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Geospatial multi-criteria decision-making for land suitability analysis for rice cultivation in Liberia

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Abstract

Achieving food security and sustainable resource management has become the main goal for many developing countries. Rice is a staple crop in Liberia and its demand is increasing while yield remains low. Rapidly changing climate patterns and persistent low yields necessitate a systematic, data-driven identification of the most resilient and productive agricultural areas for rice, contributing to food security. Currently, there is a gap on empirical and national-scale rice suitability assessment for Liberia. This study aims to identify suitable areas for rice cultivation in Liberia, based on climate, geomorphologic and geochemical factors. We used a GIS-based Multi-Criteria Decision-Making (MCDM) approach, applying the Analytic Hierarchy Process (AHP) to derive expert-weighted criteria layers (climate, geomorphologic, and geochemical) for the final suitability map. Results show that 5.57% of Liberia is highly suitable, 44.57% suitable, 42.41% semi-suitable, and 7.45% unsuitable. Primary limiting factors for rice suitability in Liberia include: pH, slope, and soil texture. Most suitable areas are found in the central, northern, and southeastern regions, including counties such as Lofa, Bong, Nimba, Gbarbolu, Grand Gedeh, and River Gee. These findings indicate that 50.14% of the land presents favorable conditions for rice cultivation in Liberia, including potential land (42.41%) that can be harnessed using agricultural technologies. This study provides important aids for agricultural sector, particularly for land accessibility and planning, and further provides a critical baseline for the government and stakeholders to strategically target land-use planning, input subsidies, and enhance rice production through expansion of land in the suitable areas indicated hereof, thereby, directly supporting national food security goals.

Keywords Analytic hierarchy process, GIS, Multi-criteria decision-making, Rice cultivation, Land suitability, Liberia

1 Introduction

Rice is one of the major cultivated food sources worldwide [1]. It is a primary food and income source in many Sub-Saharan African countries including Liberia [2, 3]. Its demand is continuously rising, due to the population growth, however, production remains low to meet the demand of the consumers [3–5], leading to food insecurity and malnutrition in many low-income countries with food deficits [6].

In Liberia, rice plays a major role in the daily diet. It is preferred because it is easy to store and prepare compared to other staple food [2, 5]. The country accounts for 50% of adult caloric intake, with nearly 133 kg annual per capita consumption [3]. This makes rice to be one of the most important crops for food security and economic livelihood that is produced by 69% of farmers in the country [7]. Rice consumption in Liberia has increased over the past years, reaching approximately 560,000 metric tons in 2021, with annual increase of 4.6% [8]. Liberia struggles to meet its annual rice needs, importing over 90% of its rice, costing over USD 100 million annually [9]. The country's average rice yields is approximately between 1.1 and 1.2 tons/ha, considerably below the regional average of 4–6 tons/ha, putting food security at risk [3, 10, 11]. Therefore, enhancement of rice productivity would contribute to reducing hunger and poverty indices, bring relief, domestic food safety, and financial stability growth [12, 13].

The importance of rice in Liberia extends even far; it serves as a platform for income generation [7]. The chain of value linked to rice cultivation involves a range of tasks, encompassing growing, processing, allocation, and selling, generating job prospects and revenue sources throughout the journey. Its accessibility and cost have traditionally affected the nation's socio-political environment in the past, like in 1979, where high rice tariffs resulted in major riots, highlighting its essential importance in the Liberian society.

Due to the country's demand for rice, the Liberian government launched the National Agriculture Development Plan (NADP) 2024–2030, also known as "Feed Yourselves" Agenda, intending to enhance food security. With this regard, the Liberian government has identified counties with potential for rice production, such as, Lofa, Bong, and Nimba. However, these areas have not been thoroughly assessed for their suitability. To achieve optimal rice production, it is crucial to identify the most appropriate locations, through a land suitability analysis. Suitability is determined by the combination of different factors, such as climate and land/soil characteristics, assessing how well the local match or satisfy the crop's needs [14].

Recent studies have increasingly utilized Geographic Information System (GIS)-based Multi-Criteria Decision-Making (MCDM) approach, as effective tool for assessing land suitability for crop production, supporting sustainable agriculture, and food security [14–18]. The integration of MCDM and GIS enhances the capacity to capture, manage, manipulate, analyze, model, and display geographic data effectively, allowing evidence-based decision-making. For instance, [15] used GIS-based MCDM for land evaluation and suitability mapping for rice cultivation in Oye-Ekiti, Nigeria. Similarly, [18] conducted a study in Northern Ghana, aimed at evaluating land suitability for crop production with the adoption of GIS-based MCDM and the Analytical Hierarchy Process (AHP). These techniques were also used by [17] to develop a suitability map for rice production in the Great Mwea region, Kenya, based on physical and climatic factors, and by [19] to evaluate a land suitability model for rice production in northern Bangladesh.

Despite these advances, a comprehensive land suitability analysis for rice cultivation in Liberia is still a gap. This study aims to identify agricultural land suitable for rice cultivation in Liberia, using a GIS-based MCDM and AHP, considering ten key factors: precipitation, temperature, elevation, slope, soil texture, soil pH, soil organic carbon, nitrogen, phosphorus and potassium. Several studies across neighboring and sub-Saharan Africa regions have employed similar approach to determine land potential for crop production, including Nigeria [15, 20], Ethiopia [14], Kenya [17], and Ghana [18]. This is the first GIS- and remote sensing-based study for assessing countrywide land suitability for rice crop cultivation in Liberia.

Findings include partial suitability assessment to identify optimal and limiting factors to rice productivity in Liberia. Additionally, future suitability against climate change is also assessed. In general, Liberia's agriculture appears to be relatively climate-resilient, with greater constraints arising from factors such as soil texture, pH and slope. This study provides important baselines for stakeholders and policy makers to make evidence-based decisions on their interventions in addressing the current challenge in rice crop productivity, contributing to increased rice production and yield, thereby, supporting enhanced food security.

2 Materials and methods

2.1 Characterization of the study area

The study area, Liberia, is located in the upper Guinea rainforest region of West Africa, bordered by Guinea to the north, Sierra Leone to the west, Côte d'Ivoire (Ivory Coast) to the east, and the Atlantic Ocean to the south. Liberia is one of the smallest countries in the west African region (Fig. 1), and its total area covers 111,350 km^2, with a population of 5.3 million [21]. The country lies between the latitudes 4° 20' N and 8° 30' N and longitudes 7° 18' W and 11° 30' W [22].

Major part of the country is characterized by mixed vegetation and savanna. Agriculture is the major socioeconomic activity in Liberia [23], and rice is produced by nearly 70% of farmers, with cultivation predominantly undertaken by smallholder farmers under rainfed conditions [3]. The country's average rice yields is approximately 1.2 t/ha,

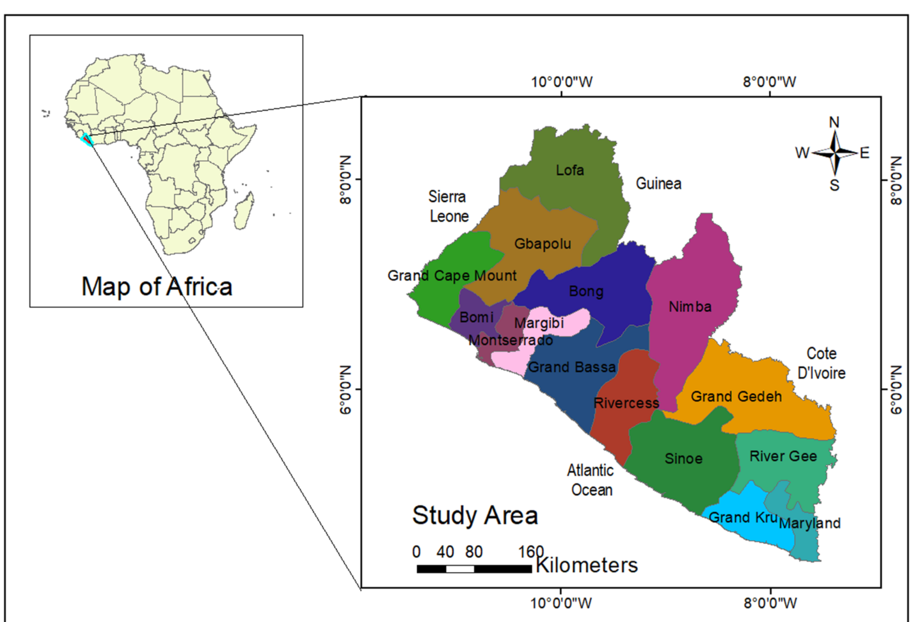

Fig. 1 The study area, Liberia and its county divisions

with notable production in Nimba, Bong, and Lofa counties, which account for 56% of the country's rice production [11, 24].

Figure 2 presents the historical variability of rice production and yield from 1990 to 2023, processed using national data provided by FAOSTAT open data (https://www.fao.org/faostat/en/#home). Based on this data, the total production in Liberia increased from 180,000 tons in 1990 to 256,200 tons in 2023 representing a gain of 76,200 tons in 33 years, while the yield remains nearly constant and its average converge to the value presented above, reported in literature.

2.1.1 Climate

Liberia presents a tropical and humid climate, subdivided in three sub-groups namely: monsoon, savanna, and equatorial climate [25, 26]. Liberia temperature is typically within the range from 23 to 33 °C throughout the year [27] and the mean temperature for the country is 25.7° [26]. On the other hand, the average annual precipitation in

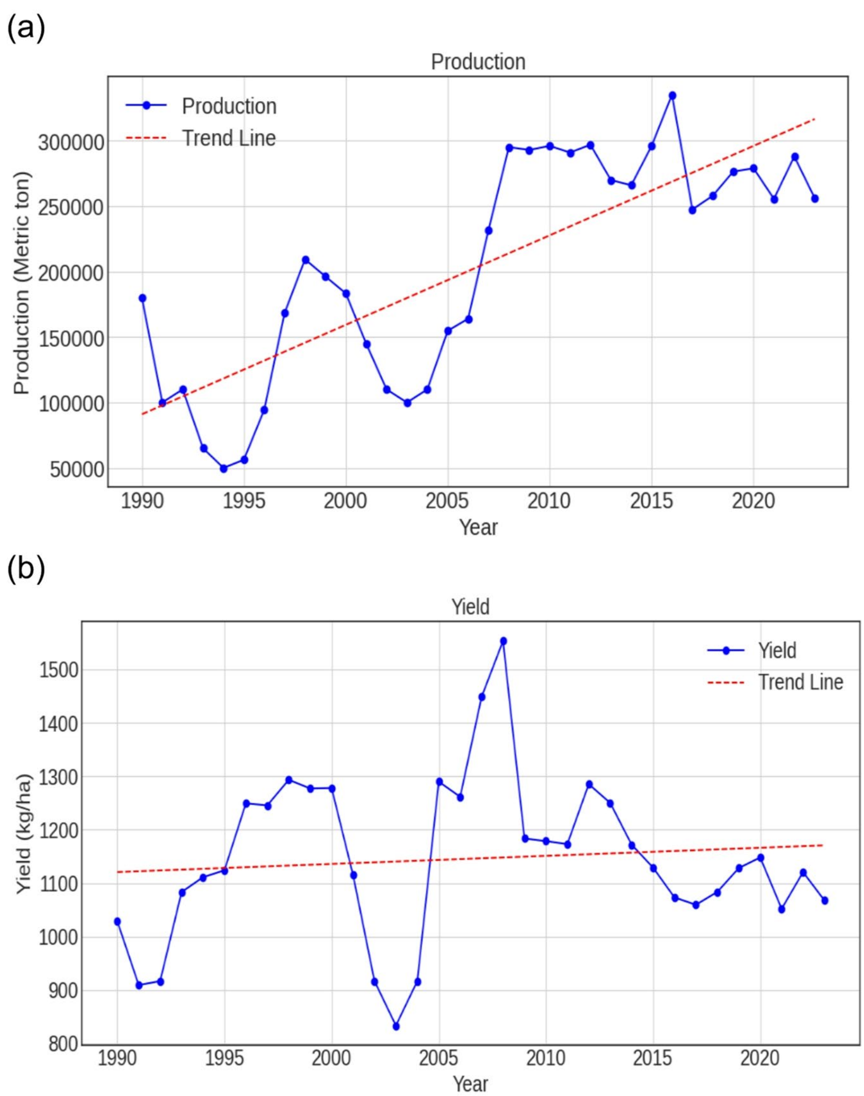

Fig. 2 Variability of the time series of rice **a** production and **b** yield, from 1990 to 2023. Data provided by FAOSTAT open data (https://www.fao.org/faostat/en/#home)

