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Original Research

Demarcation of Suitable Land for Rice Cultivation Using GIS-based Multi-Criteria Decision Analysis: A Case Study in Southern Highlands Province of Papua New Guinea

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ABSTRACT

Papua New Guinea (PNG) has abundant land resources that are not fully utilized. Rice is a key food staple in urban areas and some rural regions. The demand for rice products remains high in Papua New Guinea due to changes in dietary preferences. Despite substantial consumption levels, rice is the principal imported crop grain, addressing the needs of a rapidly growing population. Maximizing the potential of land resources is crucial for properly assessing and categorizing land for specific purposes. This research project aims to address this pressing concern through land suitability analysis. An approach incorporating a multi-criteria decision analysis (MCDA) was employed to define and evaluate land suitability for rice cultivation. This research was conducted in the Southern Highlands Province, which is prominently located in the center of mainland Papua New Guinea (PNG). Fourteen parameters, including soil depth, texture, drainage, nitrogen, phosphorus, potassium, pH, cation exchange capacity, topographic wetness index, land use land cover, altitude, slope, aspect, rainfall, and temperature, were selected and analyzed further through Pairwise Comparison to derive weights and ranks. The resulting output from the MCDA was categorized into five distinct classes: unsuitable land with extreme limitations, unsuitable land with severe limitations, suitable land with moderate limitations, suitable land with minor limitations, and appropriate land with negligible limitations. According to the findings, approximately 29.59% of the study area is ideal for rice cultivation. Although applied exclusively to the rice crop, this technique holds potential for adaptation to various crops.

INTRODUCTION

Papua New Guinea is one of the most beautiful island nations located in the southern hemisphere of the Oceania continent. It is regarded as a resource-rich nation known for extracting non-renewable resources such as oil and Liquefied Natural Gas. PNG is rich in rainforests with fast-flowing rivers and streams. It consists of four regions: the New Guinea Islands, the Momase region, the Southern region, and the Highlands region. There are 22 provinces and 111 districts with an estimated total population of eight million. Almost forty percent of the population in PNG lives below the national poverty line, while eighty-six percent falls within the Multidimensional Poverty Measure stage (Li et al. 2023). The soil fertility in PNG is very high, and numerous commercial agricultural activities have been taking place and continue to do so (Singh et al. 2019). In Papua New Guinea (PNG), agriculture is a key income-generating sector, contributing significantly to the country's economic stability (Schmidt and Fang, 2021). The Momase region is renowned for cultivating some of the most significant cash and cereal crops, including vanilla, copra, cocoa, coffee, rice, wheat, and maize. The provinces in the highland region have not traditionally cultivated rice crops (Bourke 2009). Although the Southern Highlands have a cold climate due to their elevation, they experience rainfall throughout the year, increasing soil moisture content. The crops that thrive in these climatic conditions include long and short pipit, sweet potato, sugar cane, native taro, yam, banana, and sago. In some districts within the province, a few other selective crops can grow, depending on the soil and climatic conditions. Numerous studies have been conducted on various crops, extending beyond rice. Therefore, this study will integrate Geographical Information Systems (GIS) and Remote Sensing (RS) to identify the most suitable land for rice cultivation with minimal limitations. The implementation of the results will facilitate large-scale rice cultivation (Samanta and Pal 2014). It is hoped that significant improvements in agricultural production, particularly in rice crop production, will be achieved.

Traditionally, agricultural activities have occurred in low-lying areas rather than in steep and mountainous regions (He et al. 2025). A wide range of crop cultivation is recommended below 2,500 meters in the mountainous areas

(Araya et al., 2010). The rice crop can be grown and recommended up to 3,050 meters above sea level in specific high-altitude regions (Gautam et al. 2022). More people reside near floodplains, where sedimentation and deposition occur, resulting in higher fertility. Nearly ninety percent of the land in the Southern Highlands Province has a moderate production rate of the core staple food, sweet potato. Between twenty and thirty percent of the land has a greater potential for producing additional crops. The districts south of the provincial capital have more land suitable for cultivation compared to a smaller percentage found in the western and central parts of the province. The Southern Highlands Province has successfully practiced commercial cash crops (Bourke 2009). Initially, coffee was planted as a large-scale project funded externally by the government, and it tends to produce higher yields in the southern part of the province, which leads to better income (Imbun 2014).

