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Glutinous paddy land suitability under stress condition using multi-criteria AHP-GIS approach

Hardanto, A.[1*], Ardiansyah.[1], Setyawan, C.[2], Mandala, M.[3], Saparen, S.[4] and Asrijal.[5]

[1]Department of Agricultural Engineering, Faculty of Agriculture, Jenderal Soedirman University, Purwokerto, Indonesia; [2]Department of Agricultural Engineering, Faculty of Agricultural Technology, Gadjah Mada University, Yogyakarta, Indonesia; [3]Department of Soil Science, Faculty of Agriculture, Jember University, Jember, Indonesia; [4]Department of Agronomy, Faculty of Agriculture, Andi Djemma University, Indonesia; [5]Department of Agro-technology, Faculty of Agriculture, Puangrimaggalatung University, Indonesia.

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Abstract The results indicated that the southern Java region is primarily classified as marginally suitable (S2), comprising 48.96% of the area (3,407.7 km²), followed by moderately suitable (S3) at 40.59% (2,825.3 km²). In contrast, the areas classified as not suitable (N) and highly suitable (S1) were relatively similar, comprising 5.55% (386.4 km²) and 4.90% (341.4 km²), respectively. Therefore, this region is presented a significant opportunity for cultivating glutinous rice, allowing for the productive use of less fertile land in Indonesia's glutinous rice production.

Keywords: Glutinous rice, Land suitability, Marginal land, Spatial variability

Introduction

Climate change has affected various sectors for over two decades, particularly agriculture and food security (Duchenne-Moutien and Neetoo, 2021; Misiou and Koutsoumanis, 2022; Molotoks *et al*., 2021; Wheeler and von Braun, 2013). It impacts the ability of plants to adapt to challenges such as water stress from flooding and drought, salinity, and erosion (Aslam *et al*., 2023). As a result, rice production has declined significantly, dropping to 51% due to these extreme weather events (Hussain *et al*., 2020). Increased rainfall and challenging topography have also led to more significant soil erosion in upland areas (Quan *et al*., 2020). These adverse conditions also affect soil properties, disrupting plant growth and reducing rice productivity.

Glutinous rice is a well-known agricultural product, particularly in Asia. It is commonly featured in traditional cultural and social activities, often

[*] **Corresponding Author:** Hardanto, A.; **Email:** afik.hardanto@unsoed.ac.id

accompanied by dishes made from glutinous rice (Sakamoto, 1996). Various functional foods made from glutinous rice have also been developed to enhance food security. Glutinous paddy is known for its tolerance to stressful conditions, such as waterlogging, drought, salinity, and low nutrient levels (Suwannakhot *et al*., 2022). In Indonesia, particularly in the southern region of Java Island, there is a significant amount of marginal land, approximately 60 million hectares (Hazmi *et al*., 2022). These challenging conditions can be addressed by utilizing stress-resistant varieties like glutinous paddy.

Information on the distribution of land suitability is essential for developing glutinous paddy cultivation. Several criteria influence the selection of appropriate land, making a multi-criteria approach to spatial data necessary. The Analytical Hierarchical Process (AHP) is a multi-criteria pairwise assessment algorithm that provides more accurate stage results (Anane *et al.,* 2012; Hardanto *et al.,* 2023; Radulović *et al.,* 2022; Saaty, 2008). Meanwhile, a Geographic Information System (GIS) analyzes spatial data to derive valuable spatial information. The AHP-GIS approach has been successfully employed in various sectors, such as the environment, water resources, industry, education, and agriculture, yielding accurate and efficient results (Anane *et al.,* 2012; Arulbalaji *et al.,* 2019; Ruiz *et al.,* 2020). The involvement of multidisciplinary experts significantly enhances this accuracy (Ferrando *et al.,* 2021).

The objective was to evaluate land suitability for glutinous rice cultivation through the multi-criteria AHP-GIS approach.