Liberia is 2500 mm, with some spatial differences between regions [28]. Rainfall along the coastal areas exceeds 4000 mm per year and reduces to 1300 mm in the country's interior. For instance, in Monrovia, precipitation reaches 5000 mm annually, with the pick in June and July, where monthly precipitation reaches about 1000 mm [29, 30]. Daily relative humidity along the coastal belt remains high (> 80%), decreasing to nearly 20% inland during the dry season [25].

2.1.2 Geomorphology

Liberia's geomorphology is shaped by a combination of ancient geological formations and fluvial processes, resulting in diverse landforms across the country. Landscape is characterized by four distinct regions, which include coastal plains, rolling hills, plateaus and coastline, and northern highland [27]. The coastal area has an upland extension of 32–40 km, and consist of moderately rolling hills or low plains with an altitude not exceeding 15 m [27]. Rolling hills reach 90 m and are mostly used for agricultural purposes. The plateau extends over 120 km, with heights up to 300 m, while mountains rise to 600 m, including the Mano River mountains [26, 27]. The northern highlands feature significant ranges with Mount Wutivi reaching 1440 m, and these areas are also rich in minerals and biodiversity. Mount Nimba nearby Yekepa reaches about 1752 m above sea level, but it is not completely within Liberia, as it shares a border with Guinea and Côte d'Ivoire [27].

2.2 Data for suitability analysis

Climate, soil, topographical and land use land cover data were used for achieving the purpose of this study. These data were obtained from various sources with varying resolutions as depicted in Table 1. Ten factors were considered for the suitability analysis, namely: temperature, precipitation, elevation, slope, soil texture, soil pH, soil organic carbon (SOC), nitrogen, phosphorus and potassium. In general, there is no a rule of thumb for the number of factors to include in the multi-criteria decision-making (MCDM) method. In our case, the inclusion of the 10 factors was determined by their influence or contribution to rice crop development based on previous studies [12, 14, 16, 31] and by data availability and quality.

2.2.1 Climate data

Climate information consisted of air temperature and precipitation, which have a direct interference in agriculture and they can affect either positively or negatively the growth, development, and yield of agricultural crops [31]. Rice is typically cultivated in tropical and sub-tropical regions, and based on its tropical characteristics, it grows well in

Table 1 Data types and their sources

Data	Format	Data source	Web link
Temperature and precipitation	Raster	ERA5	https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels
Elevation and slope	Raster	SRTM	http://earthexplorer.usgs.gov
Soil texture	Shapefile	FAO	https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/
Chemical properties	Shapefile	LIBSIS	https://libsislr.com
Land use land cover	Raster	ESA	http://due.esrin.esa.int/page_globcover.php

a climate with relatively high temperatures between 20° and 40 °C and annual rainfall levels ranging from 1250 to 2000 mm [15, 20]. Data of precipitation and temperature from 1980 to 2023 were obtained from Copernicus Climate Change Service (C3S), consisting of AgrERA5 reanalysis (Agrometeorological Indicators), with a spatial resolution of 0.1° × 0.1° (available online at https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels). For the purpose of this study, we have considered the seasonal data from April to September, for both temperature and precipitation, which is the rice growing season in Liberia. Figure 3 shows the spatial variability of long-term averages of precipitation and temperature over this season. For assessing future implication of climate change on land suitability, we have considered projections of precipitation and temperatures derived from the Coordinated Regional Climate Downscaling Experiment, phase 5 (CORDEX5), the most updated CORDEX phase for Africa, available by the moment of this study, covering the period of 2006–2100, accessed at https://esg-dn1.nsc.liu.se/search/cordex/. Instructions for downloading the data can be found at http://www.csag.uct.ac.za/cordex-africa/how-to-download-cordex-data-from-theesgf/. We have downloaded the CORDEX for Africa with spatial resolution of 0.22° × 0.22°. For the purpose of this study, we have assessed the worst greenhouse gas emission scenario RCP8.5. Available data consisted of a total of 6 simulations from the ensemble "r1i1p1" (6 ensemble members), as a result of the combination of two regional models (CCLM and REMO) and three driving models (MOHC-HadGEM2-CC, NCC-NorESM1-M, and MPI-M-MPI-ESM-LR). The ensemble mean was averaged over Liberia for two future periods: mid-twenty-first century (2031–2060) and the end of twenty-first century (2071–2100).

2.2.2 Soil data

Data on soil physical properties (soil texture) was sourced from FAO (Food and Agricultural Organization) world soil map, and chemical properties including pH, nitrogen, phosphorus, and potassium were obtained from the Liberia Soil Information System (LIBSIS) database of 2023 (accessible online at https://libsislr.com). Figure 4 shows the soil data considered for this study.

Soil texture plays a key role in rice cultivation, as it is the level of coarseness of the soil, and rice being a tropical crop, requires a soil texture that can retain water for a longer

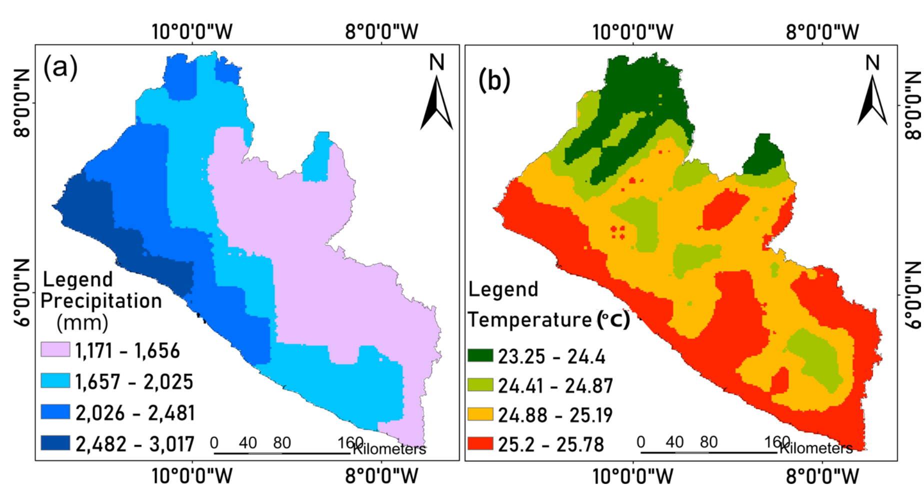

Fig. 3 Spatial variability of **a** precipitation in mm and **b** temperature in °C, averaged during the rice growing season (April to September) in Liberia

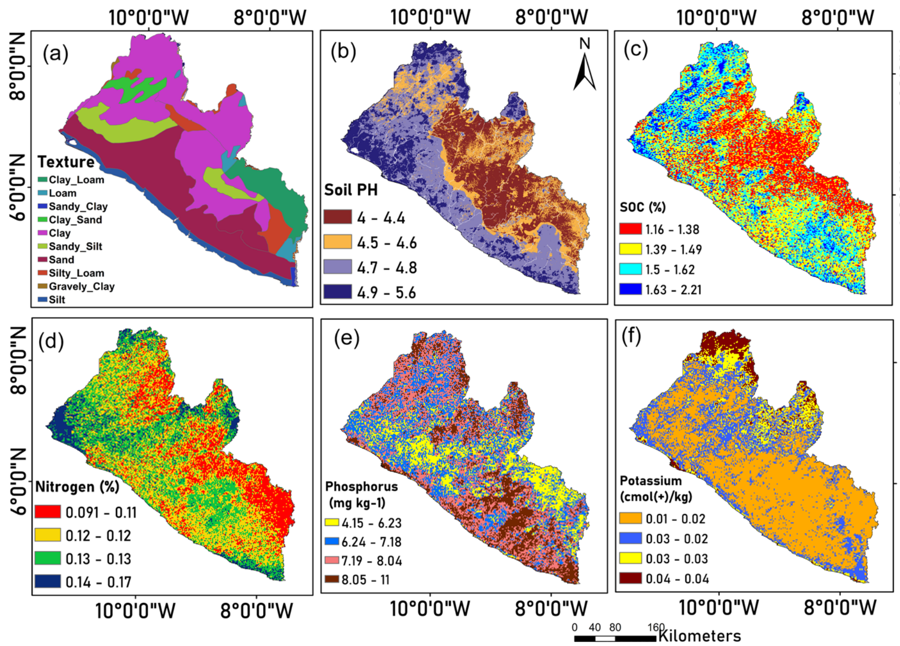

Fig. 4 Geomorphological maps for soil parameters in Liberia: **a** soil texture, **b** pH, **c** soil organic carbon, **d** nitrogen, **e** phosphorus, and **f** potassium

period [15]. Liberia is generally characterized by 4 major soil types, with sub-classes (the combination of these soil types). These soil types include clayey (60–70%), sandy (10–15%), loamy (7–10%), and silty (5–8%). The clayey soil covers most parts of Liberia (upland and interior regions) due to the widespread presence of heavily weathered, iron-riched Ferralsols (clay), which is mostly found in counties including Lofa, Bong, Nimba, and Sinoe (Fig. 4a). The sandy class is mostly found in the south and south-central parts of Liberia. Soil texture is a limiting factor for rice crop production in Liberia, as poor soils are found even in the major rice producing counties. Lofa in particular, is predominantly covered by Ultisols, typically acidic and with limited nutrient availability, while Bong and Nimba are largely Oxisols, which are deeply weathered, low in nutrient fertility, and highly prone to nutrient depletion without inputs [3, 32]. Both soil types (Ultisols and Oxisols) are classified under the USDA Soil Taxonomy system and are common in humid tropical and subtropical regions [32].

2.2.3 Topographic data

Topographic data such as elevation and slope were accessed through the Shuttle Radar Topography Mission (SRTM) which is among the most commonly utilized Digital Elevation Model (DEM) data sources [19]. In this study, the 30 m spatial DEM data from STRM was utilized, and is available from the United States Geological Survey (USGS) through the link http://earthexplorer.usgs.gov. Figure 5 shows the spatial variability of elevation and slope in Liberia.