Many studies have been conducted to identify suitable land for crops (commercial and daily consumables) plantations throughout Papua New Guinea (Samanta et al. 2011; Singh et al. 2019; Michael 2020). Some research emphasizes the broad utilization of Geographical Information Science (GIS) and Remote Sensing (RS) techniques for land suitability analysis (Wotlalan et al. 2021; Yatu and Samanta 2022). These tools enable researchers to understand geographical phenomena, including topography, hydrology, soil types, geomorphology, cultural features, and climatic conditions (Singha and Swain 2016). Medium-resolution satellite data, such as Landsat and Shuttle Radar Topography Mission (SRTM), and a national-level GIS database, serve as significant sources for preparing the conditioning factor databases. However, there is a lack of Pairwise comparison studies conducted to identify suitable areas for rice planting in the Southern Highland province. Therefore, this research aims to fill this gap. The concepts will be demonstrated through knowledge based on multiple spatial analyses using multi-criteria decision analysis (MCDA). Multi-criteria evaluation is performed when multiple criteria are required to make a decision. This process involves tabulating all factors and performing statistical calculations through comparative analysis. The analysis further assigns a weight and rank to each parameter (Maddahi et al. 2017). To create the comparison matrix, all parameters are tabulated in pairs, and then a range of values on a scale of 1 to 9 is assigned to indicate the relative importance of each parameter to the other. Value 1 represents equal importance, “3” indicates moderate importance, “5” signifies strong importance, value “7” denotes extreme importance, and value “9” also signifies extreme importance. Values 2, 4, 6, and 8 are intermediate values. The values of 1/3, 1/5, 1/7, and 1/9 represent inverse comparisons (Temesi 2019), indicating that one value is less important than another. While making comparisons, measurements are taken against columns and rows (Zolekar and Bhagat 2015). Numerous studies have engaged critical decision-making tools, including the frequently used Fuzzy

Analytic Hierarchy Process (FAHP) (Noorollahi 2016; Zahedifar 2023), Multi-Criteria Decision Making (MCDM) (Mistri and Sengupta 2020), Multi-Criteria Evaluation (MCA) (Ustaoglu 2022), Analytic Hierarchy Process (AHP) (Choudhary et al. 2023), and Multi-Criteria Decision Analysis (MCDA) (Kumne and Samanta 2023, Mohamed et al. 2019). The integrated approach of GIS yields productive results in identifying suitable land for rice planting (Samanta et al. 2011). The concepts of MCDA and FAHP have been fully utilized in this research to assess land suitability in the Southern Highland Province. The rice crop has experienced increased demand due to a shift in dietary preferences (Schmidt and Fang 2021). Rice products remain among the two most sought-after food crops. The province is renowned for its breathtaking landscape, rugged terrain, and expansive flat valleys. It has the potential for extensive cultivation of any suitable crop type, including rice. The fuzzy Multi-criteria decision-making (FMCDM) method analyzes various factors influencing land suitability.

Although the AHP/MCDA for agricultural suitability has been used worldwide, PNG is much behind in technological advancements compared to other countries as a study location, which leads to less focus on agricultural suitability analysis in the mountain environment. Earlier studies did not focus on the mountain environment and the parameters that could be important for suitability analysis (Samanta et al. 2011; Riwasino and Kerua 2020). A combination of 14 parameters with a detailed explanation of each parameter's favorability to rice cultivation, compared to an average of 10 or fewer parameters in many research studies (Hussain et al. 2024; Oladimeji 2024). All these parameters were selected based on local expert interviews, including experts from the National Agriculture Research Institute, the School of Agriculture, and Trukai Rice Industries Limited. Most land suitability research related to agriculture was conducted based on ranking and weight methods, where an estimated rank and weight were assigned based on literature (Samanta et al. 2014; Yatu and Samanta 2022; Mohamed et al. 2024). These ranks and the weights were assigned differently by different researchers. This research attempted to fill these gaps and uncertainties using the pairwise comparison method.

This research aims to utilize GIS and remote sensing knowledge, employing the Multi-Criteria Decision-Making Approach alongside a fuzzy analytical hierarchy process (FAHP), to identify suitable land with minimal limitations for cultivating rice crops in the Southern Highlands Province. It focuses on assessing the suitability of large-scale agricultural cropland in the region. This primary aim is supported by three key objectives: (a) To evaluate the spatial correlation of soil, climatic, and topographic characteristics that influence rice crop growth, (b) To determine appropriate land for rice cultivation in SHP utilizing the multi-criteria decision-making approach (MCDA) and AHP, and (c) To create a thematic map for identified rice crop suitability zones using multi-criteria analysis. Throughout the research process, five key research questions were posed: (a) What are the spatial patterns of the soil attributes, climatic conditions, and topographic features within the Southern Highlands Province?, (b) How do these spatial patterns correlate with the rice crop's growth requirements?, (c) What are the primary factors determining land suitability for rice cultivation in the Southern Highlands Province?, (d) How does MCDA assist in identifying suitable land for rice cultivation in SHP?, and finally (e) What thematic maps depict the suitability zones for rice cultivation in the Southern Highlands Province as determined?