Materials and methods

Study area

The research was conducted in the southern region of Java, Indonesia, precisely positioned south of Mount Slamet. Several significant river basins, including the Serayu, Cintanduy, Tipar, Ijo, Telomoyo, Luk Ulo, Wawar, and Donan rivers characterize this area. The geographical coordinates of the study area range from 7°09'40" to 7°47'05" South latitude and from $108^0$33’27" to $109^0$55’03" East longitude, encompassing a total area of approximately 6,960.7 square kilometres. Administratively, this region is divided into five districts: Purbalingga, Banjarnegara, Banyumas, Cilacap, and Kebumen. This administrative region is known as Barlingmascakeb. The diverse topography and varying climatic conditions of this mountainous region make certain areas susceptible to drought and flooding (Figure 1).

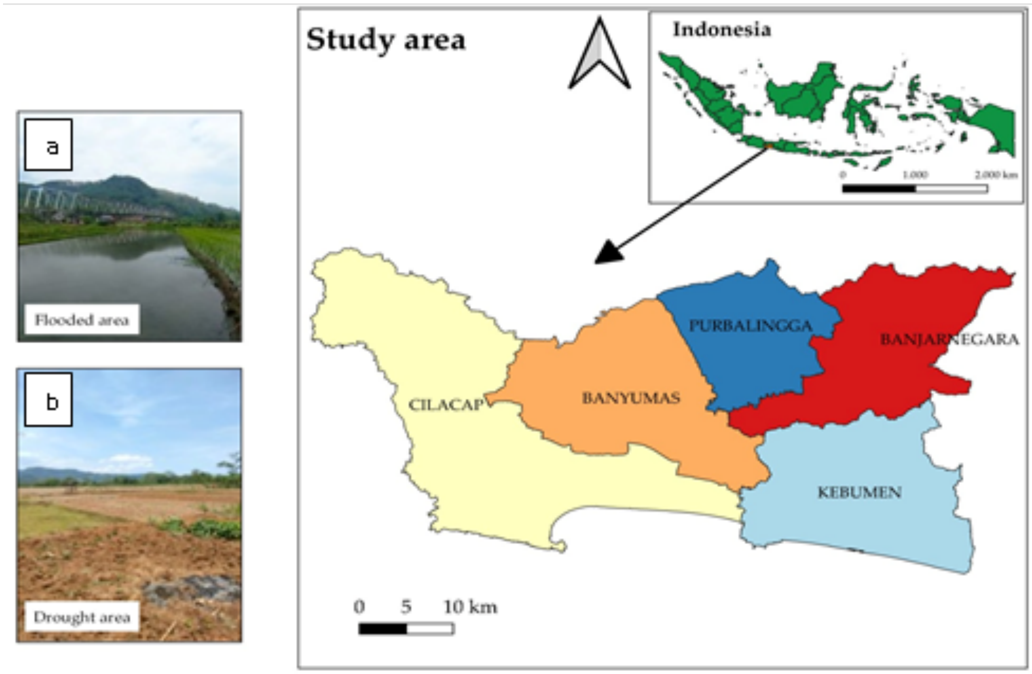

Figure 1. The study area of southern Java (Indonesia) with five regencies and various extreme conditions, such as flooded (a) and drought (b) areas

AHP and GIS conceptual framework

Selecting appropriate criteria is a crucial step in assessing land suitability. Based on literature reviews, three main criteria significantly influence land suitability for rice cultivation: topography, climatology, and soil properties. Each criterion includes specific sub-criteria that apply to establish weighting and assess the parameters affecting land suitability.

Topography was processed using a Digital Elevation Model (DEM), whereas climatology and soil properties were analyzed from WorldClim.org and Isric.org, respectively (Table 1). All spatial data analysis in the GIS platform employs QGIS 3.16 with a 1 x 1 km^2 resolution. After acquiring all the sub-criterion maps, data processing was carried out using the AHP approach to determine the weighting and ranking of each criterion (Lamidi and Ijaware, 2022; Saaty, 2008; Tashayo *et al.,* 2020). The land suitability map was evaluated using the QGIS environment (Figure 2).