2.2.4 Land use land cover data

The land use land cover (LULC) data was used at the end of the suitability analysis for masking out areas covered by permanent water bodies, settlements and dense forests, as shown in Fig. 6. LULC data was extracted from the GlobCover 2009, which is

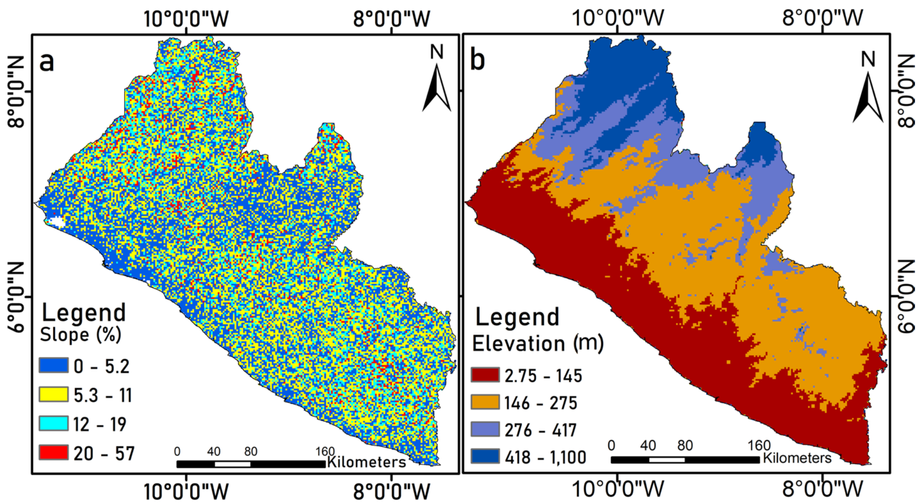

Fig. 5 Topographical characterization of Liberia: **a** slope (%) and **b** elevation (m)

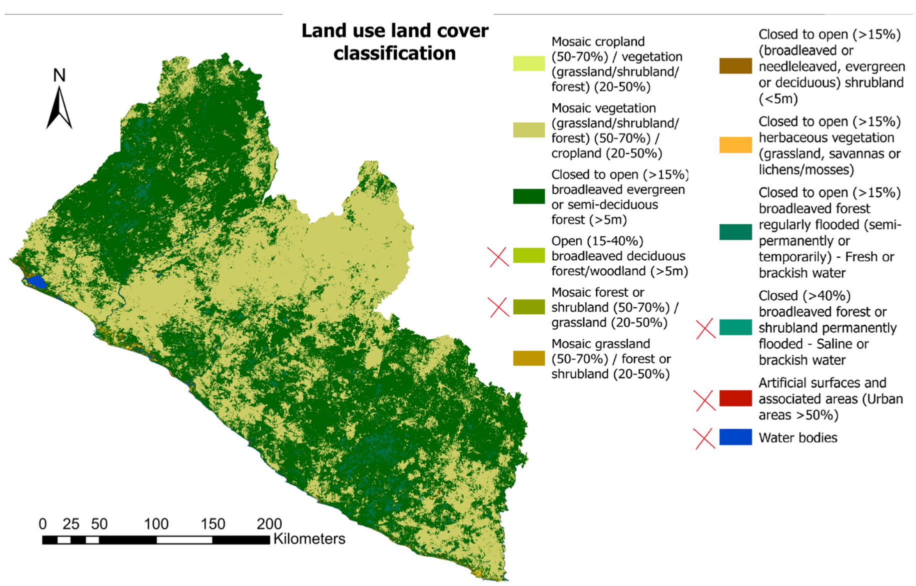

Fig. 6 Land use land cover map for Liberia. Data extracted from [33]. Land cover classes marked by red "X" were masked out from the final suitability map

a global land cover map based on ENVISAT's Medium Resolution Imaging Spectrometer (MERIS) Level 1B data acquired in full resolution mode with a spatial resolution of approximately 300 m [33]. Table 1 summarizes all data types and their respective sources.

2.3 Data processing and analysis

GIS technology was employed to gathering, analyzing and visualizing spatial data. Various suitability map layers were created [12], based on the criteria presented in Table 2. The preparation of the map layers involved interpolation of gridded data to get the same spatial resolution, which was fixed at $0.01° \times 0.01°$ (~1 km) using Ordinary Kriging, a native ArcGIS interpolation method, which performs relatively well for sparse data [34].

Table 2 Criteria for suitability rating for rice development

Factors	Very suitable	Suitable	Semi suitable	Not suitable	Sources
Rainfall within growing season (mm)	1000–2000	2000–3500	> 3500	< 1000	[19, 35]
Temperature within growing season (°C)	22–27	27–32	32–37	< 22 and > 37	[36]
Slope (%)	0–2	2–5	5–8	> 8	[36]
Elevation (m)	0–400	400–800	800–1400	> 1400	[36]
Soil Texture	C, SC, SCL	S, CL	SL, L	Sandy	[19, 36, 37]
Nitrogen (%)	> 0.3	0.2–0.3	0.1–0.2	< 0.1	[37]
Phosphorus (mg kg^{-1})	10–12	7–10 and 12–15	5–7 and 15–18	< 5 and > 18	[36]
Soil Organic Carbon (%)	> 3	2–3	1–2	< 1	[36]
Potassium (mg kg^{-1})	200–250	150–200 250–300	100–150	< 100 and > 300	[36]
pH	5.5–6.5	4.5–5.4	7.6–8.5	< 4.5 and > 8.5	[38]

Table 3 Degree of importance of the AHP scale for pairwise comparison. Source: [39]

Value of importance	Description
1	Equal importance
3	Moderate importance of one over another
5	Strong or essential importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments
Reciprocals	Values for inverse comparison

2.3.1 Multi-criteria decision-making

The study employed Multi-Criteria Decision-Making (MCDM) method integrated with Geographical Information System (GIS) technology. Land suitability assessment is done in a way that key consideration is given to local requirements and conditions are adequately represented in the ultimate decisions [17]. As such, this research adopted FAO's method of land classification as described by [14] to evaluate areas that are suitable for rice cultivation. Partial suitability map layers were produced based on the thresholds of suitability levels for each factor presented in Table 2.

2.3.2 Analytic hierarchy process

The Analytic Hierarchy Process (AHP) is a widely recognized and reliable technique for multi-criteria decision-making, used in both, its original and optimal forms [19, 36]. A key step in many decision-making processes is accurately assessing relevant data, often involving the evaluation of the relative importance, or weights for each criterion of a decision problem [14]. In assessing the suitability of crops, especially rice, not all factors are equally significant; as such, it is important to evaluate their relative importance. As previously referred in Sect. 2.2, ten factors including rainfall, temperature, elevation, slope, soil texture, soil organic carbon, soil pH, nitrogen, phosphorus, and potassium were considered for the AHP application. The AHP method developed by Wind and Saaty [41] employs a Pairwise Comparison Metrix (PCM) to assess two factors at a time [39]. According to the Wind and Saaty's scale, the available values for the pairwise comparisons are members of the set: {1, 2, 3, 4, 5, 6, 7, 8, 9, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9} (Table 3). In this study the relative importance assigned to each factor for the pairwise comparison matrix was judged by all four authors and through literature consultations. For example, a rating of 5 depicts that in relation to the column factor, the row factor is strongly important. Conversely, a rating of 1/5 indicates that relative to the column factor, the row factor is less important. Equal importance between column and row factors is rated as 1, as described in Table 3. AHP determines the weights (w_i) of factors using the Eigenvector related to the highest Eigenvalue and further normalize the sum of the modules to one (Eq. 1).

$$\sum_{\mathrm{i}=1}^{\mathrm{n}} w_i = 1. \tag{1}$$

The fundamental input is the two-way comparison matrix, A, of *n* criteria, created based on the scaling ratios from [39], is specified in Eq. 2.

$$\mathrm{A} = [a_{ij}]\,, \quad \mathrm{i,j} = 1, 2, 3, \ldots, \mathrm{n}, \tag{2}$$

where matrix A has the elements a_{ij} and generally has the property of reciprocity, expressed mathematically as:

$$a_{\mathrm{ij}} = \frac{1}{a_{\mathrm{ij}}}. \tag{3}$$

After generating this matrix, it is further normalized as matrix B:

$$\mathrm{B} = [\mathrm{b_{ij}}]\,, \quad \mathrm{i,j} = 1, 2, 3, \ldots, \mathrm{n}, \tag{4}$$

where B is the normalized matrix of A, with the elements $\mathrm{b_{ij}}$ denoted as:

$$\mathrm{b_{ij}} = \frac{a_{\mathrm{ij}}}{\Sigma_{\mathrm{i}}^{\mathrm{n}}\, a_{\mathrm{ij}}}, \quad \mathrm{i,j} = 1, 2, 3, \ldots, \mathrm{n}. \tag{5}$$

Finally, each weight value w_i is calculated as:

$$w_{\mathrm{i}} = \frac{\Sigma_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{b_{ij}}}{\Sigma_{\mathrm{i}=1}^{\mathrm{n}} \Sigma_{\mathrm{J}=}^{\mathrm{n}} \mathrm{b_{ij}}}, \quad \mathrm{i,j} = 1, 2, 3, \ldots, \mathrm{n}. \tag{6}$$

When applying the AHP method, it is vital that the weights obtained from the matrix of pairwise comparisons are consistent [40]. The consistency of the assessments is determined by the Consistency Ratio (CR). CR value should be less than 0.1 for the pairwise comparison matrix to be considered accurate [41, 42].

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}, \tag{7}$$

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n - 1}, \tag{8}$$

where CI is the Consistency Index, λ_{max} is the maximum Eigen value of the matrix, RI is a random index, representing the average of the resulting consistency index depending on the order of the matrix produced by [39], as shown in Table 4. In this study, CR

Table 4 Random index (RI). Source: [39]

Matrix order	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58

of 0.07 was obtained, indicating that the applied AHP model is accurate and consistent, thus, appropriate relative weights of factors were determined.

The two-way comparison matrix (A) and the normalized matrix (B) are shown in Table 5 and Table 6, respectively. Weights determined by Eq. 6 are also presented in Table 6.

2.3.3 Preparation of final land suitability map

The final land suitability map of the study area was produced by applying a weighted linear combination of the ten partial suitability maps obtained for each factor using the criteria from Table 2. The weighted linear combination is denoted by the Eq. 9. The ArcGIS-based raster calculator was used for this process.

$$S = \sum_{i=1}^{n} (R_i * w_i), \tag{9}$$

where S is final land suitability map; R_i is the partial suitability regarding the i-th factor; w_i is the weight assigned to the i-th factor, derived from the AHP; and n is the total number of factors. Applying the weights from Table 6, the Eq. 9 can be expanded to the Eq. 10:

$$\begin{aligned} S = {} & (RF * 0.206) + (TEM * 0.163) + (SOC * 0.157) + (STEX * 0.029) + (ELV * 0.044) \\ & + (pH * 0.070) + (SLP * 0.043) + (N * 0.096) + (P * 0.096) + (K * 0.096) \end{aligned} \tag{10}$$

Figure 6 outlines all the process to come up with the final land suitability map (Fig. 7).

