a critical role in food security and economic development in Nigeria; however, low productivity and inefficient land utilization continue to limit sustainable production. This study assessed agricultural land suitability for rice cultivation (RC) in the Jibia Irrigation Project Area (JIPA), Katsina State, Nigeria, using an integrated Fuzzy Analytical Hierarchy Process (FAHP) and Geographic Information System (GIS) approach based on Food and Agriculture Organization (FAO) standards. Five criteria were used in the analysis Soil Physical Properties, Soil Reaction & Salinity, Soil Fertility, Exchangeable Bases, Nutrient Retention The soil parameters were spatially interpolated using kriging and standardized into suitability classes. Pairwise comparison matrices based on the Saaty scale were created and transformed into Triangular Fuzzy Numbers (TFNs) to address uncertainty in expert judgment. Fuzzy weights were derived using the fuzzy geometric mean method, defuzzified, normalized, and integrated into a GIS weighted overlay model to generate the final rice land suitability map. The consistency ratio (CR) of 0.0172 confirmed acceptable consistency in the FAHP judgment matrix. The study further incorporated a gap analysis comparing the actual areas currently utilized for rice cultivation within the irrigation project and the areas identified suitable by the FAHP-GIS model. Results revealed that 10.37% (387.46 ha) of the study area was highly suitable for rice cultivation, 52.05% (1945.68 ha) marginally suitable, 31.31% (1170.33 ha) marginally suitable, while 6.27% (234.28 ha) was unsuitable. Highly suitable zones were predominantly concentrated within the Wushin buku and parts of the Jibia hydrological sections. The comparison between actual cultivated areas and predicted suitable areas revealed that 15% (542 Ha) of land are currently cultivated rice fields are located within

highly and marginally suitable zones, while some highly suitable lands remain underutilized. This mismatch indicates inefficiencies in land allocation and highlights the need for optimized agricultural planning within the irrigation scheme.

**Keyword:** Rice suitability, Fuzzy Analytic Hierarchy Process AHP, Jibia Irrigation Project Area

## *Introduction*

Rice is a staple crop that plays a vital role in global food security, particularly in many regions of Africa (Ozkan et al., 2020). It serves as a primary source of sustenance for millions of people and is a cornerstone of agricultural economies. Rice has become one of the most important staple crops in Nigeria, playing a central role in food security and economic development. Over the past decade, rice production in Nigeria has increased significantly due to policy interventions and expansion in cultivated land. Annual paddy rice production is estimated at approximately 8.5–9.0 million tonnes, equivalent to about 5.0–5.5 million tonnes of milled rice (FAO, 2023). The total cultivated area is estimated at 4.5–5.0 million hectares, with an average yield of about 2.0–2.5 tonnes per hectare, which remains below the global average of 4–5 tonnes per hectare (FAO, 2023).

Rice consumption in Nigeria has grown rapidly due to population growth, urbanization, and changing dietary preferences. Current estimates indicate that national consumption ranges between 7.5 and 8.0 million tonnes per year, with per capita consumption estimated at 32–40 kg per person annually (FAO, 2020; DUJOPAS, 2019). Rice accounts for approximately 25% of the caloric intake of many Nigerian households, making it a critical component of food security (Annex, 2018).

Despite improvements in domestic production, Nigeria continues to experience a significant supply–demand gap. Domestic production of milled rice is estimated at 5.0–5.5 million tonnes, while demand ranges from 7.5 to 8.0 million tonnes annually, resulting in a deficit of approximately 2.0–3.0 million tonnes (FAO, 2020; KPMG, 2019) in the last half decade. This deficit is largely filled through imports and informal cross-border trade.

Historically, rice imports have ranged between 2 and 3 million tonnes per year, positioning Nigeria as one of the largest rice importers globally (Babban Gona, 2020). Several factors constrain rice production in Nigeria. These include mismatch between the seed and the soil. Low mechanization, limited irrigation infrastructure, high cost of inputs such as fertilizers, and climate variability (IFAD. (2023). Additionally, post-harvest losses and poor processing quality reduce the effective supply of rice. These challenges contribute to the relatively low yield levels observed in Nigeria compared to global standards (FAO, 2019). The persistent supply deficit and low productivity highlight the need for optimized land suitability assessment for rice production in the study

area. Multi-Criteria Decision Analysis (MCDA) is a complex process where decision-makers evaluate various alternatives with different characteristics to choose the best one (Kordi, 2008). This process is often difficult because it involves data from diverse social and environmental fields and must balance multiple conflicting qualitative and quantitative criteria (Malczewski, 2006).

Analytic Hierarchy Process (AHP), introduced by Saaty (Saaty, 1980), is a widely used MCDA methodology. It organizes complex problems into a hierarchical structure (similar to a family tree) consisting of objectives, criteria, and alternatives (Shapiro and Koissi 2017; Eakin and Bojorquez, 2008). It uses mathematical theory based on ratio scales to analyze judgment and preferences through pairwise comparison matrices (Sengupta et al., 2022).

Fuzzy set theory was developed by (Zadeh, 1965) and extensively applied in previous decade. Although many techniques have been applied to MCDA, the targets of conventional MCDA based on geographical information system (GIS) research principally involved applications to fields around the spatial data and spatial analysis.

Fuzzy Analytical Hierarchy Process (FAHP) incorporates fuzzy set theory into the hierarchical structure of AHP. While traditional AHP is used for "crisp" decision applications (Yang and Chen, 2004), FAHP uses fuzzy numbers to represent linguistic variables and human judgment. FAHP is often considered more robust than traditional AHP because FAHP was specifically developed to formulate and control this uncertainty associated with mapping human judgment onto a fixed evaluation scale (Sarkar et al. (2021)). FAHP addresses ambiguity when assigning numeric values to their preferences. By using fuzzy numeric values rather than exact ratios, which helps decision-makers better understand the final importance and the inherent uncertainty of the factors (Chang, 1996). FAHP uses fuzzy numbers for linguistic terms to better handle the influenced by the personal judgment and preferences of the decision-maker. Real-World Complexity: In complex modern environments, decision-makers are often uncertain when assigning scores in crisp values. FAHP provides a systematic method to synthesize these uncertain group decisions (Ching, 1997).

Integrating GIS into the MCDM process significantly enhances the ability to solve complex spatial problems (Pilevar et al., 2020). Traditional MCDA techniques were non-spatial and assumed that study areas were spatially homogenous; however, in real-world scenarios, evaluation criteria vary across space (Takukdar et al., 2022). GIS improves the process through allowing decision-makers to account for the fact that data and criteria often change depending on location, moving beyond the limitations of traditional, non-spatial methods (2008). This enables the integration of disparate information sources, linking various social and environmental data points together for a more comprehensive analysis (Hanashima and Yamazaki, 2002).

GIS Provide tools for sophisticated analysis, such as the layer superposition technique, which divides study areas into sub-homogenous zones. It can recognize, correlate, and analyze spatial relationships between mapped phenomena. GIS views alternatives as collections of spatial objects—such as points, lines, and areas—which have specific criteria values attached to them

(Ozhan et al., 2020). GIS helps policy makers visualize trends and project outcomes. By combining geographic data with value judgments, the system transforms these inputs into a final decision or ranking of spatial alternatives (Vahidnia and Alesheikh, 2008). Ultimately, the integration of GIS and MCDA advances the evaluation/selection of optimum alternatives by providing a systematic method to synthesize geographic data and decision-maker preferences (Talukdar et al. (2022)

Katsina State, located in northern Nigeria, boasts a diverse range of agricultural activities and possesses several unique projects aimed at enhancing food production. One such project, the Jibia Irrigation Project Area, represents a critical endeavor in this regard. The irrigation project, designed to harness and efficiently distribute water for agricultural purposes, presents an opportunity to transform the region's agricultural landscape, particularly concerning rice production (SRRBDA. 1989).

The Jibia Irrigation Project area is a well-designed site specifically engineered for large-scale irrigation farming (Musa and Isah, 2014). Established in 1989, the project encompasses approximately 3,472 hectares of leveled farmland that was strategically converted from former agricultural lands to optimize water use (SRRBDA, 1982). The site is extensively channeled, featuring a sophisticated water distribution network of canals. The irrigation area is located close to the Jibia main market, which serves as an international trading hub on the Nigeria-Niger border. This proximity ensures that fresh farm products have rapid and easy accessibility to major commercial buyers.