Table 1. Description of the criteria and sub-criteria used for analyzing glutinous rice land suitability

Criteria	Sub-criteria	Data source	Description
Topography (Goulart *et al.,* 2020; Kikuta *et al.,* 2018; Wang *et al.,* 2019)	Slope	big.go.id	The slope affects drainage, cultivation techniques, and optimal planting area.
	Drainage density	big.go.id	Drainage prevents surface runoff, which results in a loss of nutrients in the soil and maintains good soil moisture.
Climatology (Abbas and Mayo, 2021; Xu *et al.,* 2021)	Rainfall	WorldClim.org	Rainfall is the primary input of irrigation systems, especially in drought regions.
	Temperature	WorldClim.org	Temperature significantly affects the process of filling rice grains.
Soil Properties (Li *et al.,* 2023)	Organic carbon (OC)	Isric.org	OC is a form of organic matter derived from natural carbon compounds.
	Cation exchange capacity (CEC)	Isric.org	CEC is a chemical property that helps maintain and improve soil fertility. High CEC can also support the availability of nutrients.
	pH	Isric.org	Soil pH describes the level of nutrient availability and absorption in the soil.
	Coarse fragments (CF)	Isric.org	The presence of rocks on the surface or in the soil, CF, can interfere with plant rooting.

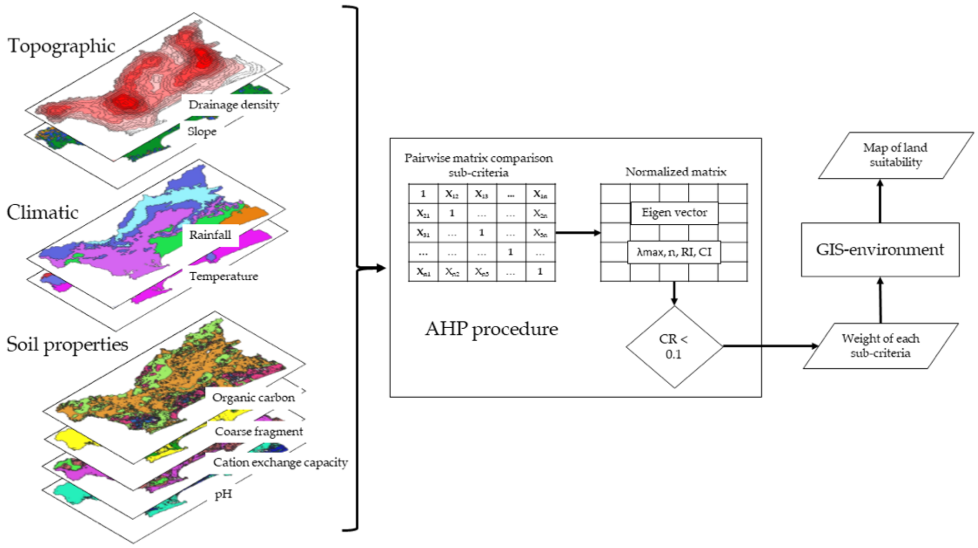

Figure 2. Flowchart of AHP-GIS methodology for assessment of glutinous rice land suitability

The analytic hierarchy process (AHP) is employed to assign weights to each sub-criterion. AHP is a widely used multi-criteria decision-making technique. A pairwise comparison matrix is generated by evaluating the scores for each sub-criterion (Saaty, 2008). This paired matrix has been developed based on assessments collected through a semi-structured questionnaire distributed to five experts: specialists in agricultural cultivation, agro-climatology, geographic information systems (GIS), geohydrology, and practitioners in the field. The pairwise comparison matrix for the eight sub-criteria was then normalized using the eigenvector method.

The weight of each sub-criterion is derived from the maximum eigenvalue in the normalized eigenvalues of the pairwise comparison matrix. The reliability of this assessment hinges on the consistency ratio (CR), which should be less than or equal to 0.1 (Saaty, 2008). If the CR exceeds this threshold, a revision of the pairwise assessment process for the sub-criteria is necessary. For the CR value, Eq. 1 was applied.

$$CR = \frac{CI}{RI} \qquad \text{(Eq. 1)}$$

RI is a Random Index based on the number of sub-criteria. The RI value in the research is 1.41 because there are eight sub-criteria. CI is a Consistency Index calculated by Eq. 2.