2. STUDY LOCATION

The Southern Highlands Province is situated in the highland region of Papua New Guinea. SHP is positioned at the coordinates of 6.4179°S 143.5636°E, with its county headquarters in Mendi. It encompasses a total area of 89 square kilometers and consists of five districts. According to the 2011 census records, its total population is 515,511. It features a unique attraction in the country: Mount Giluwe, the second-highest mountain, stands at 4265.95 meters above mean sea level. The province shares its boundaries with Hela, Enga, Western Highlands, Jiwaka, Chimbu, Gulf, and Western Province. It lies at an altitude of 1341.65 meters above average sea level. With a tropical rainforest climate, its annual mean temperature is 17.03 degrees Celsius. The area receives 713.39 mm of rainfall, occurring on almost 99 percent of days throughout the year.

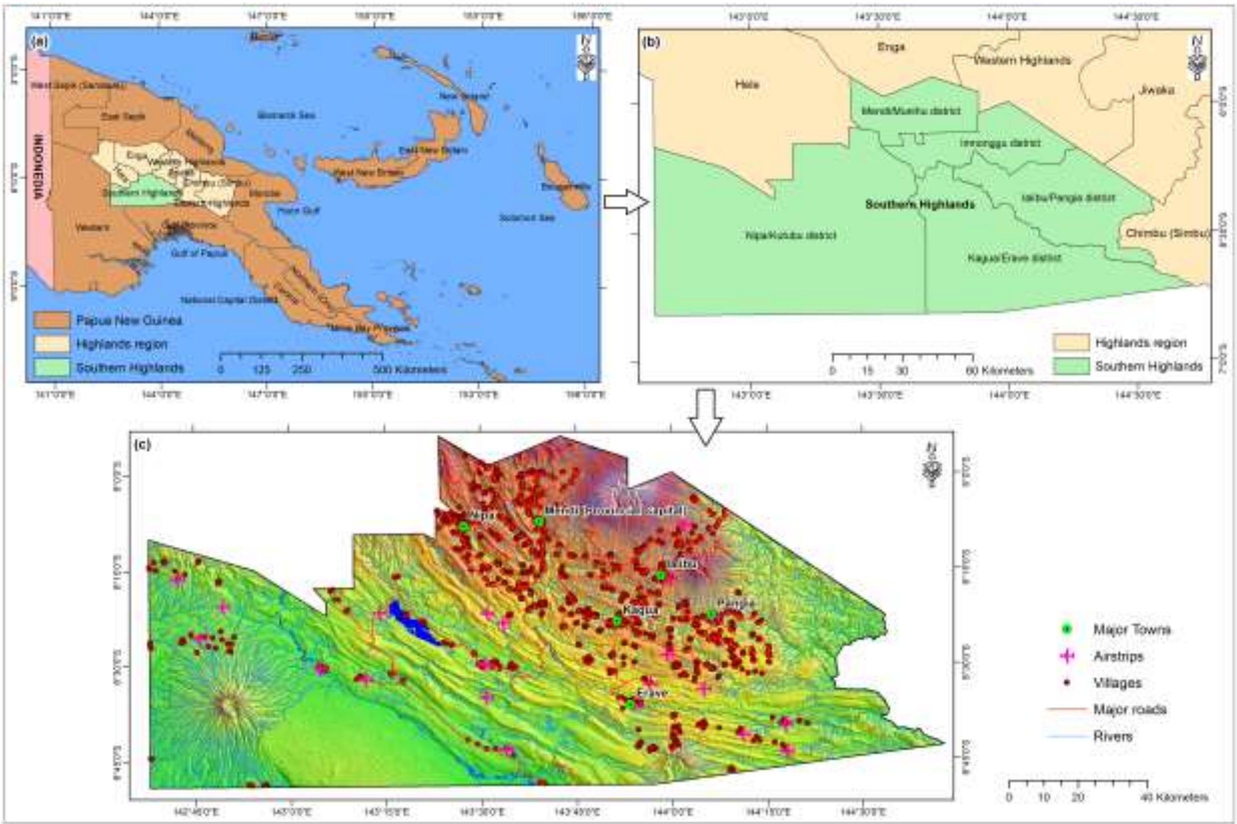

Fig. 1: Location map (a) Papua New Guinea with the Highland region, (b) Southern Highlands Province with district boundary, (c) Southern Highlands Province with major roads, rivers, and villages