The project operates under a uniform Tropical continental climate with distinct wet and dry seasons. Because the irrigation system provides a constant water supply independent of the season, a wide variety of crops are produced year-round, including vegetables and cereals like rice. To facilitate seamless farm operations, the area is integrated with an advanced road network that surround the entire irrigation area, providing direct access to every plot (SRRBDA, 1991). The reasoning that a study focused specifically on chemical and physical properties of the soil in the area is due to the uniform climatic conditions, well-prepared terrain, integrated roads network and proximity to markets of the Jibia Irrigation Project.

This study intend to used 14 suitability factors analyzed from the soil laboratory to map and spatially analyse sites suitable for rice cultivation in the Jibia Irrigation project area (JIPA). In order to achieve this major aim, the suitability factors were ranked based on Food and Agricultural organization (FAO) standard, weighted using FAHP and generated suitability map using weighted overlay. It is essential to explore the various factors that affect rice farming in this specific region, from chemical to physical properties. By conducting this analysis, this study provided valuable insights that can guide agricultural development strategies and inform policy decisions, fostering sustainable rice production in Katsina State.

The findings of this research can serve as a foundation for understanding the potential challenges and opportunities of rice cultivation in the Jibia Irrigation Project Area, contributing to the sustainable development of agriculture in the region and the broader goals of food security in Nigeria. This study also underscores the importance of localized

assessments when planning and implementing agricultural projects, as the suitability of a given area for a specific crop can vary considerably based on local conditions.

**Review of Related Studies**

Studies on rice land suitability using FAHP integrated with GIS have been conducted across different parts of the world to support efficient land resource management Maddahi et al., 2021. Xue et al., (2023) applied FAHP-GIS techniques to evaluate land suitability and demonstrated that fuzzy multicriteria spatial analysis improves land allocation efficiency. Similarly, Li et al., (2022) developed an integrated FAHP-GIS framework for agricultural land evaluation, showing that the combination of fuzzy logic and spatial analysis enhances suitability classification accuracy. Sengupta et al., (2022) also employed multicriteria GIS suitability modeling for crop production. Sarkar et al., (2021) demonstrated that GIS-based FAHP are effective for identifying highly suitable agricultural zones and reducing uncertainty in land evaluation processes. Furthermore, Günal et al., (2022) conducted soil suitability assessment studies for sustainable agricultural production and highlighted the significance of soil fertility. Han et al., (2021) examined the influence of soil pH on nutrient dynamics and rice productivity, confirming that soil chemical properties remain critical indicators in rice suitability analysis. Islam et al., (2021) applied GIS-based multicriteria decision analysis for crop suitability assessment and concluded that FAHP-GIS methods provide reliable spatial decision-support tools for agricultural management. Tashayo et al., (2020) used AHP and GIS for agricultural land suitability assessment and reported that multicriteria evaluation significantly improves the identification of suitable cultivation areas. Pilevar et al., (2020) further demonstrated the effectiveness of GIS-based multicriteria decision analysis in agricultural land evaluation.

In Nigeria, Mustapha et al., (2021) successfully applied GIS and multicriteria evaluation techniques for rice cultivation suitability assessment. Bashiru et al., (2024) reviewed smart farming technologies for sustainable agriculture in Sub-Saharan Africa and confirmed that GIS-based multicriteria techniques enhance agricultural suitability assessment and resource management. Rahman et al., (2024) assessed rice productivity under salinity stress and demonstrated that soil salinity mapping and suitability modeling are essential for sustainable rice cultivation under climate change conditions. Nguyen et al., (2024) also analyzed soil nutrient dynamics and rice productivity in tropical agricultural systems and found that soil fertility indicators such as pH, organic carbon, and nutrient retention strongly influence suitability classification.

Collectively, these recent studies confirm that FAHP-GIS has become one of the most widely adopted modern approaches for rice land suitability analysis because of its ability to integrate expert judgment, fuzzy logic, environmental variables, and spatial analysis within a scientifically robust decision-making framework.

Although several studies on rice land suitability using FAHP integrated with GIS have been conducted in different parts of the world, there is still a strong scientific need to carry out such

studies in areas where they have not previously been implemented, such as Jibia Irrigation Project Area (JIPA). Land suitability is highly location-specific suitability results obtained from one irrigation project cannot be generalized directly to another area without proper local evaluation. Every irrigation project possesses unique characteristics that influence rice production potential and land performance.

One of the major reasons such studies must be conducted in Jibia is the peculiarity of the irrigation project itself, particularly in terms spatial distribution of irrigation canals, drainage systems, access roads, reservoirs, water-control, road accessibility, and market access. JIPA is climatically uniform, factors such as temperature variation, relative humidity, evapotranspiration rates, rainfall distribution, atmospheric pressure, wind patterns, and seasonal flooding across the area are almost uniform

**Study Area**

The study area is the irrigation water distribution areas from Jibia Dam Project (Figure 1). These areas are bounded by Latitude and Longitude of 13°00'7" N, 7°1'5"48E and 12°57'8" N, 7°16'15" E respectively. The Jibia Irrigation Project area is a well-designed site specifically engineered for large-scale irrigation farming. Established in 1989, the project encompasses approximately 3,472 hectares of leveled farmland that was strategically converted from former agricultural lands to optimize water use.

The site is extensively channeled, featuring a sophisticated water distribution network of 192 km of canals, which includes 17 km of primary canals and 175 km of secondary and lateral canals. To facilitate seamless farm operations, the area is integrated with an advanced road network consisting of 50 km of service roads and 110 km of farm roads that surround the entire irrigation area, providing direct access to every hydrological section (Musa, 2018). Crucially, the irrigation area is located close to the Jibia main market, which serves as an international trading hub on the Nigeria-Niger border. This proximity ensures that fresh farm products have rapid and easy accessibility to major commercial buyers.

The project operates under a uniform Tropical continental climate with distinct wet and dry seasons. Because the irrigation system provides a constant water supply independent of the season, a wide variety of crops are produced year-round, including vegetables and cereals like rice. This modern infrastructure has revolutionized local agriculture by replacing difficult, traditional manual watering techniques with a reliable system that supports both food and cash crop production on a massive scale (Yusuf, 2013).