$$CI = \frac{\lambda \max - n}{n-1} \qquad \text{(Eq. 2)}$$

λmax represents the principal eigenvalue of the matrix, and n indicates the number of factors used in the estimation (Saaty, 2008). These weighting values are then utilized as a reference for analyzing land suitability maps

The land suitability map was developed by overlaying eight sub-criteria maps using QGIS 3.16 software. The land suitability index (SI) is calculated by multiplying the weight assigned to each criterion (W_i) with the ranking of that criterion (μ_i), as shown in Eq. 3.

$$SI = \sum_{i=1}^{n}(W_i \cdot \mu_i) \qquad \text{(Eq. 3)}$$

The relative weight (W_i) of drainage density is 0.103, and it is assessed with five sub-criteria. This criterion is classified into four potential suitability categories: Not Suitable (N), Moderately Suitable (S3), Marginally Suitable (S2), and Highly Suitable (S1).

Results

Weight and rankings of land suitability criteria

The weights and rankings for each of the eight sub-criteria that impact land suitability assessment are shown in Table 2. Slope is the most significant criterion, with a value of 0.333, and is divided into five sub-criteria. Rainfall showed the lowest value at 0.021, primarily because much of the land in the research area already has evenly distributed technical irrigation. The weights for the other criteria included temperature (0.15), organic carbon (OC) (0.21), coarse fragment (CF) (0.31), cation exchange capacity (CEC) (0.036), and soil pH (0.155). For the GIS overlay analysis, each criterion is assigned a ranking from 1 to 4, where 1 indicates Not Suitable, 2 indicated Moderately Suitable, 3 indicated Marginally Suitable, and 4 indicated Highly Suitable. These rankings are based on expert opinions gathered through a questionnaire survey.

Topographic parameter

Topography is closely linked to regional characteristics influencing soil properties, microclimate, and water availability. Two parameters were usede as drainage density and slope. Drainage density refers to the length of rivers in relation to the total area of a region. According to GIS analysis, the highest drainage density is observed in mountainous areas, while downstream areas showed relatively lower values (Figure 3a). A slope represents the changes in height over a certain distance. It is closely related to plant productivity and soil fertility. According to the slope distribution map of the Barlingmascakeb area, the steepest slopes are found in the Upland region, located at the mountain's edge, specifically in the northern part that extended to the east, as well as in the central area stretching from east to west. The low to moderate slope regions are predominantly found in the lowland areas, particularly at altitudes below 300 msal. In the Barlingmascakeb area, 57.8% of the land was less than 20% slopes, followed by 26.8% with slopes between 20% and 35%. The remaining areas showed the slopes exceeding 35%. The most suitable slope for rice cultivation was less than 20% (Figure 3b).

Tabel 2. Weighting and ranking of sub-criteria's land suitability

Criteria	Sub-criteria	Weighting	Ranking	Potential suitable
Drainage density	< 0.56	0.103	1	N
(km/km^2)	0.56 - 1.48		2	S3
	1.48 - 1.94		3	S2
	> 1.94		4	S1
Slope	< 20	0.333	4	S1
(%)	20 -50		3	S2
	50 - 75		2	S3
	> 75		1	N
Rainfall	< 172	0.021	1	N
(mm/month)	217 - 261		2	S3
	261 - 305		3	S2
	> 305		4	S1
Temperature	< 18	0.105	1	N
(^{0}C)	18 -22		2	S3
	22 - 26		3	S2
	> 26		4	S1
OC	< 6.7	0.216	1	N
(%)	6.7 - 11.4		2	S3
	11.4 - 16.1		3	S2
	> 16.1		4	S1
CF	<6.5	0.031	1	N
(cm^3/dm^3)	6.5 - 13.1		2	S3
	13.1 -19.7		3	S2
	> 19.7		4	S1
CEC	< 20.6	0.036	1	N
(cmolc/kg)	20.6 - 37.2		2	S3
	37.2 – 70.4		3	S2
	> 70.4		5	S1
pH	< 4.75	0.155	1	N
	4.75 - 5.50		2	S3
	5.50 - 6.25		3	S2
	> 6.25		4	S1