3 Results

This study applied the GIS-based MCDM and AHP for agricultural land suitability analysis to identify areas that are suitable for rice cultivation in Liberia. Ten factors were considered for this purpose. A weighted linear combination was used to overlay partial suitability layers and determine the overall suitability map of the country.

3.1 Partial suitability

Figure 8 presents the reclassified maps with different suitability levels for each factor. Precipitation, which is the highly weighed factor, showed two suitability levels, which are very suitable (nearly 75% of Liberia) and suitable (approximately 25%) as observed from

Table 5 Pairwise comparison matrix (A) of selected factors: Slope (SLP), elevation (ELV), soil texture (STEX), soil organic carbon (SOC), soil acidity or alkalinity (pH), temperature (TEM), rainfall (RF), nitrogen (N), phosphorus (P) and potassium (K)

Criteria	Pairwise comparison matrix (A)									
	SLP	ELV	TEM	RF	pH	N	P	K	SOC	STEX
SLP	1	1/2	1/5	1/5	1/3	1/3	1/3	1	1/5	3
ELV	2	1	1/5	1/5	1/4	1/3	1/3	1/2	1/3	3
TEM	5	4	1	1/5	2	2	2	2	3	4
RF	5	5	2	1	2	2	2	2	3	5
pH	4	3	1/2	1/2	1	1/3	1/3	1/3	1/2	2
N	3	3	1/2	1/2	3	1	1	1	1/3	2
P	3	3	1/2	1/2	3	1	1	1	1/3	2
K	3	3	1/2	1/2	3	1	1	1	1/3	2
SOC	5	5	1/4	1/3	2	3	3	3	1	3
STEX	1/3	1/3	1/4	1/5	1/4	1/3	1/3	1/3	1/3	1

Table 6 Normalized pairwise comparison matrix (B) and calculated weights (w_i) for the selected factors: Slope (SLP), elevation (ELV), soil texture (STEX), soil organic carbon (SOC), soil acidity or alkalinity (pH), temperature (TEM), rainfall (RF), nitrogen (N), phosphorus (P) and potassium (K)

Criteria	Normalized pairwise comparison matrix (B) and weights (w_i)											
	SLP	**ELV**	**TEM**	**RF**	**pH**	**N**	**P**	**K**	**SOC**	**STEX**	**Weight**	**Rank**
SLP	0.032	0.018	0.034	0.048	0.020	0.029	0.029	0.082	0.021	0.111	0.043	7
ELV	0.064	0.036	0.034	0.048	0.015	0.029	0.029	0.041	0.036	0.111	0.044	6
TEM	0.160	0.144	0.169	0.048	0.119	0.176	0.176	0.164	0.320	0.148	0.163	2
RF	0.160	0.180	0.339	0.242	0.119	0.176	0.176	0.164	0.320	0.185	0.206	1
pH	0.128	0.108	0.085	0.121	0.059	0.029	0.029	0.027	0.053	0.074	0.070	5
N	0.096	0.108	0.085	0.121	0.178	0.088	0.088	0.082	0.036	0.074	0.096	4
P	0.096	0.108	0.085	0.121	0.178	0.088	0.088	0.082	0.036	0.074	0.096	4
K	0.096	0.108	0.085	0.121	0.178	0.088	0.088	0.082	0.036	0.074	0.096	4
SOC	0.160	0.180	0.042	0.081	0.119	0.265	0.265	0.247	0.107	0.111	0.157	3
STEX	0.011	0.012	0.042	0.048	0.015	0.029	0.029	0.027	0.036	0.037	0.029	8
CR = 0.07		Maximum Eigen value = 10.99									Σ = 1	

Fig. 8a. This implies that the entire country is favorable for rice cultivation with respect to precipitation, or it would be if we assume that all other factors are also optimal. However, among the ten factors, only two others were found to be optimal in Liberia, which are, the air temperature that showed a single class of very suitable for rice cultivation (Fig. 8b) and the elevation which is very suitable to suitable (Fig. 8h).

Great suitability variation is observed from the remaining factors. For instance, as observed in Fig. 4a–f, soil properties such as soil texture, pH, soil organic carbon, nitrogen, phosphorus, and potassium present greater spatial variations. Soil texture ranges from clay loam to silt, while the remaining factors present the following ranges: pH (4.0–5.6), soil organic carbon (1.16–1.21%), nitrogen (0.091– 0.17%), phosphorus (4.15–11 mg/kg), and potassium (0.01–0.04 cmol(+)/kg). In particular, soil organic carbon and nitrogen, which are important inputs for crop development, are critical, falling in the semi-suitable class for the whole country (Fig. 8c,f), indicating potential implication on rice cultivation. Slope, soil texture and pH presented significant areas that are unsuitable for rice cultivation (Fig. 8g,i,j), implying that rice productivity in Liberia is mostly constrained by these three factors, with pH being the most limiting factor as attested by Fig. 8j.

3.2 Final suitability map

The overall suitability analysis identified four suitability classes in Liberia: very suitable, suitable, semi-suitable, and not suitable, as presented in Fig. 9a. Their corresponding percentages within the country's area are presented in Fig. 9b. Considering the different categories of suitability in the country, 5.57% of the land is very suitable, and can be found mostly in the northeastern regions, with more emphasis to Bong and Nimba, where the combination of the ten considered factors provides optimal conditions for rice production, suggesting that these areas could be fundamental for intensive rice cultivation.

About 44.57% of land was classified as suitable, covering the northeastern and coastal southeastern regions, with more emphasis to Lofa, Bong, Nimba, and parts of Grand Gedeh, Sinoe and Maryland. These areas generally meet the minimum conditions for rice cultivation, presenting no relevant limitations that can significantly affect the rice cultivation. With the adoption of improved management practices and improved rice varieties, these lands can provide high yields.

Semi-suitable areas correspond to approximately 42.41% of the country, mostly found in the western part (parts of Grand Cape Mount and Gbapolu) and partially in the eastern (parts of Grand Gedeh, Sinoe, River Gee and Grand Kru). These regions are affected by improper/poor conditions such as higher slopes, more acidic soils, and predominantly sandy soils. Although these factors minimize the natural productivity of the land, targeted interventions (e.g., soil fertility management, adequate land preparation, irrigation, and improved rice varieties) could reduce these limitations, and make these areas feasible for production.

Lastly, 7.45% of the country is considered not suitable for rice production, mostly in the southwestern areas (Riversess, Grand Bassa, Montserrado, Margiti, Bomi and parts of Grand Cape Mount). These areas consist of ecologically unfit ecosystems for supporting rice growth, influenced by acid soils, higher slopes, sandy soils, and combination of other poor soil properties such as soil organic carbon, nitrogen, phosphorus, and

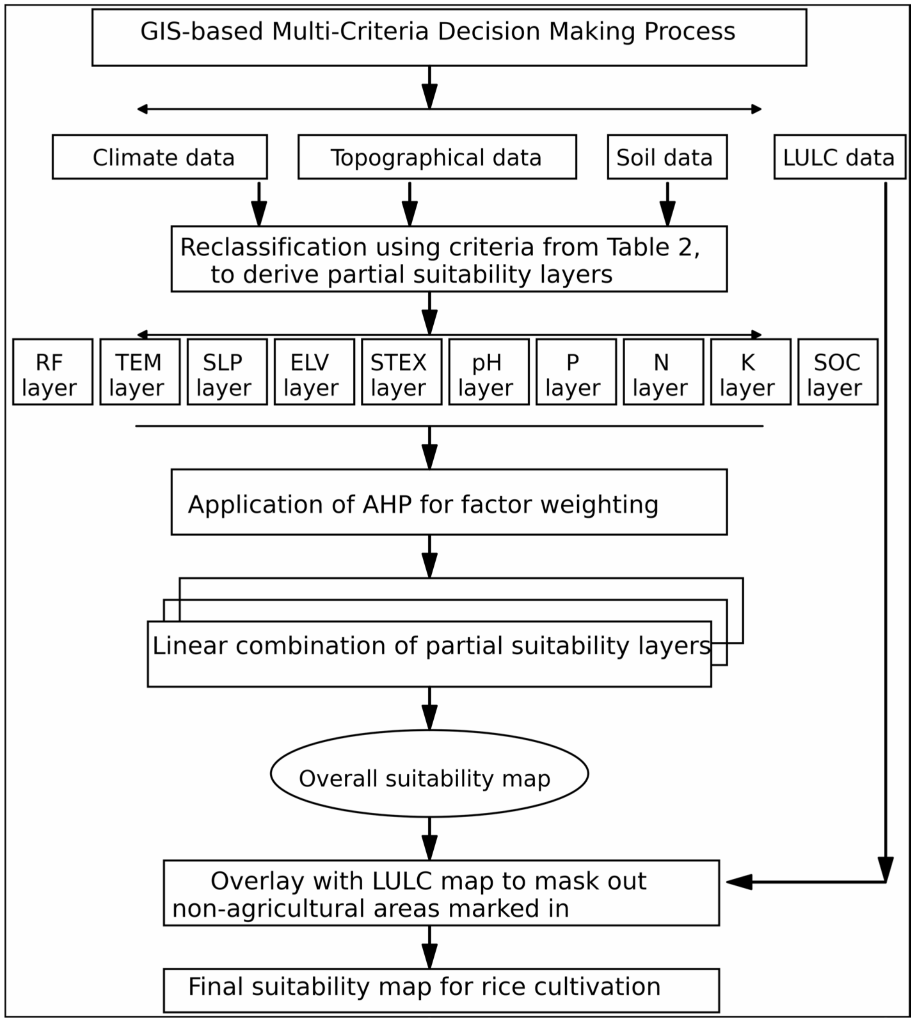

Fig. 7 Workflow outlining the methodology applied for land suitability

potassium. Expansion of rice cultivation in these areas may not only be unproductive and unsustainable but may also increase environmental degradation, contributing to biodiversity loss.Fig. 9a Final rice cultivation suitability map for Liberia, and b percentages of suitability classesFig. 9a Final rice cultivation suitability map for Liberia, and b percentages of suitability classesFig. 9a Final rice cultivation suitability map for Liberia, and b percentages of suitability classes

3.3 Sensitivity analysis

Sensitivity analysis was conducted in this study to investigate the influence of shifting the weights of factors to the overall suitability result [16, 31]. Sensitivity analysis is typically conducted using three ways: changing the relative importance of factors, changing the value of the parameters, and changing the weights of the factors. In this study, the sensitivity analysis has been carried out based on changing weights of the factors following the "what-if" approach [31]. It offers the possibility of identifying the key factor that influences the initial decision the most. In this study, factors were assigned weights obtained through the AHP pairwise comparison. Each weight was perturbed +/− 20%, with a moving step of 1%, resulting in 40 simulations per factor, and a total of 400