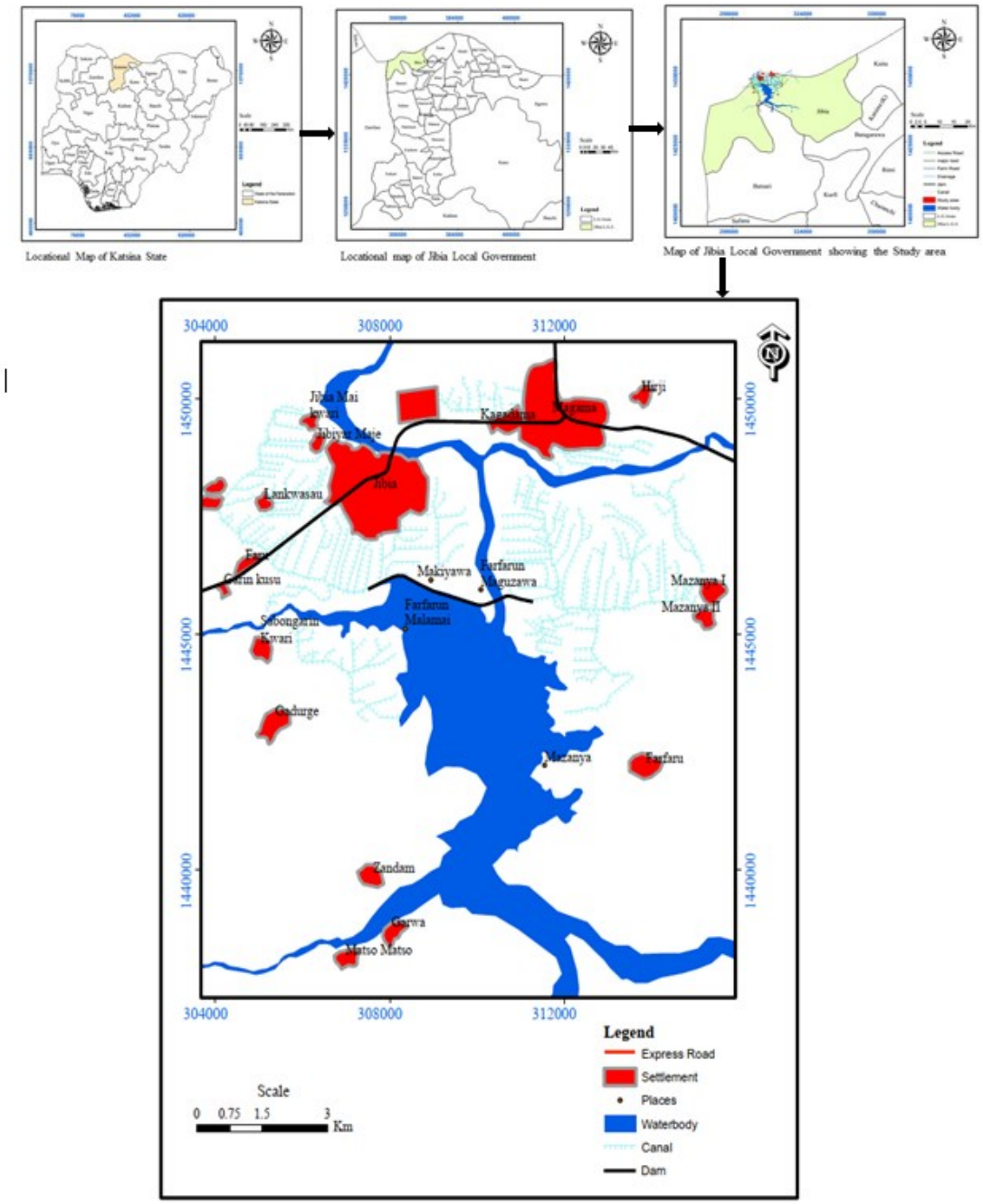



Figure 1. Locational map of the study area

**Methodology**

The aim of this study was to assess the agricultural land suitability for rice cultivation in Jibia Irrigation Project Area, using the integrated FAHP and GIS approach. The methodological framework followed in the study area is illustrated in Fig. 2. It involved five steps: 1) build a

hierarchical structure; 2) collect data and preprocess; 3) determine weights by FAHP; 4) generate a land suitability map;; and 5) perform a gap analysis between the actually utilized and highly suitable areas for rice production.

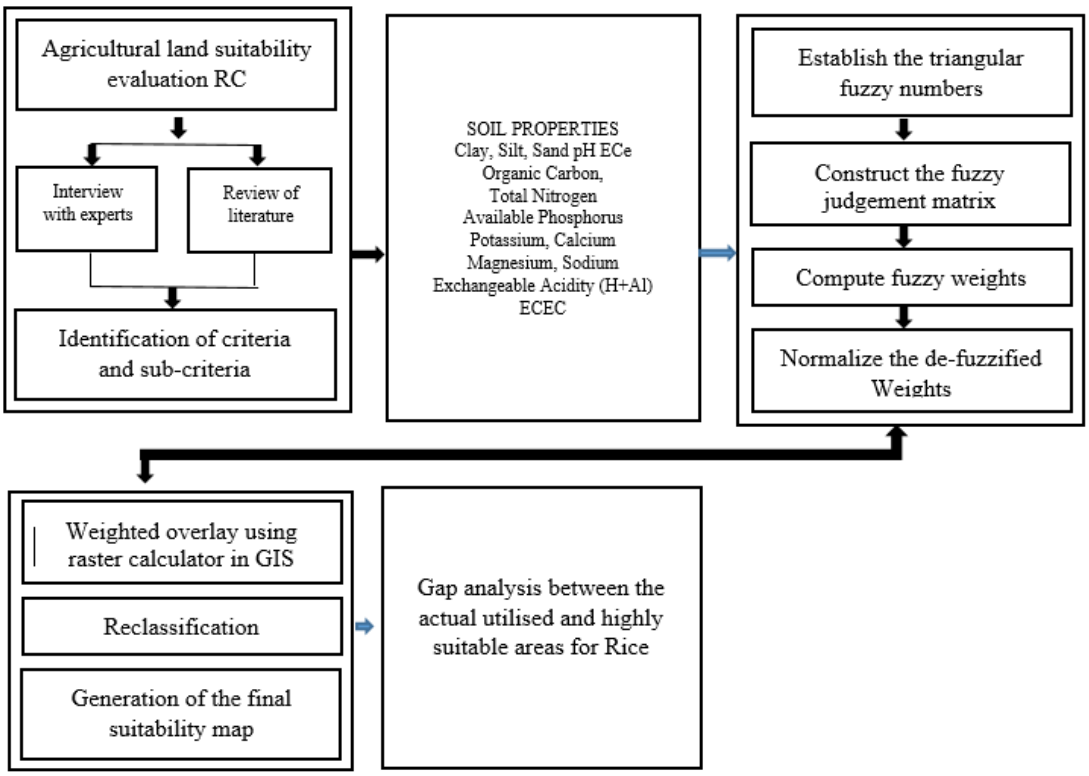



Figure 2. Flowchart of the methodology.

Table 1. Details of the criteria and sub-criteria used for agricultural land suitability evaluation.

| Criteria | Sub-criteria | Data sources | References |
|---|---|---|---|
| **Soil Physical Properties** | Clay (%) | Soil test from Ahmadu | *Akpoti et al. (2019)* |
| | Silt (%) | Bello University Zaria | *Brady & Weil (2016)* |
| | Sand (%) | Soil Laboratory | *Ozkan et al. (2020)* |
| **Soil Reaction and Salinity** | pH (CaCl2) | | *Thomas (1996)* |
| | ECe (dS/m) | | *Akpoti et al. (2019)* |
| **Soil Fertility** | Organic Carbon (%) | | *Danyi et al., 2021* |
| | Total Nitrogen (%) | | *Han J., (2021)* |
| | Phosphorus (mg/kg) | | *Havlin et al. (2014)* |
| **Exchangeable Bases** | Calcium (Ca) | | *Han J., (2021)* |
| | Magnesium (Mg) | | *Fageria, et al. (2011).* |
| | Potassium (K) | | *Han J., (2021)* |
| | Sodium (Na) | | *Qadir, M., et al. (2014)* |
| **Soil Nutrient Retention** | H+Al | | *Brady & Weil (2016)* |
| | ECEC | | *Havlin et al. (2014)* |

**Identification of criteria and sub-criteria for rice suitability and processing**

The soil-related sub-criteria considered in this study were grouped into four major criteria based on their functional roles in rice cultivation suitability.

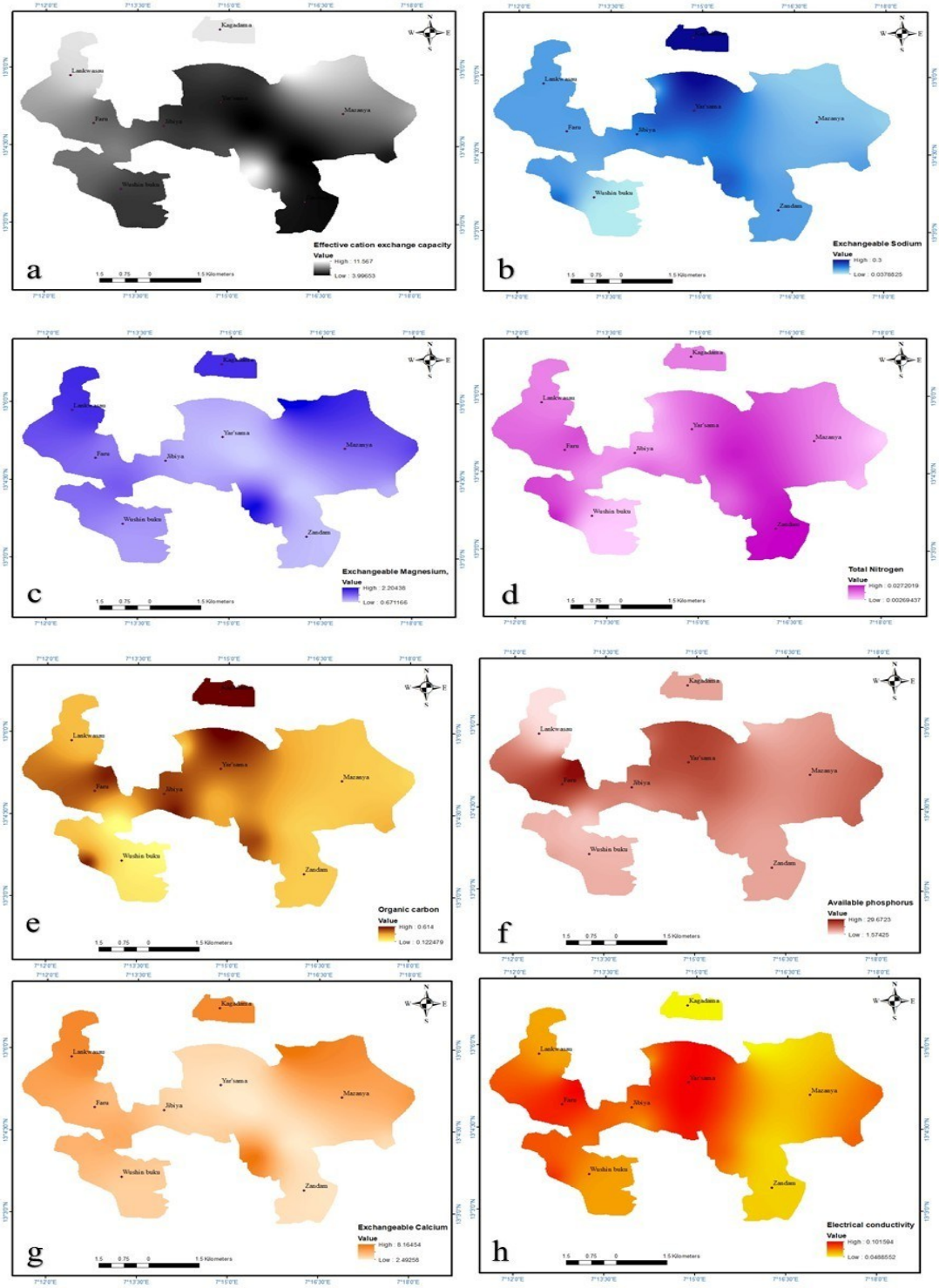
***Soil Physical Properties,*** which includes clay, sand, silt termed as soil texture. These parameters influence water retention, drainage, aeration, and the general physical condition of the soil. Clay-rich soils are particularly suitable for rice cultivation because it possess high water-holding capacity, while sandy soils are less suitable due to excessive drainage and poor nutrient retention (Cao et al., 2017). Silt contributes positively to moisture and nutrient retention, thereby improving rice productivity. Soil texture, which represents the relative proportion of sand, silt, and clay, determines the overall physical suitability of the soil for rice cultivation (*Akpoti et al. (2019)*; Sys et al., 1993).