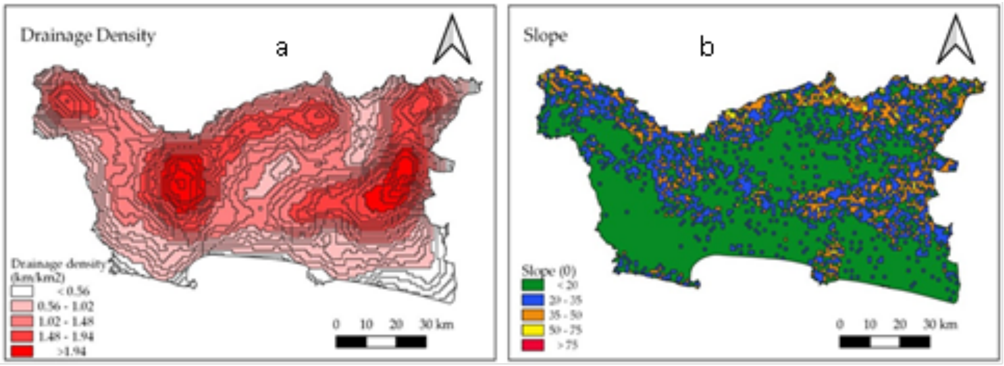

Figure 3. Topographic parameter for assessing glutinous rice land suitability, i.e., drainage density (a) and slope variability (b)

Climatic parameter

Climate change is a global issue that increasingly exposes countries to natural disasters. Reports indicated a decline in various agricultural commodities in several regions, primarily due to changes in temperature and rainfall. According to the thematic rainfall map for Barlingmascakeb, the highest rainfall is observed in the upland areas, specifically in the northern region (Figure 4a). This phenomenon is attributed to orographic rainfall when sea breezes carrying water vapor rise to higher elevations. As the air temperature cools at these heights, the water vapor is condensed and precipitated resulting in rainfall. The rainfall weighting factor was low (0.021) because the irrigation system in Barlingmascakeb is interconnected, and there is sufficient river water for irrigation distribution. Furthermore, high temperatures can be very detrimental to grain crops, especially paddy rice. In regions like Barlingmascakeb, temperatures often exceed 26°C, particularly in the southern lowlands, while cooler temperatures are typically found in the upland areas (Figure 4b).

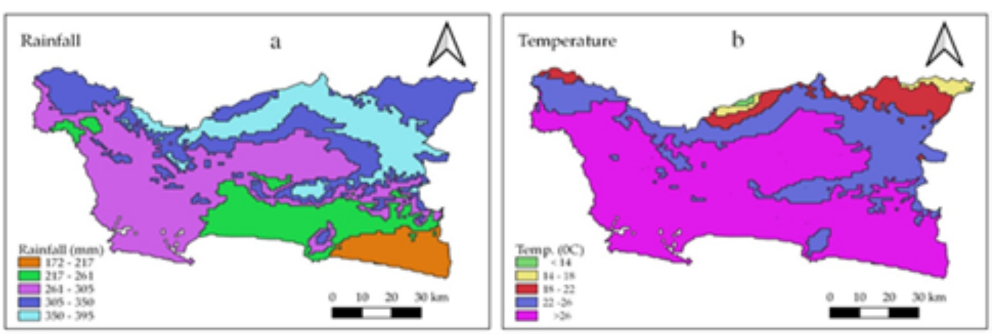

Figure 4. Climate parameter of study area for assessing glutinous rice land suitability, i.e., rainfall (a) and temperature (b)

Soil properties parameter

The link between soil pH, organic carbon (OC), cation exchange capacity (CEC), and coarse fragments significantly affects paddy development and production. The soil pH of parts of the study area was slightly acidic, namely 5-6 (Figure 5a). Soil organic carbon in highland areas was also relatively low (2-11%), while lowland areas showed relatively high values (Figure 5b). The distribution pattern of soil pH and OC was also similar to that of CEC and CF, where the highlands had lower CEC and CF values than the lowlands (Figures 5c and 5d).