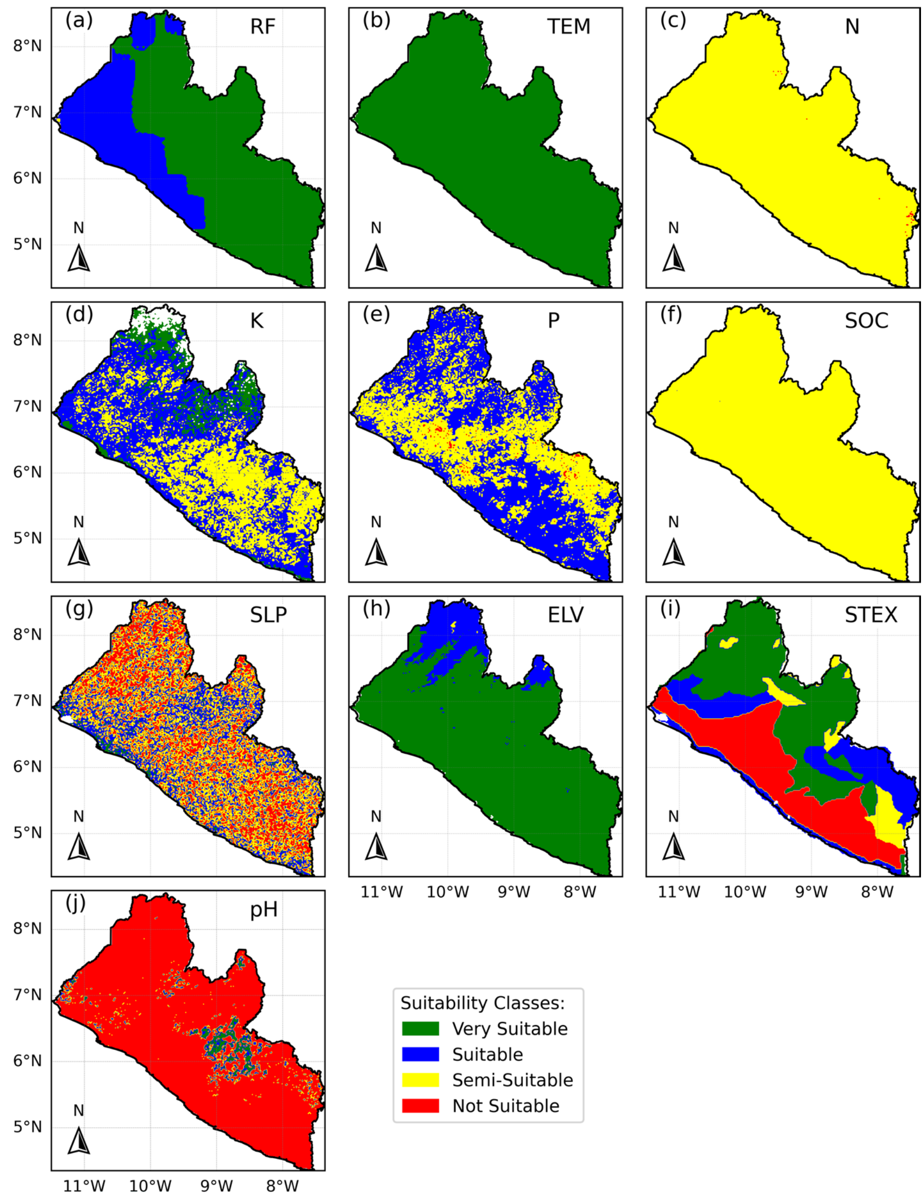

Fig. 8 Partial land suitability maps derived from each factor: **a** precipitation, **b** temperature, **c** nitrogen, **d** potassium, **e** phosphorus, **f** soil organic carbon, **g** slope, **h** elevation, **i** soil texture, and **j** pH

simulations for the ten factors. For each weight perturbation the others were readjusted so that the sum of all weights is maintained equal to 1. Figure 10 presents the sensitivity results, which indicate a relative stability of the model, with slight classes' changes. Notable sensitivity is observed for precipitation and pH, where shifting of the semi-suitable and suitable classes appear more pronounced. For precipitation, suitability shifts from semi-suitable to suitable when the weight change becomes above 5%, while for pH it shifts from suitable to semi-suitable when the weight change becomes above −10%. More stable factors are: temperature, nitrogen, soil organic carbon, and elevation.

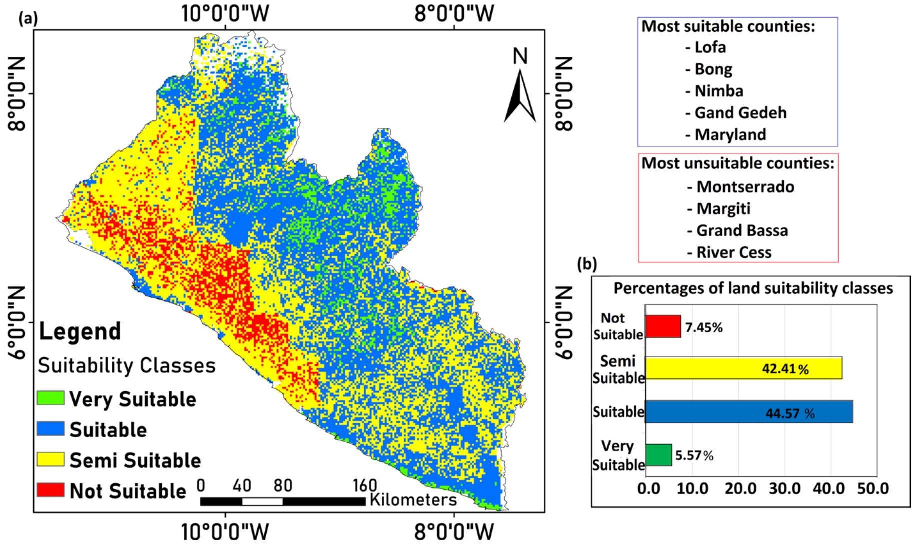

Fig. 9 **a** Final rice cultivation suitability map for Liberia, and **b** percentages of suitability classes

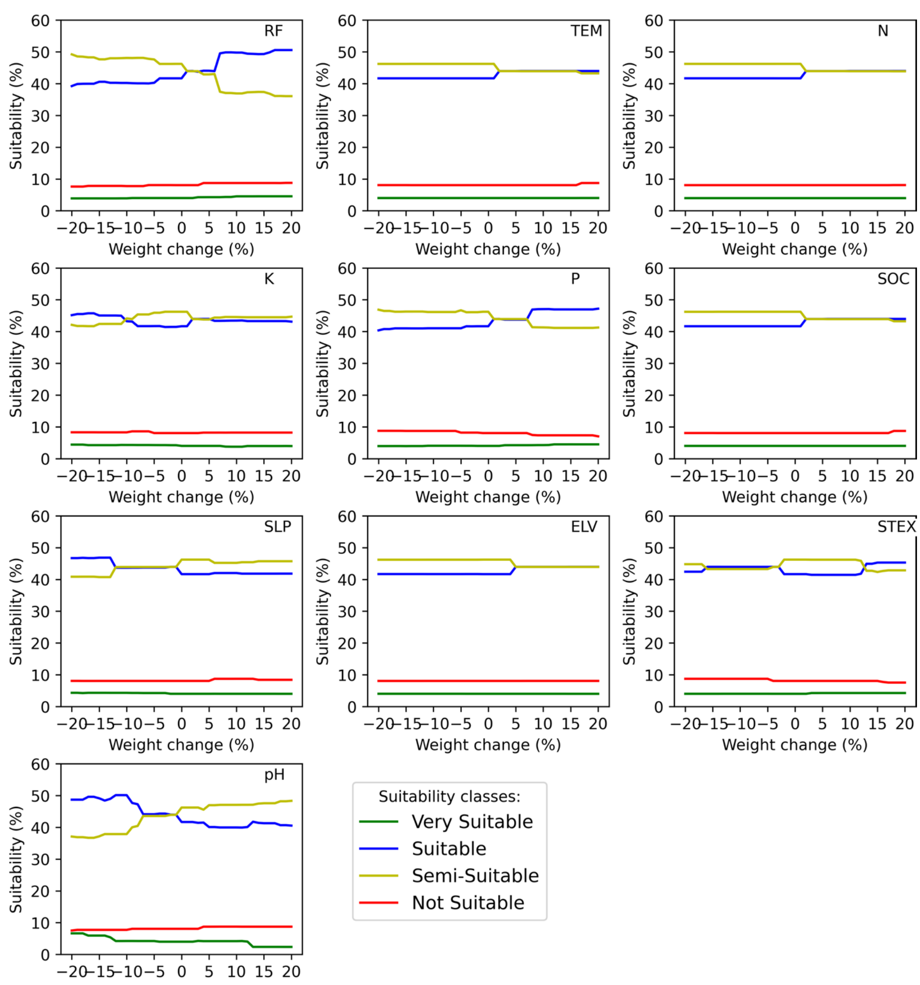

Fig. 10 Sensitivity analysis of the 10 factors used in the study. 40 simulations were computed per factor, with weight perturbation from – 20 to + 20%, and a moving step of 1%

4 Discussion

4.1 Land suitability

Climate variables (temperature and precipitation) are the two most contributing factors for accessing rice land suitability compared to the others due to their important role played in rice growth and development. Liberia is a tropical humid region, with abundant precipitation, what implies that it is not a limiting factor for rice cultivation in Liberia due to its adequate availability. Air temperature also falls in the optimal range. During the rice growing season in Liberia (April to September), long-term seasonal temperature ranges from 23 to approximately 26 °C, and precipitation from approximately 1000–3500 mm (Fig. 3a, b). These seasonal averages are favorable for rice cultivation according to [19, 35].

High annual rainfall and consistently warm temperatures support rainfed rice cultivation and reduce dependence on irrigation during the main growing season [43], suggesting that Liberia's agriculture is generally climate-resilient. However, potential future risks associated with climate change or climate extremes (anomalies within its variability) should be considered. Irregular rainfall patterns, prolonged dry spells, and extreme precipitation events may disrupt cropping calendars and adversely affect yields [44, 45], while heat waves associated with rising temperatures could increase evapotranspiration and heat stress, especially in upland systems [46]. Therefore, the country should still consider the importance of adaptive management strategies, including improved water management, climate-resilient rice varieties, and enhanced agronomic practices, to sustain rice productivity under changing climatic conditions [47].

The other factors presented different levels of suitability within the country, as observed from Fig. 8c–j. These factors interfered in the overall environmental conditions for suitability, and their variation across regions led to different land suitability levels for rice growth, where soil texture (sandy soils), pH (acid soils), and slope (ranging from 0 to 57%) appear to be the critical factors affecting suitability. In particular, sandy soils and higher slopes struggle to retain water, an important factor for rice growth [48]. Rice is mostly productive between 0 and 6% slopes and become unsuitable for above 8% slopes [49]. On the other hand, although elevation was found to be optimal factor for land suitability, [50] indicated that for every 100 m increase in mountain altitude, the time frame for vegetation and flowering in plants is delayed by 4–6 days. Moreover, rice crop mostly flourishes under the elevation up to approximately 500 m, mainly in lowlands [50]. These regions usually possess suitable temperature and water supply [48].

Results from the final suitability map indicate that Liberia has good potential for rice production. Putting together the two suitability classes classified as very suitable and suitable, totalizes about 50.14% of areas with optimal conditions for expanding rice production with minimal efforts, highlighting the country's capacity to increase domestic rice production and reduce importations, which currently correspond to over 60% of national rice consumption [11, 28].