***Soil Chemical Properties****,* which comprises soil pH, electrical conductivity of the saturated extract (ECe), and exchangeable acidity (H+Al). Soil pH controls several physico-chemical and biological processes in soils and strongly affects nutrient availability and microbial activity (Han et al., 2021). Rice generally performs best under slightly acidic to neutral soil conditions, while strongly acidic or alkaline soils reduce nutrient availability and crop productivity. Electrical conductivity (ECe) serves as an indicator of soil salinity, where high salinity levels reduce water uptake and negatively affect rice growth and grain formation (Qadir et al., 2014). Exchangeable acidity (H+Al) indicates the severity of soil acidity and may lead to aluminum toxicity and reduced nutrient availability when present in excessive amounts (Hazelton & Murphy, 2016).

***Soil Fertility and Nutrient Status***, which includes Organic Carbon (OC), Total Nitrogen (TN), Available Phosphorus (AP), Potassium (K), Calcium (Ca), and Magnesium (Mg). Organic carbon is a key indicator of soil fertility, aggregate stability, and overall soil health (Stevens et al., 2013). Total nitrogen is essential for chlorophyll formation, vegetative growth, and grain yield in rice, while nitrogen deficiency often results in stunted growth and poor productivity (Fageria et al., 2011). Available phosphorus supports root development, energy transfer, and crop maturity, whereas potassium plays an important role in water regulation, enzyme activation, and disease resistance in rice plants (Dobermann & Fairhurst, 2000; Fageria et al., 2011). Calcium contributes to root growth and cell wall development, while magnesium is the central component of chlorophyll and is necessary for photosynthesis and enzymatic activities in plants (Brady & Weil, 2016).

***Soil Nutrient Retention and Exchange Capacity***, which consists of exchangeable sodium (Na) and Effective Cation Exchange Capacity (ECEC). Exchangeable sodium is associated with sodicity problems that negatively affect soil structure and permeability when present in high concentrations, thereby reducing rice productivity (Qadir et al. (2014)). Effective Cation Exchange Capacity (ECEC) represents the soil's capacity to retain and exchange essential nutrient cations such as calcium, magnesium, potassium, and sodium. High ECEC values indicate greater nutrient-holding capacity and improved soil fertility status, making such soils more suitable for sustainable rice cultivation (Brady & Weil, 2016).

Before further processing, the above datasets were interpolated using kriging model and resampled into a 30 m spatial resolution. Finally it was projected to Universal Transverse Mercator (UTM) projection within Zone 32 N and WGS 1984 datum.



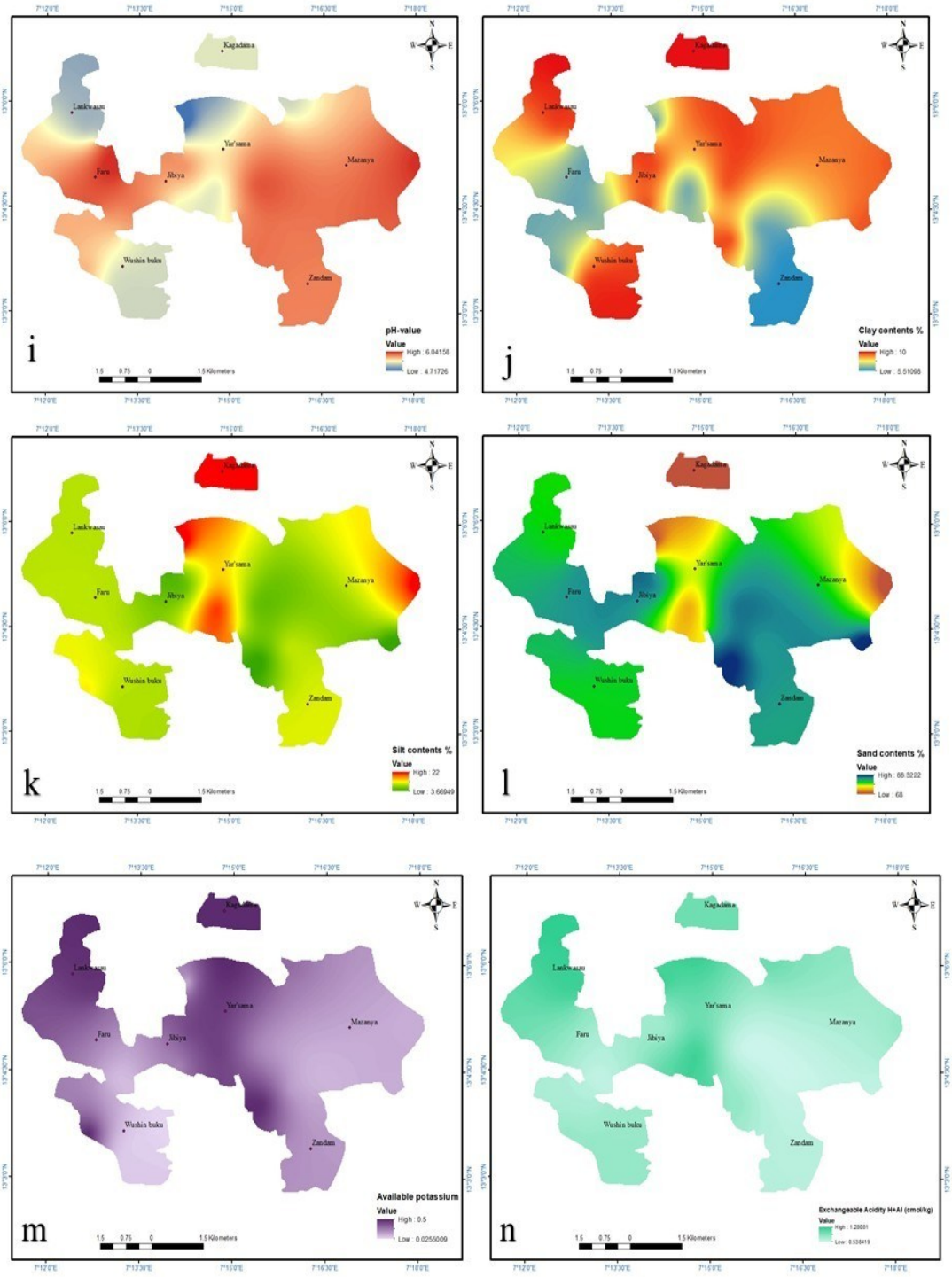



*Fig. 5.* Input parameters used in the study Effective Cation Effective Capacity (a), Exchangeable Sodium (b), Exchangeable Magnesium (c), Total Nitrogen (d), Organic Carbon (e) Available Potassium (f), Exchangeable Calcium (g), Electrical conductively (h), pH (i), Clay (j), Silt (k), Sand (L), Exchangeable potassium (m)Exchangeable Acidity (n)