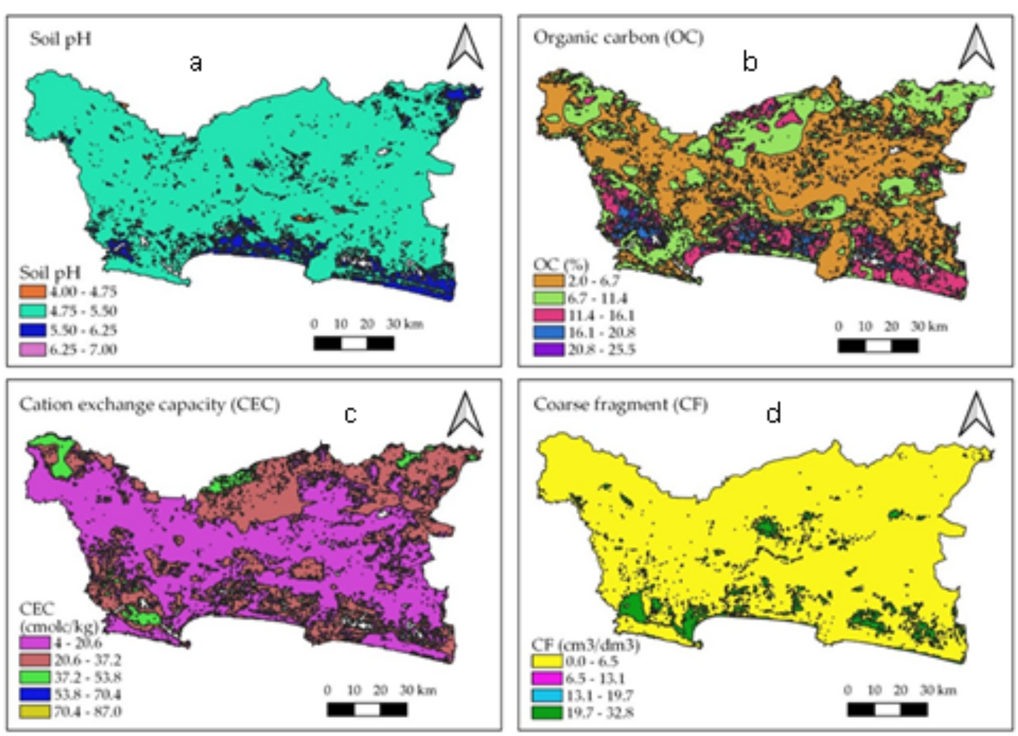

Figure 5. Soil properties parameters of study area for assessing glutinous rice land suitability, i.e., soil pH (a), organic carbon (b), cation exchange capacity (c), and coarse fragment (d).

Glutinous land suitability

The AHP-GIS analysis revealed that the Barlingmascakeb area presents an opportunity for effective land use planning, with the majority classified as marginally suitable (S2), covering an impressive 3,407.7 km² (48.96%).

Additionally, a substantial portion of the land was moderately suitable (S3), accounting for 2,825.3 km² (40.59%). While areas deemed highly suitable (S1) and not suitable (N) represented a smaller percentage, with only 341.4 km² (4.9%) and 386.4 km² (5.55%), respectively, their limited availability highlights the potential for targeted development in the more favourable zones (Table 3). This distribution underscored the necessity for strategic planning to optimize land use in this region.

Table 3. Glutinous rice land suitability in Barlingmascakeb study area (Indonesia)

Class of land suitability	Area (km^2)	% of area
N	386.4	5.55
S3	2,825.3	40.59
S2	3,407.7	48.96
S1	341,4	4.90

The distribution of marginal and highly suitable land is concentrated in the southern region, characterized by flat slopes and depressions (Figure 6). This area's soil fertility supported paddy farming, although some locations are found to be susceptible to flooding during the rainy season. Additionally, the central region also contains marginal land, primarily in riparian zones that experienced flooding. As a result, it is essential to select plant varieties resistant to waterlogging conditions, such as glutinous paddy.