While there is a lack of empirical peer-reviewed studies for land suitability for rice cultivation in Liberia, our findings are in line with those reported by CARD (2021) project [24], which conducted a study on the local rice competitiveness in 15 selected counties of Liberia, funded by Japan International Cooperation Agency. The study revealed that rice production in Liberia, is mostly produced in counties such as Lofa, Bong, Nimba, Gbarpolu, Grand Bassa, and Grand Gedeh [24], some of which were also identified as suitable for rice cultivation by our study. Additionally, the Nimba land assessment project (2021–2023) implemented by LIBSIS under the support of FAO and MOA, included in their activities, the production of a rice land suitability map for the county to serve as a pilot for the country. Findings revealed that approximately 30–40% of Nimba County is deemed moderately to highly suitable for rice production. These agreements with the existing knowledge provide more confidence and a comprehensive assessment of the spatial distribution of the country's potential for rice production.

Similar studies carried out in other Sub-Saharan African and neighboring countries, with comparable climate conditions, and characterized by more fertile soils, have shown to support relatively higher rice productivity [20, 35, 41], highlighting the effects of the Liberian poor soil conditions identified in this study. Recent studies have shown that Liberia's average national rice yield has remained low in recent decades, at around 1.2 metric tons per hectare, which is considerably lower than in other west African countries, 3.0 t/ha in Côte d'Ivoire, 2.7 t/ha in Ghana, 3.4 t/ha in Mali and 4 t/ha in Benin [10, 11]. Several underlying factors account for this stagnation in yield. These include traditional farming systems, the use of low-yield varieties, limited use of modern inputs such as improved seed, fertilizers, mechanization, and limited access to farm credit [10, 11, 51]. Reports from World Bank [52] and the World Food Programme (WFP) [53] indicate that yield improvements in Liberia and other West African countries have been constrained by limited access to improved rice varieties, irrigation technologies, fertilizers, and extension services. Farmers often rely on traditional practices and local seed varieties, which are less responsive to modern yield-enhancing technologies, thus limiting productivity per hectare [5].

Using GIS-based MCDM and AHP approach for assessing potential land for rice cultivation, [15] conducted a study in Oye-Ekiti, Nigeria, and found a relatively high potential for rice cultivation, classifying suitability into three categories: Highly suitable (18%), moderately suitable (70%), and marginally suitable (12%); having pointed inadequate water supply and low nutrients capacity as a constraint in some areas such as Eruwa, Oyo, and Shaki, where irrigation is needed to supplement rainfall for better yields. [54] used slightly different classification names in their land suitability assessment in Cote d'Ivoire (Poro region) and found 59.13% optimal, 12.38% suitable, 19.23% moderately favorable, and about 10% unsuitable; indicating constraints such as the combination of unfavorable ecological conditions, poor soil quality, competing land uses, and constraints in human and animal resources for rice cultivation. Additionally, in Denguele (North West of Côte d'Ivoire), [55] classified 74.04% of the total area of the region as very good and good. In Amhara region, Ethiopia, [14] found 23.15% highly suitable, 49.28% moderately suitable, 24.44% marginally suitable, and 3.13% not suitable, having pointed the same suitability constrains as in our study, such as, soil pH and slope, including rainfall deficit at some locations. A study carried out in Mwea region, Kenya [17] presented two suitability categories of moderately suitable (23.08%) and highly suitable (77.92%) for rice cultivation.

The above studies highlight the great potential of African countries for rice cultivation. However, despite this high potential rice is still not substantially produced in many African countries, including Liberia. For instance, [17] reported that by their study period, only 12% of suitable land was under rice cultivation. This is also the case of Liberia, where only a small portion (less than 10%) is currently under cultivation [51, 56], despite the existence of a significant area of the country with optimal conditions for rice production, as indicated by this study.

Beyond the total suitable area in Liberia (50.14%), our study also found a considerable proportion of semi-suitable land, corresponding to nearly 42.41%, revealing the existence of potential areas for productivity enhancement through targeted management interventions, or that can be harnessed using agricultural technologies. While these areas face certain agronomic constraints, such as soil texture, pH and slope, they are not fundamentally unproductive. With appropriate policies and investments such as land leveling, optimized fertilizer application, improved irrigation systems, and adoption of adaptive rice varieties, this land could add important contribution to national food production, thus, supporting national agriculture development plans (NADP), including the objectives of the NADP 2024–2030 "Feed Yourselves" Agenda, aimed at enhancing food security.

Furthermore, these interventions could contribute to fostering domestic production, leading to socio-economic stability, given that, despite the existence of favorable conditions in Liberia, only small fraction of this arable land is currently under cultivation, estimated in less than 30% [51]. Major constraints pointed in literature for the limited agricultural production include factors such as post-war-conflict, inadequate infrastructure, limited access to inputs, land tenure insecurity, limited extension services, vulnerability to extreme climate events, lack of mechanization, inadequate credit facilities, poor market access and weak value chains, as well as deforestation and environmental degradation [7, 51].

4.2 Climate change implications to land suitability

Agriculture is a climate-sensitive sector. Changes in climate variables, such as rainfall and temperature, have significant implications on crop production and yield [57–60]. This study found that the current precipitation and temperature patterns are generally favorable for rice cultivation in Liberia, categorizing the country as suitable to very suitable for precipitation and very suitable for temperature, implying that land suitability for rice cultivation in Liberia is not constrained by the current climate state. However, at the worst climate change scenario, simulations from the regional climate model CORDEX 5 in Liberia indicated that temperatures are expected to rise significantly by the end of the twenty-first century, while precipitation change is not statistically significant, although a slightly decrease is expected (Fig. 11). These findings suggest that the land suitability map obtained in this study is not static. It is more likely to change in future as attested by Fig. 12, compromising rice production in some regions of Liberia, especially in the northeast part, where unsuitability is indicated by precipitation. Although the average of future temperature is still indicated as suitable (Fig. 12c,d), it is important to consider the extremes within the future warmer climate variability, which may have negative impacts on rice crop production. Past studies [61–63] have revealed that temperature increases during the reproductive stage of rice, especially during panicle initiation, flowering, and fertilization, may severely reduce yield and grain quality. [62] found that an increase of 1 °C of temperature above the optimum threshold reduced the yield by 8%. Other several studies conducted over the Sub-Saharan Africa reported that climate variability and change have resulted in a reduction in crop yields, altered planting seasons, and increased vulnerability of smallholder farmers to food insecurity [64–66]. Higher

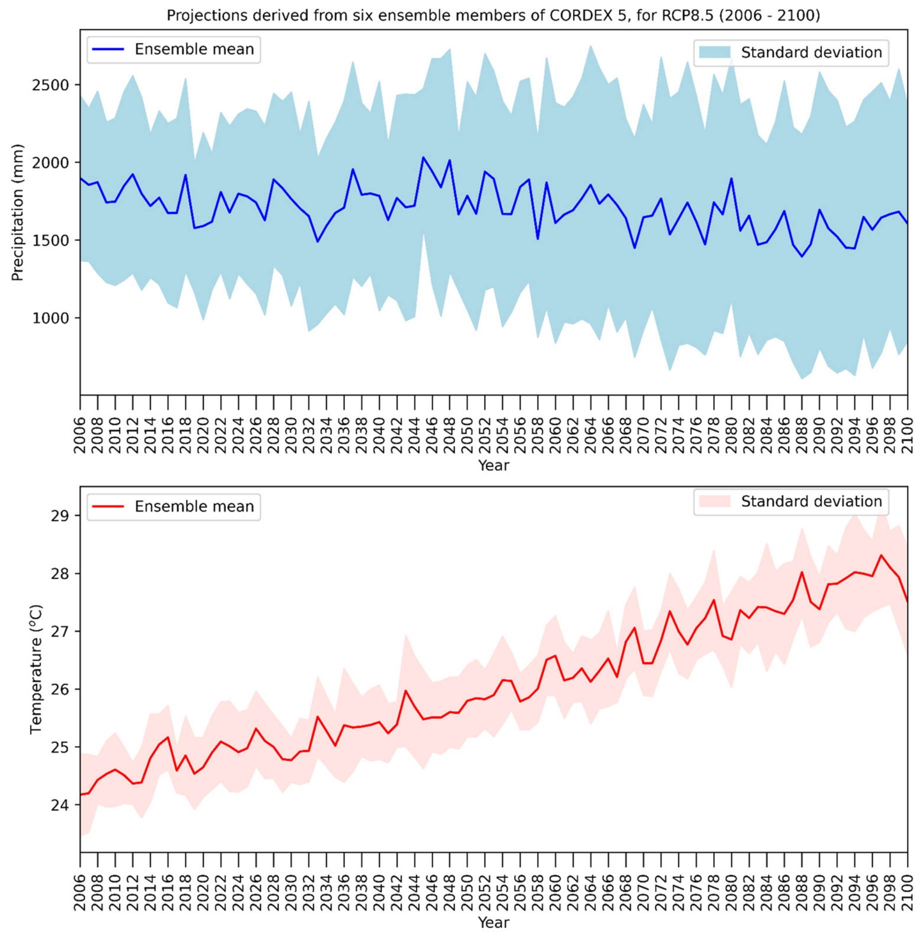

Fig. 11 CORDEX 5 projections of precipitation (upper panel) and air temperature (lower panel) averaged over Liberia, using six ensemble members, for the RCP8.5 scenario, from 2006 to 2100

minimum temperatures may impair crop performance possibly due to increased respiration rates, which can lead to energy loss, disruption of physiological recovery process and stress on sensitive growth stages such as flowering and grain filling [1, 67]. Similarly, [68] and [69] acknowledged that increased temperature affects the growth and development of rice plants, particularly during germination, flowering and grain filling stages. Overall, the results suggest that temperature disparities particularly minimum temperature, plays more critical role in rice production than precipitation [70, 71]. This highlights the crop's sensitivity to temperature during flowering and grain-filling stages [72].

5 Conclusions and recommendations

This study aimed at developing rice land suitability map, which holds important applications for developing sustainable land use, agricultural planning, and shaping environmental policies aligned with local natural characteristics.

Our findings indicated that about 50.14% of the total producible area of Liberia is favorable for rice production, including potential land of about 42.41% that can be harnessed using agricultural technologies. Most suitable areas are found in the northern, central and southeastern regions, with emphases to the following counties: Bong, Lofa, Nimba, Grand Gedeh, and parts of Sinoe and Maryland.