**Table 2** Fuzzy pairwise comparison matrix and fuzzy weights of criteria

| Criteria | Soil Physical Properties | Soil Reaction & Salinity | Soil Fertility | Exchangeable Bases | Nutrient Retention |
|---|---|---|---|---|---|
| Soil Physical Properties | (1,1,1) | (2,3,4) | (3,4,5) | (4,5,6) | (5,6,7) |
| Soil Reaction & Salinity | (1/4,1/3,1/2) | (1,1,1) | (2,3,4) | (3,4,5) | (4,5,6) |
| Soil Fertility | (1/5,1/4,1/3) | (1/4,1/3,1/2) | (1,1,1) | (2,3,4) | (3,4,5) |
| Exchangeable Bases | (1/6,1/5,1/4) | (1/5,1/4,1/3) | (1/4,1/3,1/2) | (1,1,1) | (2,3,4) |
| Nutrient Retention | (1/7,1/6,1/5) | (1/6,1/5,1/4) | (1/5,1/4,1/3) | (1/4,1/3,1/2) | (1,1,1) |

Building FAHP-GIS Rice Land Suitability model

The methodology includes factor identification, FAHP, pairwise comparison, fuzzy transformation, fuzzy weight derivation, Defuzzification, normalization, consistency analysis, GIS weighted overlay, and validation procedures.

**Pairwise Comparison Matrix**

The fuzzy analytical hierarchy process (FAHP) requires the assignment of relative importance scores to each factor before pairwise comparison is carried out. The scoring system follows the Saaty importance scale ranging from 1 to 9, where larger values indicate stronger influence on rice suitability. If one factor is more important than another, a value between 1 and 9 is assigned. The reciprocal value is assigned when the factor is less important.

The pairwise comparison matrix is represented mathematically as:

$$A = [aij]. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 1$$

Where aij represents the relative importance of factor i over factor j.

The reciprocal condition is expressed as:

$$aij = 1 / aij. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 2$$

The crisp pairwise comparison matrix forms the foundation of the FAHP model. It quantitatively expresses expert judgment and FAO suitability standard.

**Crisp Values into Triangular Fuzzy Numbers (TFNS)**

FAHP is the transformation of the crisp Saaty comparison values into triangular fuzzy numbers (TFNs). This process incorporates uncertainty and vagueness associated with human judgment during pairwise comparison (Zadeh, 1965). A TFN proposed by van Laarhoven and Pedrycz, 1983 was proved to be an effective way of formulating decision problems where information is imprecise and subjective (Shapiro and Koissi, 2017).

A fuzzy number $\tilde{A}$ on $\square$ can be a TFN if its membership function $x \in \tilde{A}, \mu \square (x) : \square \to [0,1]$ is equal to the following:

$$\mu\square(x)=\begin{cases}(x-l)/(m-l), \le x \le \\ (u-x)(u-m), m \le x \le u \\ 0, otherwise\end{cases} \quad \ldots \quad 3$$

Where *l*, *m*, and *u* are the lower, mean, and upper bounds of the fuzzy number $\tilde{A}$ respectively. The TFN can be denoted by $\tilde{A}$ = (*l, m, u*) and the operational laws used in computation between two or more TFNs $\tilde{A} = (l_1, m_1, u_1)$ and $\tilde{A}_2 = (l_2, m_2, u_2))$ are displayed as follows:

Addition of a fuzzy number $\oplus$

$$\tilde{A} \oplus \tilde{A} = (l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \quad \ldots \quad 4$$

Multiplication of a fuzzy number $\otimes$

$$\tilde{A}_1 \otimes \tilde{A} = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 l_2, m_1 m_2, u_1 u_2) \quad \ldots \quad .5$$

For $l_1 l_2 > 0; m_1 m_2 > 0; u_1, u_2 > 0$

Subtraction of a fuzzy number $\Theta$

$$\tilde{A}\Theta\tilde{A} = (l_1, m_1, u_1)\Theta(l_2, m_2, u_2) = (l_1 - u_2, m_1 - m_2, u_1 - l_2) \quad \ldots \quad 6$$

Division of a fuzzy number $\varnothing$

$$\tilde{A}_1 \varnothing \tilde{A}_2 = (l_1, m_1, u_1) \varnothing (l_2, m_2, u_2) = (l_1 / u_2, m_1 / m_2, u_1 / l_2) \quad \ldots \quad 7$$

$l_1, l_2 > 0; m_1, m_2 > 0; u_1, u_2 > 0$

Reciprocal of a fuzzy number.

$$\tilde{A}_1 = (l_1, m_1, u_1)^{-1} = (1/u_1, 1/m_1, 1/l_1) \quad \ldots \quad 8$$

For $l_1 > 0; m_1 > 0; u_1 > 0$

**Table 3** Fuzzy pairwise comparison matrix and fuzzy weights of sub-criteria

| **Soil Physical Properties** | **Clay** | **Silt** | **Sand** | | **Fuzzy weights** | | |
|---|---|---|---|---|---|---|---|
| Clay | (1,1,1) | (3,4,5) | (2,3,4) | | 0.0371 | 0.0661 | 0.1254 |
| Silt | (0.2,0.25,0.333) | (1,1,1) | (0.333,0.5,1.0) | | 0.0163 | 0.0275 | 0.0498 |
| Sand | (0.25,0.333,0.5) | (1,2,3) | (1,1,1) | | 0.0108 | 0.0186 | 0.0358 |
| **Soil Reaction & Salinity** | pH | Ece | | | | | |
| pH | (1,1,1) | (1,2,3) | | | 0.0889 | 0.1629 | 0.2789 |
| ECe | (0.333,0.5,1.0) | (1,1,1) | | | 0.0581 | 0.1063 | 0.1921 |
| **Soil Fertility** | Organic carbon | Total Nitrogen | Phosphorus | | | | |
| Organic Carbon | (1,1,1) | (1,1,1) | (1,1,1) | | 0.0581 | 0.1063 | 0.1921 |
| Total Nitrogen | (1,1,1) | (1,1,1) | (1,1,1) | | 0.0889 | 0.1629 | 0.2789 |
| Available Phosphorus | (1,1,1) | (1,1,1) | (1,1,1) | | 0.0581 | 0.1063 | 0.1921 |
| **Exchangeable Bases** | Calcium | Magnesium | Potassium | Sodium | | | |
| Calcium (Ca) | (1,1,1) | (1,1,1) | (1,1,1) | (1,2,3) | 0.0163 | 0.0275 | 0.0498 |
| Magnesium (Mg) | (1,1,1) | (1,1,1) | (1,1,1) | (1,1,1) | 0.0163 | 0.0275 | 0.0498 |
| Potassium (K) | (1,1,1) | (1,1,1) | (1,1,1) | (1,2,3) | 0.0371 | 0.0661 | 0.1254 |
| Sodium (Na) | (1,1,1) | (1,1,1) | (1,1,1) | (1,1,1) | 0.0084 | 0.0136 | 0.0242 |
| **Nutrient Retention** | ECEC | H+Al | | | | | |
| ECEC | (1,1,1) | (0.333,0.5,1.0) | | | 0.0371 | 0.0661 | 0.1254 |
| Exchangeable Acidity (H+Al) | (1,2,3) | (1,1,1) | | | 0.0219 | 0.0422 | 0.0861 |

**Fuzzy Geometric Mean**

Computation of the fuzzy geometric mean for each soil suitability factor. The fuzzy geometric mean summarizes the relative influence of each factor within the fuzzy comparison matrix. Fuzzy geometric mean aggregates all pairwise comparisons associated with a particular factor into a single fuzzy value. This value reflects the overall importance of the factor relative to the remaining soil suitability criteria.

The geometric mean technique proposed by Buckley (1985) was used to calculate the fuzzy geometric mean and fuzzy weight of each criterion (Tables …. and ….) as follows:

$$\tilde{r} = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \cdots \otimes \tilde{a}_{in})^{1/n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 9$$

$$\tilde{w} = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \cdots \oplus \tilde{r}_n)^{-1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 10$$

where $\tilde{a}_{in}$ is a fuzzy pairwise comparison value of criteria *i* and criteria *n*, thus $\tilde{r}_i$ is the geometric mean of the fuzzy pairwise comparison value of criteria *i* with each criterion, $\tilde{w}$ is the fuzzy weight of criteria *i* and is expressed as $\tilde{w} = (lw_i, mw_i, uw_i)$, $lw_i, mw_i,$ and $uw_i$ represent the lower, middle, and upper values of the fuzzy weight of criteria *i*, respectively.