3. MATERIALS USED IN THE STUDY

The primary source of all the factors (data) included in this study is extracted from the Papua New Guinea Resource Information System (PNGRIS) database. The information system consists of all soil, climatic, and topographic data. Satellite images were acquired from the School of Surveying and Land Studies (SSLS) at Papua New Guinea University of Technology (PNGUoT). The topographic wetness index (TWI) was calculated using digital elevation model (DEM) data using ArcGIS 10.5 software. The Landsat 8 satellite image was used to classify Land use and land cover (LULC). These factors were used in a pairwise comparison to generate weights and ranks. Each parameter has individual spatial information that is described in Table 1.

Table 1: Parameters considered for the land suitability model

Data Type	Parameters Layers name	Spatial resolution (m) / Coordinate system	Data source
Soil (Physical)	Texture Drainage Depth	30 m / World Geodetic System (WGS) 1984, universal traverse Mercator (UTM) Zone 55	PNGRIS
Soil (Chemical)	Nitrogen (N) Phosphorus (P) Potassium (K) pH Cation Exchange Capacity (CEC)	30 m / WSG 1984, UTM Zone 55	PNGRIS
Physiography	Altitude, Slope Aspects	30 m / WSG 1984, UTM Zone 55	PNGRIS
Digital Elevation Model	Topographic Wetness Index (TWI)	90 m / WSG 1984, UTM Zone 55	SSLS, PNGUoT
Climate	Rainfall Temperature	30 m / WGS 1984, UTMZone 55	PNGRIS
Landsat Satellite Image	Land use land cover (LULC)	15m-PanSharp/ WGS 1984	SSLS, PNGUoT

4. METHODOLOGY

Multiple factors have been considered, providing vital information that could assist in suitability analysis. These parameters were derived from various data sources. Soil possesses both physical and chemical properties. Physical properties refer to the appearance and structure of the soil, which can be observed and felt, such as coarseness, roughness, or smoothness. Chemical properties, on the other hand, include micronutrients that are essential for plant growth and maturity. Topographical factors are also crucial as they influence soil erosion: soil fertility, nutrient availability, and sunlight exposure to plants. Additionally, topography determines the temperature of a particular area, which depends on its location above or below mean sea level. Physiographic features also impact the availability of soil moisture content. Climatic factors are equally important, as different areas experience varying climatic conditions. For instance, the Southern Highlands Province of Papua New Guinea has a distinct climate compared to the coastal regions. This results in variations in rainfall and temperature conditions. The choice of 14 parameters was based on interviews conducted with scientists from the National Agricultural Research Institute, rice scientists from Trukai Indistries, and academics from the School of Agriculture at the Papua New Guinea University of Technology. They are: Fourteen parameters, including (i) soil texture, (ii) soil depth, (iii) soil drainage, (iv) soil nitrogen, (v) soil phosphorus, (vi) soil potassium, (vii) soil pH, (viii) soil cation exchange capacity, (ix) slope, (x) aspect, (xi) topographic wetness index, (xii) land use/land cover, (xiii) rainfall, and (xiv) temperature.

4.1 Description of the Parameters for Rice Land Suitability Analysis

Healthy soil is crucial for successful agricultural activities (Tahat et al., 2020). Three parameters were selected from the soil physical characteristics, and five from chemical characteristics. Soil texture plays a significant role as it governs water and moisture content in the soil. Loam texture is cogent for cultivating rice crop since it consists of three soil particles: sand, clay, and silt (Dou et al. 2016). Rice can be cultivated in clay soil since it retains adequate water for optimal growth. Rice can adapt to grow in a wide range of soil textures. Five different types of soil texture categories are found in the study area, namely (i) coarse texture, (ii) medium texture, (iii) fine texture, (iv) very fine, and (v) peat. The soil depth can be defined as the thickness or depth of the surface soil, which always has a greater influence on the crop (Zuo et al. 2017). The root system can spread deeper and absorb nutrients if the soil depth is high without gravel and rocks (Jobbagy and Jackson 2001). Rice has roots that can access nutrients from a maximum depth of about 50 cm. Four types of soil depth categories are found in the study area they are (i) not stony/rocky, (ii) slightly stony/rocky, (iii) moderately stony/rocky, and (iv) very stony/rocky. The rice crop has fibrous root systems that can grow well in soil depths that are not stony or rocky. Soil drainage efficiently controls the amount of water available in the soil. It plays a significant role in plant growth by maintaining nutrient retention and promoting soil health through aeration (Usharani et al. 2019). The drainage level indicated the optimal level at which the rice crop should be cultivated. Four types of soil drainage categories are found in the study area, namely (i) well drained, (ii) imperfectly drained, (iii) poorly to very poorly drained, and (iv) waterlogged (Swampy). However, rice is a semi-aquatic crop that grows well with an adequate water supply (Das and Uchimiya 2002). Poorly drained soil may also provide sufficient water, allowing rice crops to survive (Bouman et al. 2007). Both drainage levels can supply enough water and nutrients to crops.