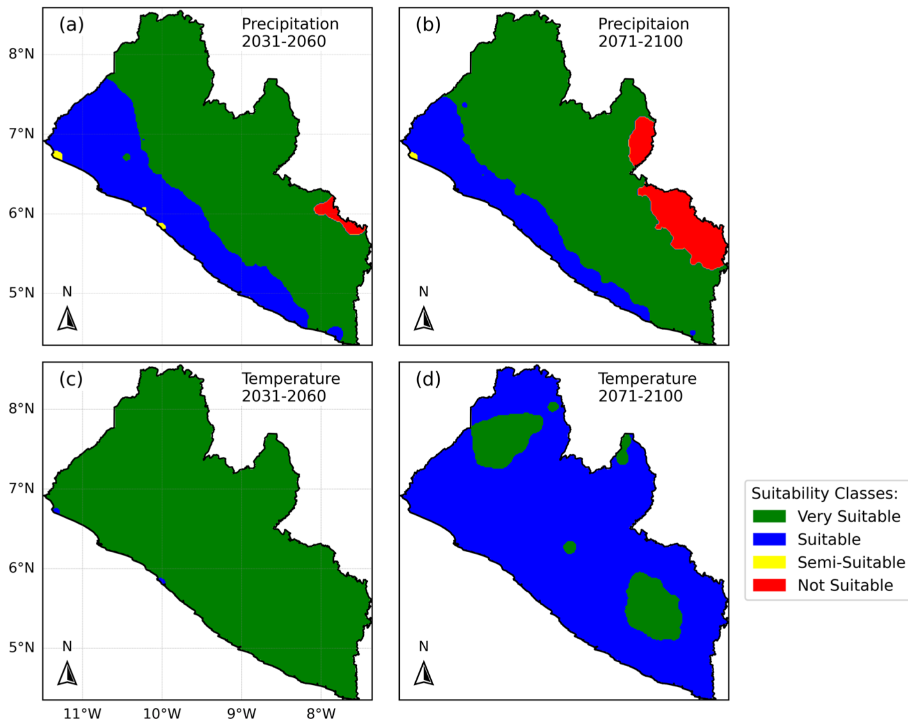

Fig. 12 Future land suitability in relation to future CORDEX 5 projections of precipitation (**a**, **b**) and temperatures (**c**, **d**) averaged over Liberia from six ensemble members, at the worst scenario RCP8.5, by 2031–2060 and 2071–2100, respectively

Liberia is overall a climate-resilient country. Current climate conditions are optimal for rice cultivation in the entire country. Precipitation exerted the most substantial influence on the overall suitability, followed by air temperature. Suitability was limited by the combination of the others factors. In particular, unsuitable areas were mostly influenced by slope, pH and soil texture.

By integrating spatial data with various criteria, the study offers key insights to the government and stakeholders to make evidence-based decisions on land management for rice production. Rice production in Liberia can be improved through the expansion of land within the indicated favorable areas. Government and stakeholders should prioritize mechanized agriculture and provide extension services in the counties listed above, including infrastructure development, such as storage facilities and roads, connecting regions with high rice production suitability to gross markets, and to those locations with limited conditions, enhancing production value chain. Semi-suitable areas should be improved by encouraging sustainable use of fertilizers and other agricultural inputs, including soil conservation practices to boost rice productivity in the country. This strategy could improve domestic rice production and reduce Liberia's dependence on importation, thus, impacting directly on farmer's socio-economic stability, such as food security and household income.

The research also highlights the potential of GIS in fostering sustainable development initiatives. A comprehensive approach, combining GIS, MCDM and empirical data, may serve as a valuable asset in advancing sustainable agriculture and tackling food security issues.

As limitations of the study, it was not feasible to use field-based validation of suitability results, though, for example, a field surveys or observed yield data, due to large geographic extent of the study area (national scale) and the lack of systematic records of rice production data. Thus, rather than empirical field observations, validation relied on existing literature, general knowledge on the land use/cover, and consistency check from the AHP model. Another limitation is related to the study reliance on global datasets, what may somehow not adequately capture local-scale variability in soils, topography, microclimate, and land cover, which are critical for rice production, potentially affecting suitability classification accuracy.

Despite field data limitations, the study offers an essential first step to countrywide assessment to identify suitable areas for rice cultivation. More importantly, it provides valuable baselines to Liberia on suitability mapping, serving as a tool for agricultural planning, policy and decision-making, as well as it establishes a foundational framework for future studies, which should incorporate other relevant factors and a field validation (ground surveys and crop yield data) to refine the suitability results.

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Author contributions
B.T.S. and J.L.M.U. proposed the study objectives, methodology, performed the data analysis, wrote original draft and reviewed the manuscript. C.M.M. and A.N. supervised, critically revised the manuscript. All authors approved the last version of manuscript to be published.

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Data availability
Data supporting reported results can be made available upon request, through the following contacts: Bondo Simpson: bondosimpson@gmail.com and Jone Ussalu: jonemedja@gmail.com.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors declare no competing interests.

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References

1. Su Q, Rohila JS, Ranganathan S, Karthikeyan R. Rice yield and quality in response to daytime and nighttime temperature increase—a meta-analysis perspective. Sci Total Environ. 2023;898:165256. https://doi.org/10.1016/j.scitotenv.2023.165256.
2. Adjah KL, Asante MD, Toure A, Aziadekey M, Amoako-Andoh FO, Frei M, et al. Improvement of rice production under drought conditions in West Africa: application of QTLs in breeding for drought resistance. Rice Sci. 2022;29:512–21. https://doi.org/10.1016/j.rsci.2022.06.002.
3. Pope et al. Assessment of upland rice production constraints and farmers' preferred varieties in Liberia. Int J Res Innov Soc Sci 2023;7:1175–1189. https://doi.org/10.47772/IJRISS.
4. Daszkiewicz T. Food production in the context of global developmental challenges. Agric. 2022. https://doi.org/10.3390/agriculture12060832.
5. Saito K, Senthilkumar K, Ali I, Johnson J, Rodenburg J, Senthilkumar K, et al. Status quo and challenges of rice production in Sub-Saharan Africa. Plant Prod Sci. 2023;26:320–33. https://doi.org/10.1080/1343943X.2023.2241712.
6. Ibrahim A, Saito K, Kokou A, Johnson JM, Diagne M, Fagnombo DJ, et al. Seizing opportunity towards sustainable rice cultivation in Sub-Saharan Africa. Environ Sustain Indic. 2022;15:100189. https://doi.org/10.1016/j.indic.2022.100189.
7. MOA Liberia National Rice Development Agriculture Republic of Liberia. 2018. https://riceforafrica.net/wp-content/uploads/2021/09/liberia_nrds1.pdf. Accessed 12 Jan 2025.

8. MOA Liberia National Rice Development Strategy—LNRDS. 2012, 52. https://riceforafrica.net/wp-content/uploads/2023/01/liberia_nrds2.pdf. Accessed 12 Jan 2025.
9. Pluato et al. Impact of post-harvest losses on the profitability of rice production amongst smallholder farmers in Liberia. Agric Res Technol Open Access J 2024;28, https://doi.org/10.19080/artoaj.2024.28.556414.
10. Saysay JL, Gabagambi DM, Mlay GI, Mined IJ. Technical efficiency in rice production among smallholder farmers in Central Liberia : a stochastic production frontier analysis. J Econ Sustain Dev. 2018;9:47–53.
11. Sumo TV, et al. Determinants of smallholder rice farmers' willingness-to-pay for private extension services in Liberia: The case of Gibi district. Sustainability. 2023;15:14300. https://doi.org/10.3390/su151914300.
12. Hashim N, Ali MM, Mahadi MR, Abdullah AF, Wayayok A, Mohd Kassim MS, et al. Smart farming for sustainable rice production: an insight into application, challenge, and future prospect. Rice Sci. 2024;31:47–61. https://doi.org/10.1016/j.rsci.2023.08.004.
13. World Bank Ending Poverty and Hunger by 2030 An Agenda for the Global Food System. Second Edition with Foreword. 2015. https://documents1.worldbank.org/curated/en/700061468334490682/pdf/95768-REVISED-WP-PUBLIC-Box391467B-Ending-Poverty-and-Hunger-by-2030-FINAL.pdf. Accessed 10 Feb 2025.
14. Ayehu GT, Besufekad SA. Land suitability analysis for rice production: a GIS based multi-criteria decision approach. Am J Geogr Inf Syst. 2015;4:95–104. https://doi.org/10.5923/j.ajgis.20150403.02.
15. Victor OK, Samson AO. An application of GIS-based multi-criteria decision making approach for land evaluation and suitability mapping for rice cultivation in Oye-Ekiti, Nigeria. J Agric Environ Sci. 2019;8:25–33. https://doi.org/10.15640/jaes.v8n1a3.
16. Hossen B, Yabar H, Mizunoya T. Land suitability assessment for pulse (green gram) production through remote sensing, GIS and multicriteria analysis in the coastal region of Bangladesh. Sustainability. 2021. https://doi.org/10.3390/su132212360.
17. Kihoro J, Bosco NJ, Murage H. Suitability analysis for rice growing sites using a multicriteria evaluation and GIS approach in great Mwea region, Kenya. Springerplus. 2013;2:1–9. https://doi.org/10.1186/2193-1801-2-265.
18. Salifu E, Agyare WA, Abdul-ganlyu S. Evaluation of land suitability for crop production in northern Ghana using GIS and AHP based techniques. Int J Environ Geoinform. 2022;9:45–56. https://doi.org/10.30897/ijegeo.1022275.
19. Islam MM, et al. Land suitability and insurance premiums: a GIS-based multicriteria analysis approach for sustainable rice production. Sustainability. 2018;10:1759. https://doi.org/10.3390/su10061759.
20. Adeboboye AJ, Agada AS, Joel PC, Dike CE, Augustina J, Rice farming suitability assessment in Anambra state using multi-criteria decision-making process. To Cite This Version : HAL Id : Hal-04575685 Rice Farming Suitability Assessment in Anambra State Using Multi-Criteria. 2024.
21. LISGIS Evaluation of the 2022 Liberia Population and Housing Census. 2023. https://lisgis.gov.lr/document/LiberiaCensus2022EvaluationReport.pdf. Accessed 21 Feb 2025.
22. EPA Republic of Liberia Liberia ' s First Adaptation Communication to the United Nations Framework Convention on Climate Change (UNFCCC). 2021. https://epa.gov.lr/wp-content/uploads/2024/10/Liberias-Updated-NDC_RL_FINAL-002.pdf. Accessed 23 Feb 2025.
23. CBL Central Bank of Liberia Annual Report 2022. 2023. https://www.cbl.org.lr/sites/default/files/documents/CBL_2022_ANNUAL_REPORT.pdf. Accessed 21 Feb 2025.
24. CARD Data Collection Survey on Rice Related Programs/Projects in the CARD Member Countries (with Competitiveness Analysis of Local Rice to Imported Rice. 2021. https://riceforafrica.net/wpcontent/uploads/2023/12/Mozambique_competitiveness-analysis_20210808.pdf. Accessed 22 December 2024.
25. EPA National Policy and Response Strategy on Climate Change Final Document-Min_0. 2018. https://www.undp.org/liberia/publications/national-policy-and-response-strategy-climate-change. Accessed 23 Feb 2025.
26. Climate Risk Profile: Liberia Liberia Climate Risk Country Profile. 2021. https://climateknowledgeportal.worldbank.org/sites/default/files/202107/15917-WB_Liberia%20Country%20Profile-WEB.pdf. Accessed 30 Mar 2025.
27. EPA Liberia's First Biennial Update Report to UNFCCC. 2020. https://unfccc.int/sites/default/files/resource/BUR1.pdf. Accessed 23 Feb 2025.
28. EPA Liberia's Revised Nationally Determined Contribution (NDC). Minerva. Int. Verzeichnis Wissenschaftlicher Institutionen. 2021, 307–307. Republic of Liberia, July 2021. https://faolex.fao.org/docs/pdf/lbr206208.pdf. Accessed 23 Feb 2025.
29. EPA Liberia Initial National Communication 2013. 2013. https://unfccc.int/sites/default/files/resource/lbrnc1.pdf. Accessed 23 Feb 2025.
30. NAP Liberia National Adaptation Plan 2020–2030. 2022. https://unfccc.int/sites/default/files/resource/LIBERIA_%20NAP_%20FINAL_%20DOCUMENT.pdf. Accessed 20 Feb 2025.
31. Singh RP, Bisht H, Jain R, Suna T, Bana RS, Godara S, et al. Crop-suitability analysis using the analytic hierarchy process and geospatial techniques for cereal production in North India. Sustainability. 2022;14:5246. https://doi.org/10.3390/su14095246.
32. Soil Surve Staf Keys to Soil Taxonomy Thirteenth Edition. 2022. Vol. 12. https://www.nrcs.usda.gov/sites/default/files/2022-09/Keys-to-Soil-Taxonomy.pdf. Accessed 20 Feb 2026.
33. ESA 2010 and UCLouvain. Global land cover map. http://due.esrin.esa.int/page_globcover.php. Accessed 05 Aug 2025.
34. Du, R., Yang, J. Application of ordinary Kriging method in data processing of magnetic survey. 2012 7th International Conference on Computer Science & Education (ICCSE), pp. 771–774, https://doi.org/10.1109/ICCSE.2012.6295186. 2012.
35. Samanta S, Pal B, Pal DK. Land suitability analysis for rice cultivation based on multi-criteria decision approach through GIS. Int J Sci Emerg Technol. 2011;2(1):12–20.
36. Bazkiaee PA, Kamkar B, Amiri E, Kazemi H, Rezaei M, Araji HA. Multi-criteria GIS-based land suitability analysis for rice cultivation: a case study in Guilan province, Iran. Environ Monit Assess. 2024. https://doi.org/10.1007/s10661-024-12811-y.
37. Ozsahin, et al. Determination of suitable lands for rice cultivation in Edirne plain: GIS supported FAO limitation method. Paddy Water Environ. 2022;20:325–38. https://doi.org/10.1007/s10333-022-00895-6.
38. Robertson N, Oinam B. Rice suitability mapping using the analytic hierarchy process approach in a river catchment. Glob J Environ Sci Manag. 2023;9:141–56. https://doi.org/10.22034/gjesm.2023.01.11.
39. Wind Y, Saaty TL. Marketing applications of the analytic. Manage Sci. 1980;26:18. https://doi.org/10.1287/mnsc.26.7.641.
40. Pant S, Kumar A, Ram M, Klochkov Y, Sharma HK. Consistency indices in analytic hierarchy process: a review. Mathematics Basel. 2022;10:1–15. https://doi.org/10.3390/math10081206.