**Fuzzy Weights**

The fuzzy weights represent the relative contribution of each factor to rice land suitability under FAO standards. The fuzzy weight of each factor is obtained by dividing its fuzzy geometric mean by the summation of all fuzzy geometric means (Buckley (1985)

The fuzzy weight equation is expressed as:

$$\tilde{w}i = \tilde{r}i \otimes (\Sigma \tilde{r}i)^{-1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 11$$

Where:
$\tilde{w}i$ = fuzzy weight of factor i
$\tilde{r}i$ = fuzzy geometric mean of factor i
$\Sigma \tilde{r}i$ = summation of all fuzzy geometric means
$\otimes$ = fuzzy multiplication operator
$-1$ = inverse fuzzy number

**Defuzzification of Fuzzy Weights**

Defuzzification converts triangular fuzzy numbers into single crisp values that can easily be interpreted and used in GIS weighted overlay analysis. GIS-based spatial analysis requires a single numerical weight. Defuzzification therefore transforms the fuzzy weights into crisp values.

The Center of Area (COA) method, also called the centroid method, is one of the most commonly used approaches for Defuzzification in FAHP studies (Özkan *et al.,* 2020).

The crisp weight is calculated using the following equation

$$Ci = (l + m + u) / 3 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 12$$

Where:
Ci = defuzzified crisp value
l = lower fuzzy value
m = middle fuzzy value
u = upper fuzzy value

**Normalization of Defuzzified Weights**

Normalization ensures that the total contribution of all soil suitability factors is standardized to unity (1.0). This step is necessary before integrating the weights into GIS weighted overlay analysis. The defuzzified weights obtained from the Center of Area (COA) method may not sum exactly to one. Therefore, normalization is required to convert the weights into proportional values that collectively represent 100% influence in the land suitability model.

The normalized weight is calculated using the following equation:

$$Wi = Ci / \Sigma Ci \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 13$$

Where:
$W_i$ = normalized weight of factor I, Ci = defuzzified crisp weight of factor i
$\Sigma Ci$ = summation of all defuzzified weights

Table 4. *Weights of criteria and sub-criteria based on FAHP*

| Criteria | Normalised weight | Sub-criteria | Normalised Weight | Combined Weight |
|---|---|---|---|---|
| Soil Physical Properties | 0.38 | Clay | 0.1292 | 0.1159 |
| | | Silt | 0.0369 | 0.0331 |
| | | Sand | 0.0585 | 0.0525 |
| Soil Reaction & Salinity | 0.27 | pH(CaCl2) | 0.1521 | 0.1365 |
| | | ECe | 0.0729 | 0.0654 |
| Soil Fertility | 0.18 | Organic Carbon | 0.111 | 0.0996 |
| | | Total Nitrogen | 0.105 | 0.0942 |
| | | Available Phosphorus | 0.105 | 0.0942 |
| Exchangeable Bases | 0.1 | Calcium | 0.0669 | 0.06 |
| | | Magnesium | 0.0585 | 0.0525 |
| | | Potassium | 0.0669 | 0.06 |
| | | Sodium | 0.0478 | 0.0429 |
| Nutrient Retention | 0.07 | H+Al | 0.0369 | 0.0331 |
| | | ECEC | 0.0669 | 0.06 |

**Consistency Analysis**

Consistency analysis is necessary to determine whether the pairwise comparison judgments are logically reliable and acceptable for decision-making. The Consistency Index (CI) measures the degree of deviation from complete consistency within the pairwise comparison matrix (Saaty, 1980),

The Consistency Ratio (CR) compares the Consistency Index (CI) with the Random Index (RI). The CR indicates whether the level of inconsistency is acceptable.

The Consistency Ratio is expressed as:

$$CR = CI / RI. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 14$$

Where:

CR = Consistency Ratio, CI = Consistency Index RI = Random Index

According to Saaty (1980), the pairwise comparison matrix is considered acceptable when the Consistency Ratio (CR) is less than 0.10.

CR = 0.0172

**GIS Weighted Overlay and Final Rice Land Suitability Classification**

Integrating the normalized FAHP weights into a GIS-based weighted overlay model to generate the rice land suitability map. Weighted overlay analysis combines all standardized soil suitability factors according to their relative importance (Pramanik, 2016), before weighted overlay analysis, all soil suitability factors must be reclassified into common suitability classes based on FAO land evaluation standards. The suitability classes generally include:

The weighted overlay model is mathematically expressed as:

$$LSI = \Sigma (Wi \times Xi) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 15$$

Where:
LSI = Land Suitability Index
Wi = normalized FAHP weight of factor i
Xi = standardized suitability score of factor i

The final land suitability map identifies areas that are highly suitable, marginallyly suitable, marginally suitable, and unsuitable for rice cultivation. Areas classified as possess optimal soil conditions including favorable pH, high fertility status, adequate nutrient retention, and low salinity levels. Marginallyly suitable and marginally suitable areas possess increasing levels of limitations, while unsuitable areas exhibit severe soil constraints.

**Gap Analysis**

Finally, the predicted highly suitable areas were compared with the areas actually utilized (which was identified through ground trothing and mapped) for Rice in the hydrological areas to devise a strategy for intervention to ensure the rational and sustainable development of Rice.

**Distributions of the Sub-Criteria and their Contributions to Land suitability**

The area and percentage distributions of the 14 sub-criteria and for rice suitability cultivation presented in Table 5. The Nitrogen phosphorous and Potassium which are the main chemical properties of the soil and can be improved. Phosphorus ranged from 25 to 29 mg/kg covered 33.1 % of the study area, which was mostly distributed in the Wushin buku, Lankwasau and Jibia axis (Fig. 3). The range of nitrogen analyzed from the study area is below the minimum requirement set by the FAO. Potassium level range from 0.05 to 0.50 cmol/kg covered the extend of the study area at various level from moderate to high.

Clay, Silt and sand content in the soil indicate soil texture present in the area. The clay analysis showed that marginally value from 40 to 50% which is the most suitable for rice growth occupied 21.35 and 50.36% of the study area and were prevalent in all the hydrological areas except part of zandam, Jibia and Wushin buku section. Sand only at marginally level covered 37.63% of the study area. The actual value measured, ranged from 68 to 88% sand content in the study area. This represent marginally suitability for rice production nearly 6.87, 20.85, and 24.95 % of the study area. The irrigation project area have neither Strong acid soils (pH $<4.5$) nor weak acidity soil because the whole result analyzed ranged between 4.73 and 6.02. *pH* is a factor with high influence in rice growth. The extent of the study area covered from moderate to high soil OC (0.15-0.61) was determined to cover 63.83 % of the total area. Effective cations exchange capacity (ECEC) range from (4.13 to 11.35 cmol/kg), covered 45.76, 23.55 and 14.75 % of the study area only.

About 53.76% of the study area was covered by moderate to high electrical conductivity (0.05 – 0-10) which is 26.99 and 26.77% respectively. Acidity values which is also a very good indicator of rice growth and development appeared to cover 33.90 and 35.95% of the

project area. Calcium (2.60 – 8.00 cmol/kg) covered all the classes of suitability at various level, 43.39, 22.26 and 16.94% high, moderate and marginally suitability respectively. Calcium was below minimum requirements in about 17.37% of the study area. It can be improved using fertilizer.