Discussion

Glutinous paddy and the environmental adaption

The influence of topography on regional characteristics is crucial, as it significantly impacts soil properties, microclimate, and water availability (Fan *et al.,* 2020). However, glutinous paddy able to adapt in various challenging topographic conditions. For instance, certain upland rice varieties can be grown in steep areas where access to irrigation water is difficult. Similarly, inundation-resistant paddy varieties thrive in regions with depressed topography. Depressed topographic areas tend to retain high soil moisture, often leading to flooding (Zhang *et al.,* 2022). Water flow is faster in areas with a steep slope, which can lead to nutrient loss (Zhang *et al.,* 2020). In contrast, basin areas benefit from soil sedimentation and water runoff. High-slope regions also require appropriate technologies to mitigate soil erosion. Drainage density linked to the availability of surface runoff water; a higher drainage density indicates greater groundwater availability. In regions with both high drainage density and heavy rainfall, flood erosion can occur, leading to significant loss of top soil and resulting in nutrient-depleted soil (Mosavi *et al.,* 2020). Additionally, slope parameters and drainage density are topographic factors that can significantly impact the paddy-growing environment.

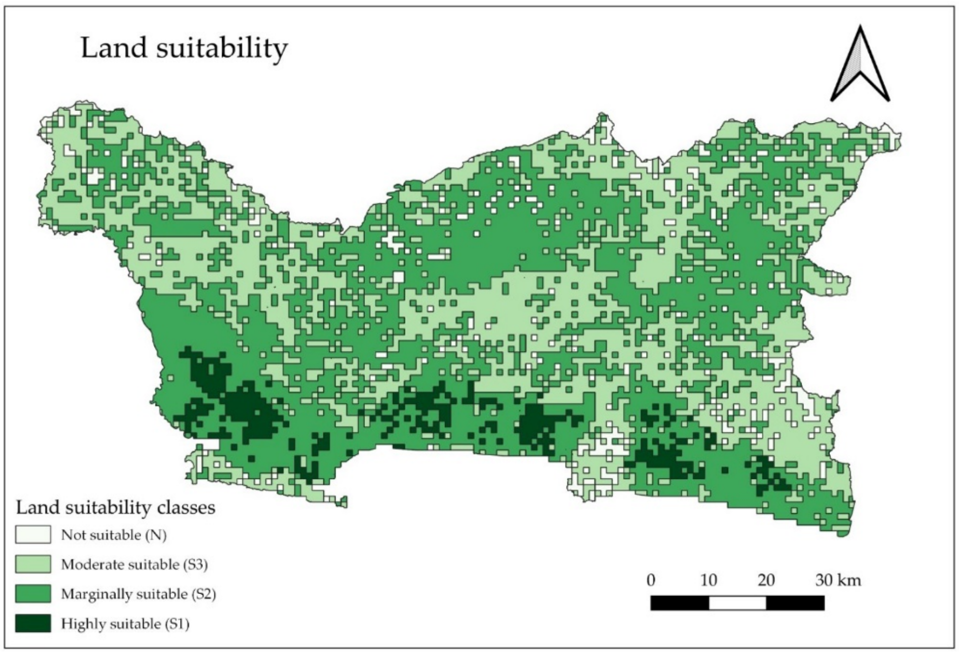

Figure 6. The gradient of glutinous rice land suitability in the Barlingmascakeb study area

Comparative studies between sloping, relatively flat, and depressed lands have shown that the highest rice production occurs in depressed areas due to better availability of water and nutrients, followed by flat and sloping terrains. These findings highlight the importance of water and nutrient management in rice cultivation (Ghosh *et al.,* 2014; Kikuta *et al.,* 2016). The strategy for selecting rice varieties and the technology used aims to optimize land functions while promoting environmental conservation for sustainable agriculture. Glutinous rice is a type that thrives optimally at high altitudes and in challenging water conditions, whether tense or flooded. Additionally, cultivation technologies such as plant spacing, tillage, and landscape engineering have enhanced rice production across various slopes while preserving environmental conditions.