41. Hagos YG, Mengie MA, Andualem TG, Yibeltal M, Linh NTT, Tenagashaw DY, et al. Land suitability assessment for surface irrigation development at Ethiopian Highlands using geospatial technology. Appl Water Sci. 2022;12:1–11. https://doi.org/10.1007/s13201-022-01618-2.
42. Mohidem NA, Hashim N, Shamsudin R, Man HC. Rice for food security: revisiting its production, diversity, rice milling process and nutrient content. Agriculture. 2022. https://doi.org/10.3390/agriculture12060741.
43. Maiti A, Hasan MK, Sannigrahi S, Bar S, Chakraborti S, Mahto SS, et al. Optimal rainfall threshold for monsoon rice production in India varies across space and time. Commun Earth Environ. 2024;5:1–8. https://doi.org/10.1038/s43247-024-01414-7.
44. Habte A, Worku W, Mamo G, Ayalew D, Gayler S. Rainfall variability and its seasonal events with associated risks for rainfed crop production in Southwest Ethiopia. Cogent Food Agric. 2023. https://doi.org/10.1080/23311932.2023.2231693.
45. Nguyen PTM, Ho PT, Pham HX. Impacts of seasonal climate variation on rice yield: evidence from the Central Coast of Vietnam. Cogent Econ Finance. 2024. https://doi.org/10.1080/23322039.2024.2421894.
46. IPCC, Summary for policymakers. In: Core Writing Team, Lee H, Romero J editors Climate change 2023: Synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change. Geneva : IPCC, 2023, pp. 1–34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001. Accessed 10 June 2024.
47. Van Oort PAJ, Zwart SJ. Impacts of climate change on rice production in Africa and causes of simulated yield changes. Glob Change Biol. 2018. https://doi.org/10.1111/gcb.13967.
48. Hussain W, Sohaib O, Ahmed A, Khan MQ. Geographical information system based model of land suitability for good yield of rice in Prachuap Khiri Khan Province , Thailand. Sci Tech Dev. 2012;31:1–9.
49. Oktaviano O, Yuwana Y, Barchia F, Reflis R. Evaluation of the suitability of irrigated paddy fields (*Oryza sativa* L.) in the Kelingi Irrigation Area, Tugumulyo District, Musi Rawas Regency. Jurnal Teknik Pertanian Lampung (J Agric Eng). 2025;14:1758–66.
50. Bozdağ A, et al. AHP and GIS based land suitability analysis for Cihanbeyli (Turkey) county. Environ Earth Sci. 2016;75:813. https://doi.org/10.1007/s12665-016-5558-9.
51. Allen AD Jr, Diallo K. Agricultural dynamics in Liberia: Current issues and solutions. Int J Res Innov Soc Sci. 2025;9:7430–7. https://doi.org/10.47772/IJRISS.2025.910000604.
52. World Bank Liberia Smallholder Agriculture Transformation and Agribusiness Revitalization Project; 2013. https://documents1.worldbank.org/curated/en/539361545925964964/pdf/project-appraisal-document-pad-smallholder-agriculture-transformation-and-agribusiness-revitalization-project-star-p-p160945-12192018-636810265253447785.pdf. Accessed 10 July 2024.
53. WFP Resilient Food Systems in Western Africa: WFP Contribution to Food Systems Transformation in Western Africa; 2023; WFP Contribution to Food Systems Transformation in Western Africa. https://docs.wfp.org/api/documents/WFP0000153294/download/?_ga=2.19230013.400229510.1701695545-296211395.1697009928. Accessed 20 August 2024.
54. Toure A, Assi KJ, Silué PD, Assi-kaudjhis JP. GIS approach and evaluation of lowland rice production potential in Cote d ' Ivoire: Case of the Poro Region. Int J Humanit Soc Sci Res. 2022;8:3–7.
55. Konan-waidhet AB, Dibi B, Kouadio ZA. Modeling of suitable areas for rainfed rice growing using multicriteria approach in geographic information system : case of Denguele (North West of Côte d ' Ivoire). Br J Appl Sci Technol. 2015;6:95–104. https://doi.org/10.9734/BJAST/2015/14486.
56. Allen AD Jr, et al. Assessing the impact of climate change on Liberia's agricultural sector and strategic adaptation approaches. Int J Res Innov Soc Sci. 2025;9:9545–59. https://doi.org/10.47772/IJRISS.2025.910000781.
57. Calvin K, Dasgupta D, Krinner G, Mukherji A, Thorne PW, Trisos C, Romero J, Aldunce P, Barrett K, Blanco G et al. IPCC, 2023: Climate change 2023: Synthesis report. contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change [Core Writing Team, H. Lee and J. Romero (Eds.)]. IPCC, Geneva, Switzerland.; Arias P, Bustamante M, Elgizouli I, Flato G, Howden M, Méndez-Vallejo C, Pereira JJ, Pichs-Madruga R, Rose SK, Saheb Y, Sánchez Rodríguez R, Ürge-Vorsatz D, Xiao C, Yassaa N, Romero J, Kim J, Haites EF, Jung Y, Stavins R, Birt A, Ha M, Orendain DJA, Ignon L, Park S, Park Y, Reisinger A, Cammaramo D, Fischlin A, Fuglestvedt JS, Hansen G, Ludden C, Masson-Delmotte V, Matthews JBR, Mintenbeck K, Pirani A, Poloczanska E, Leprince-Ringuet N, Péan C (eds) 2023.
58. Mulungu K, Kangogo D. Striving to be resilient: the role of crop-poultry integrated system as a climate change adaptation strategy in semiarid Eastern Kenya. Heliyon. 2022;8:e11579. https://doi.org/10.1016/j.heliyon.2022.e11579.
59. Reyes F, Gosme M, Wolz KJ, Lecomte I, Dupraz C. Alley cropping mitigates the impacts of climate change on a wheat crop in a Mediterranean environment: a biophysical model-based assessment. Agriculture. 2021. https://doi.org/10.3390/agriculture11040356.
60. Yuan X, Li S, Chen J, Yu H, Yang T, Wang C, et al. Impacts of global climate change on agricultural production: a comprehensive review. Agronomy. 2024. https://doi.org/10.3390/agronomy14071360.
61. Jagadish SVK, Murty MVR, Quick WP. Rice responses to rising temperatures—challenges, perspectives and future directions. Plant Cell Environ. 2015;38:1686–98. https://doi.org/10.1111/pce.12430.
62. Song Y, Wang C, Linderholm HW, Fu Y, Cai W, Xu J, et al. The negative impact of increasing temperatures on rice yields in Southern China. Sci Total Environ. 2022;820:153262. https://doi.org/10.1016/j.scitotenv.2022.153262.
63. Wassmann R, Dobermann A. Climate change adaptation through rice production in regions with high poverty levels Reiner. J Publ SESSO Period. 2012;1:2–24.
64. Roudier P, Sultan B, Quirion P, Berg A. The impact of future climate change on West African crop yields: what does the recent literature say? Glob Environ Chang. 2011;21:1073–83. https://doi.org/10.1016/j.gloenvcha.2011.04.007.
65. Oluwatimilehin IA, Ayanlade A. Climate change impacts on staple Crops: assessment of smallholder farmers' adaptation methods and barriers. Clim Risk Manag. 2023;41:100542. https://doi.org/10.1016/j.crm.2023.100542.
66. Sultan B, Gaetani M. Agriculture in West Africa in the twenty-first century: climate change and impacts scenarios, and potential for adaptation. Front Plant Sci. 2016;7:1–20. https://doi.org/10.3389/fpls.2016.01262.
67. Hat JL, Prueger JH. Temperature extremes: effect on plant growth and development. Weather Clim Extrem. 2015;10:4–10. https://doi.org/10.1016/j.wace.2015.08.001.
68. Li N, Zhao Y, Han J, Yang Q, Liang J, Liu X, et al. Impacts of future climate change on rice yield based on crop model simulation—a meta-analysis. Sci Total Environ. 2024. https://doi.org/10.1016/j.scitotenv.2024.175038.
69. Togbah CF. An analysis of Liberia's vulnerability to climate change in the context of least developed countries (LDCs): a review. Am J Clim Change. 2024;13:230–50. https://doi.org/10.4236/ajcc.2024.132013.

70. Birkmann J et al. Poverty, livelihoods and sustainable development. 2023. https://doi.org/10.1017/9781009325844.010
71. Zhao C, Liu B, Piao S, Wang X, Lobell DB, Huang Y, et al. Temperature increase reduces global yields of major crops in four independent estimates. PNAS. 2017;114:9326–31. https://doi.org/10.1073/pnas.1701762114.
72. Baruah U, Das S, Kalita P, Saikia M, Bhougal S, Pal S, et al. High-night temperature-induced changes in chlorophyll fluorescence, gas exchange, and leaf anatomy determine grain yield in rice varieties. J Plant Growth Regul. 2023;42:5538–57. https://doi.org/10.1007/s00344-023-10934-z.

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