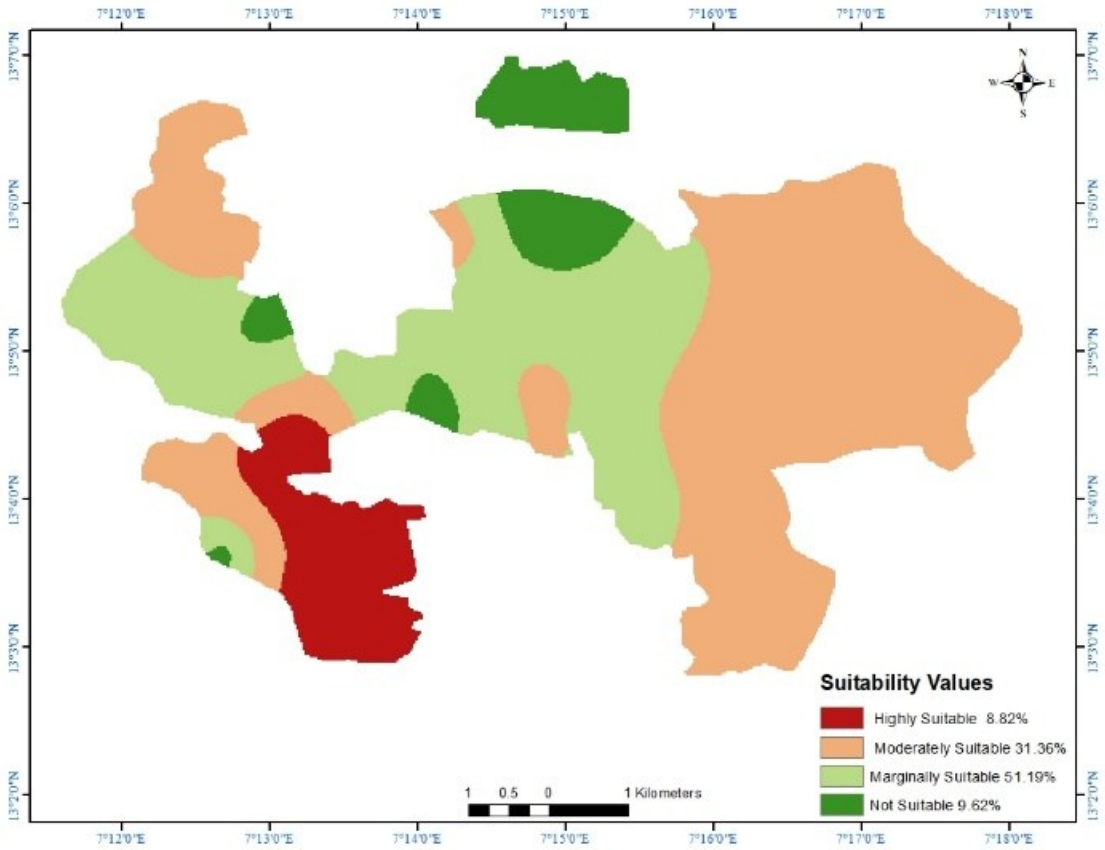
Magnesium is high in about 43.05 % of the study area, located around Lankwasau, Jibia and Mazanya hydrological areas. Moderate level of magnesium was found from 0.5 to 1.0 cmol/kg, covering 22.51 and 17.06 % in areas such as Kagadama, magama, Mazanya, zandam and part of wushin buku sections. The lower the sodium in an area the higher the suitability and vice-vasa. Sodium content in the irrigation project area is within 0.05 to 0.30 cmol/kg, this range indicated high suitability. Lowest value of sodium covered 26.39% of the study area. Hydrological areas like Magama and Wushin buku fall within this range.

By examining the weighting of five criteria it was determined that, physical properties (38 %), Soil reaction and salinity (27 %), soil fertility (18%). Exchangeable bases (10%), and nutrient retention 7% physical properties, soil reaction and salinity and soil fertility are the most important determinant used in this classification

Table 5. Area and percentage distributions of sub-criteria and scores in JIPA

| SUB-CRITERIA | MEASURED VALUE | CLASSES | AREA (Ha) | % | Rank |
|---|---|---|---|---|---|
| Phosphorous (mg/kg) | 4.90 - 29.0 | >25 | 1346.105 | 33.1 | 5 |
| | | 15-25 | 1141.69 | 28.08 | |
| | | 8--15 | 917.7501 | 22.57 | |
| | | <8 | 660.7 | 16.25 | |
| Clay (%) | 6.00 - 10.00 | 25-40 | 971.3496 | 23.89 | 11 |
| | | 40-50 | 868.5696 | 21.36 | |
| | | 50-60 | 2059.0173 | 50.64 | |
| | | <15->60 | 166.7223 | 4.1 | |
| Effective cation exchange capacity (cmol/kg) | 4.13 - 11.35 | >12 | 1860.709 | 45.76 | 3 |
| | | 8--12 | 957.633 | 23.55 | |
| | | 4--8 | 599.774 | 14.75 | |
| | | <4 | 648.126 | 15.94 | |
| Electrical conductivity | 0.05 - 0.10 | <2 | 1097.65 | 26.99 | 5 |
| | | 2.4 | 1088.528 | 26.77 | |
| | | 4.8 | 1035.652 | 25.47 | |
| | | >8 | 844.44 | 20.77 | |
| Exchangeable acidity (cmol/kg) | 0.60 - 1.20 | <1.0 | 1378.478 | 33.9 | 14 |
| | | 1.0-2.0 | 1461.544 | 35.94 | |
| | | 2.0-3.0 | 732.232 | 18.01 | |
| | | >3.0 | 494.026 | 12.15 | |
| Exchangeable calcium (cmol/kg) | 2.60 - 8.00 | >5 | 1764.222 | 43.39 | 8 |
| | | 3.5 | 905.133 | 22.26 | |
| | | 2.3 | 688.769 | 16.94 | |
| | | <2 | 708.419 | 17.42 | |
| Exchangeable magnesium (cmol/kg) | 0.70 - 2.16 | 1.0-3.0 | 1750.7 | 43.05 | 10 |
| | | 0.5-1.0 | 915.388 | 22.51 | |
| | | 0.2-0.5 | 693.596 | 17.06 | |
| | | <0.2 | 706.476 | 17.37 | |
| Exchangeable sodium (cmol/kg) | 0.05 - 0.30 | <0.30 | 1073.134 | 26.39 | 11 |
| | | 0.30-0.70 | 2194.2 | 53.96 | |
| | | 0.70-1.00 | 662.895 | 16.3 | |
| | | >1.0 | 136.199 | 3.35 | |

| SUB-CRITERIA | MEASURED VALUE | CLASSES | AREA (Ha) | % | Rank |
|---|---|---|---|---|---|
| Organic Carbon (%) | 0.15 - 0.61 | >1.5 | 391.765 | 9.63 | 4 |
| | | 0.75-1.5 | 2081.826 | 51.2 | |
| | | 0.5-0.75 | 1274.737 | 31.35 | |
| | | <0.5 | 318.104 | 7.82 | |
| Potassium (cmol/kg) | 0.05 - 0.50 | >0.30 | 1286.238 | 31.63 | 8 |
| | | 0.20-0.30 | 1390.913 | 34.21 | |
| | | 0.10-0.20 | 1250.843 | 30.76 | |
| | | <0.10 | 138.194 | 3.4 | |
| *pH-value* | 6.10 - 6.83 | 5.5-7.3 | 279.385 | 6.87 | 1 |
| | | 7.3-8.0 | 847.362 | 20.84 | |
| | | 8.0-8.5 | 1014.679 | 24.95 | |
| | | <4.5 - >8.5 | 1924.952 | 47.34 | |
| Sand content (%) | 68.00 - 88.00 | 20-40 | 133.603 | 3.29 | 11 |
| | | 40-55 | 631.362 | 15.53 | |
| | | 55-70 | 1530.022 | 37.63 | |
| | | >70 | 1771.767 | 43.57 | |
| Silt content (%) | 4.00 - 22.00 | 20-40 | 936.579 | 23.03 | 14 |
| | | 15-20 | 2432.415 | 59.82 | |
| | | 10--15 | 562.685 | 13.84 | |
| | | <10->60 | 134.654 | 3.31 | |
| Total Nitrogen (%) | 0.00 - 0.03 | >0.15 | 598.041 | 14.71 | 5 |
| | | 0.10-0.15 | 1314.771 | 32.33 | |
| | | 0.05-0.10 | 1180.122 | 29.02 | |
| | | <0.5 | 972.273 | 23.91 | |