The agricultural sector is highly dependent on climate cycles and weather patterns. For instance, a 4% increase in temperature could lead to damage to corn and rice plants, ranging from 5% to 50% and 27% to 46%, respectively. By 2030, rice production in Brazil, Central America, and Southeast Asia is expected to decline by 5% (Lobell *et al.,* 2008). Rainfall plays a crucial role in boosting rice production and ensuring food security in rice-producing Asian countries (Chandio *et al.,* 2022). However, rice yields are negatively impacted during the rainy season, particularly in lowland areas where flooding can occur (Tan *et al.,* 2021). In some cases, flooding has led to a decrease in yield of up to 84.5%, primarily due to the duration of the inundation in rice fields (Meng *et al.,* 2022; Zhen *et al.,* 2024). Additionally, several rice varieties, including glutinous paddy, resist waterlogging conditions (Gautam *et al.,* 2023). According to previous funding indicates that yield can be up to an 8% decrease for every 1°C increase in temperature beyond the optimum limit (Song *et al.,* 2022). Paddy rice is not highly susceptible to high temperatures during the vegetative stage. It is at the tillering stage where high temperatures have a lesser impact; however, the cumulative effects become significant during the booting stage (Oh *et al.,* 2023). Rainfall and temperature are crucial climatic factors that significantly influence plant growth.

Soil pH impacts nutrient availability, microbial activity, and the toxicity of some elements. The optimal pH for paddy fields is generally between 5.5 and 6.5 (Rendana *et al.,* 2021). Acidic soils (pH < 5.5) can reduce the availability of phosphate and calcium while increasing aluminium toxicity, harming rice roots, and decreasing nutrient absorption. On the other hand, slightly acidic to neutral pH values maximize the availability of critical nutrients and microbial activity, encouraging healthy rice development and increased yields. Soil organic carbon is crucial for enhancing soil structure, water retention, and nutrient supply. Organic carbon-rich soils enable increased microbial activity, which helps release nutrients like nitrogen and phosphate from organic matter. For rice, which requires a consistent nutrient supply across the growing season, greater organic carbon levels boost nutrient availability, resulting in better root growth and increased biomass, eventually increasing yields.

Plant development depends on the soil's capacity to retain and exchange positively charged ions or cations, such as calcium, magnesium, and potassium. High CEC soils may keep more nutrients and release them when plants need, particularly for rice crops that need a continual nutrient supply. Clay-rich soils have frequently increased CEC, contributing to improved nutrient absorption and crop health (Dey *et al.*, 2023). Soils with increased CEC improve the retention of nutrients in the root zone, minimizing leaching and enhancing rice yield. Coarse pieces, such as sand or gravel, can restrict water retention and root development, limiting the adequate amount of soil that can retain water and nutrients. High coarse fragment concentration may diminish soil fertility and water-holding capacity, making rice more sensitive to water stress and nutrient deficit (Niu *et al*., 2024). Ideally, paddy soils contain less coarse fragments, which allows for more excellent water retention and nutrient availability, directly boosting rice growth and yield. Soil should have a balanced pH, a high organic carbon content, a high CEC, and a few coarse fragments for optimum paddy development. This combination promotes nutrient availability, water retention, and root health, which are critical for sustaining rice yield.

Land suitability and strategic planning to optimize glutinous paddy

The land suitability map for glutinous paddy cultivation has been developed using the AHP-GIS multi-criteria approach. This method incorporates topography, climate, and soil properties parameters to assess factors influencing land suitability. A review informed the analysis of the literature and insights from five experts in relevant scientific disciplines. The hierarchical multi-criteria analysis effectively increases the accuracy of assigning weights to land suitability criteria. However, one limitation of the AHP process is its inability to account for the uncertainty in the pairwise comparison matrix (Liu *et al*., 2020). Therefore, an approach that can accommodate uncertainties and ambiguities is necessary.

Based on the analysis conducted using eight sub-criteria in the AHP-GIS process, the findings indicate that the land distribution in the Barlingmascakeb area is predominantly classified as marginal and moderately suitable, accounting for approximately 89.54%. This insight can serve as a valuable reference for decision-makers and practitioners involved in regional development, particularly in adapting strategies for utilizing plant varieties that can withstand stressful conditions such as waterlogging and drought. In addition, implementing proper agricultural engineering technologies is essential for achieving sustainable agriculture (Khan *et al*., 2021). This research methodology can aid in prioritizing rice cultivation areas, enhancing resource exploitation, safeguarding vital resources, and promoting sustainable management practices.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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