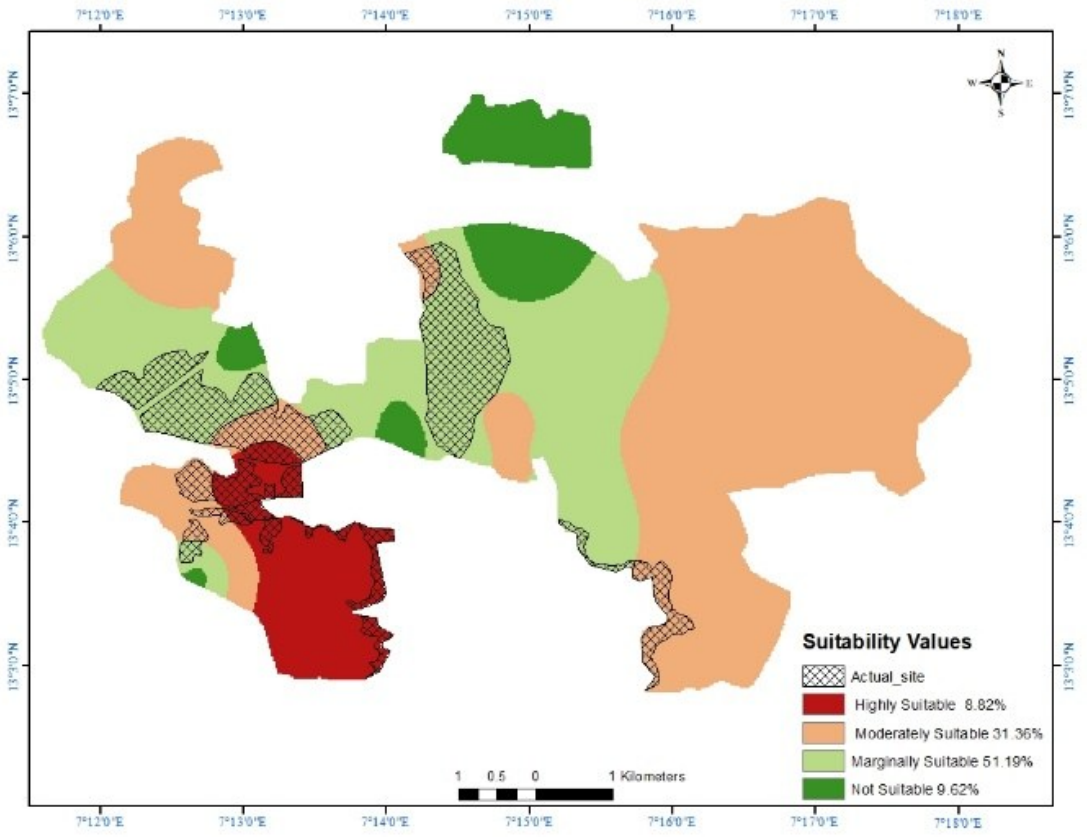



Fig. 4 (a) Land suitability map for rice cultivation (b) comparisons between the actually utilized and highly suitable areas

According to the land suitability map (Fig. 4), it was about 10.36 % (321.459 Ha) of the study area was highly suitable. Moderate suitability occupied 52.05% (1879.679 Ha), marginally suitability covered 31.311% (1104.333 Ha) and 6.265% (168.275 Ha) was unsuitable. Wushin buku hydrological were found to have high suitable areas. While the other parts of this area were mostly considered to be either moderately, marginally or not suitable.

Table 6. Land suitability evaluation using the FAHP and GIS approach

| S/N | Area | % | Suitability |
|---|---|---|---|
| **1** | 321.459 | 10.3661137 | High suitability |
| **2** | 1879.679 | 52.05487478 | Moderate suitability |
| **3** | 1104.333 | 31.31119664 | Marginally suitability |
| **4** | 168.275 | 6.267814881 | Unsuitable |

**Comparison between the actually utilized and highly suitable areas for RC**

The areas actually utilized for rice cultivation were compared with the highly suitable areas estimated through the integrated FAHP and GIS approach adopted in this study (Fig. 4b). As

shown in Table 8, it was found out that the actual rice cultivation areas (542 Ha) were less extensive than the highly suitable areas (3472 Ha). This might be attributed to lack of awareness or in the case of JIPA it was because those actual areas enjoy water supply without pumping. This study was intended to identify the potential highly suitable areas for the future expansion of rice production. The gap analysis suggested that about 59.8 % of the highly suitable areas were potentially available for further rice farming development, with these areas mainly located in all hydrological site with the exception of Kagadama. The gaps between the actually utilized and highly suitable areas were calculated for the different hydrological areas (Table 7) The results showed that Wushin buku was ranked first among 6 municipalities, contributing 73.02 % (318.51 Ha) and 15.82 % (52.45Ha) of the highly and actually utilized and areas in the region, respectively.

Table 7. Area and percentage distributions of the sub-criteria and it scores in both Actual and Suitable Areas

| S/N | Hydrological area | Actual area (Ha) | % | Suitable Area (Ha) | % |
|---|---|---|---|---|---|
| **1** | Wushin buku | 69.296 | 15.82209 | 603.242 | 73.02 |
| **2** | Jibiya | 187.678 | 72.66736 | 423.242 | 26.81 |
| **3** | Kagadama | nil | | 439.976 | 100 |
| **4** | Lankwasau | 42.558 | 12.96 | 328.346 | 51.43 |
| **5** | Magama | nil | | 242.836 | 1.3 |
| **6** | Mazanya | nil | | 498.814 | 72.14 |
| **7** | Yar sama | 195.71 | 74.1889 | 487.194 | 8.84 |
| **8** | Zandam | 47.416 | 81 | 548.786 | 80.62 |

**Discussion**

The evaluation of land suitability for specific agricultural practices plays an important role in enhancing land use efficiency (Akpoti et al., 2019; Pilevar et al., 2020). The need to consider multiple criteria made the analysis increasingly complex, because various criteria with unequal influence on land suitability, need to be considered simultaneously (El-sheikh et al., 2013; Zhang et al., 2015). An integrated FAHP and GIS approach is an efficient evaluation method, which has been commonly applied for studies of this type (Sarkar et al., 2021; Li et al., 2022; Sengupta et al., 2022).

In this study, the integrated FAHP and GIS approach was successfully used to assess the land suitability for rice production. There is no standard concerning the criteria to be taken into consideration when assessing land suitability, and the criteria used in similar studies have typically been those that are accessible (Akıncı et al., 2013). Because socio-economic factors are readily controlled and changed by human beings, land suitability evaluation is mainly based on natural environmental factors that are relatively stable (Zhang et al., 2015). In this study, a total of 5 criteria and 14 sub-criteria were considered from multiple domains to develop a land suitability map of RC based on a literature survey (Table 1) and expert opinions.

Unlike previous studies, such as those of Pramanik, 2016; Pilevar et al., 2020; Ramamurthy et al., 2020; Tashayo et al., 2020; Sengupta et al., 2022; and *Xue et al.*, 2023. In these studies great emphasis was placed on terrain, soil, climate, accessibility, and land use, in the case of study area, the site is relatively small, homogeneous, well prepared in term of leveling, infrastructure such as the dam, irrigation canals, road networks within the area uniform climate conditions and so on. That is why criteria such elevation, slope, temperature, rainfall, closeness to roads, markets etc where omitted from the analysis. Also soil depth were equally removed because it was uniform. Future research needs to evaluate the consequences of future climate changes and extreme weather events on the potential land suitability for agricultural production.

According to the comparison between the actually utilized and highly suitable areas for RC, it was found out that a much greater extent of highly suitable areas than that of actually utilized RC areas, indicating that, the area has a huge potential for further RC development. This could represent an investment opportunity to simultaneously develop agriculture not only as an activity aimed at meeting the local market demand, but also to develop competitive internal and external markets that contribute to the development of the region. However, there is an urgent need to raise awareness among farmers, agriculture extension officers, and local government regarding the sustainable development of RC. Previous studies have confirmed that there may be some constraints and problems associated with the expansion of RC areas, such as mechanization, sustainable supply of water, subsidize fertilizer, continuous soil-seed matching analysis etc.

**Conclusions**

In this study, an integrated FAHP and GIS approach was used to determine the land suitability for RC in Jibia Irrigation Project Area. Four criteria as well as 14 sub criteria were selected after reviewing the literature and consulting experts. To assign a weighting value for each criterion, the triangular fuzzy hierarchical analysis method was applied to address the issue of uncertainty bias in expert judgments. Fourteen weighted thematic layers were then integrated in a GIS environment to generate a land suitability map for RC. Highly suitable and actual suitable areas where compared through mapping, classification of the suitability and area covered

The results showed that 10.36 % (387.459 Ha) of the study area was highly suitable, 52.1 % (1945.7 Ha) was moderately suitable, 31.3 % (1170.3 Ha) was marginally suitable, and 6.3 % (234.23 Ha) was currently not suitable for RC.

This study also found out that the highly suitable areas were mainly distributed in the Jibia and Wushin buku irrigation sections, which were greater than the actual RC areas (542.688 Ha). When comparing the gap between the actually utilized and highly suitable areas for RC in the 6 municipalities and prefectures, it was observed that Wushin buku and Jibia as the top site with a large scope to further expand the area for RC. This study developed an effective

approach to increase land use efficiency and reduce environmental risks; thus, ensuring the rational and sustainable development of RC both locally and nationally.

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