Nitrogen (N) is one of the three macronutrients available in the soil for the growth of crops (Nieder et al. 2018). Rice crops require large amounts of nitrogen compounds for their growth and development. Only three classes of the percentage of total nitrogen are found in the upper surface between 0 and 25 centimeters from the topsoil. They are (i) high (> 0.5), (ii) moderate (0.2 -0.5), and (iii) low (< 0.2). Phosphorus (P) remains one of the three essential macronutrients that plants require. It plays a crucial role in rice's physiological processes. It energizes plant cells to take in nutrients. It also helps plants to respire and ensure efficient photosynthesis and respiration processes (Malhotra et al. 2018). The availability of phosphorus (P) was also classified into three classes based on its level within the soil, expressed in parts per million (ppm), namely (i) high (> 20 ppm), (ii) moderate (10 – 20 ppm), and (iii) low (< 10 ppm). Potassium (K) is the soil chemical element that plays multiple roles in the rice crop's growth, facilitating water uptake in the rice crop (Zain and Ismail 2016). It helps control the opening and closing of stomata in a leaf, where carbon dioxide and oxygen exchange can occur (Rawat et al., 2022). Three Potassium (K) zones are identified as per potassium availability in parts per million (ppm), namely (i) high (> 20 ppm), (ii) moderate (10 – 20 ppm), and (iii) low (< 10 ppm).

Soil pH remains one of the significant factors that affect the soil relatively. It is also essential in rice crop cultivation. The soil's pH also influences nutrient availability. Individual nutrients have specific pH requirements in the soil. In cultivation, the pH level determines whether the soil is too acidic or alkaline. Rice grows better in acidic conditions, with optimal pH ranges of 5 to 6.5 (Siddique et al. 2022). As per the PNGRIS database, there are four classes of pH found in the study area, namely (i) strongly acidic (< 5.0), (ii) acidic (5.0 – 6.0), (iii) weakly acidic to neutral (6.0 – 7.0), and (iv) alkaline (7.0 – 8.0). CEC's primary obligation is to allow the exchange of cations for soil chemical elements. When a higher level of CEC is available in the soil, it holds more water and sufficient nutrients. This will help rice crops withstand water stress during droughts or prolonged dry periods. Higher CEC maintains the soil structure and minimizes the potential soil erosion (Farooq et al. 2009). The CEC digital data were extracted from the PNGRIS database, which has three distinct classes based on intensity: (i) high (>10), (ii) medium (5-10), and (iii) low (<5). All these soil data are available in the form of a shape file. Each vector layer was then converted to a raster file based on the specific parameter characteristics. The necessary changes to the information were made during the reclassification process. The cell size of 30m was considered during the vector-to-raster conversion process. Its spatial reference system was changed from an unknown spatial reference to UTM WGS 1984 zone 55 South.

In cropland suitability analysis, slope is another important criterion for cultivating crops. Slope in agriculture influences the movement of nutrients, water flow, and soil erosion. The higher the slope, the higher the chance of soil erosion and nutrient loss. Water evaporates quickly on a steep slope during the dry season, causing the soil to dry. On the other hand, a gentle slope retains more water and keeps the soil moist (Zhu et al. 2014). Rice crops can grow better up to a slope of four percent (4%). A slope of 4 to 20 percent is immediately accepted for rice cultivation (Jarasiunas 2016). Slopes with a slope greater than 20% are permanently unsuitable for rice crop cultivation. The slope output measurement was assigned to degrees. The available slope degrees were classified into five classes, namely (i) gentle slope (<2 degrees), (ii) 2 to 5 degrees, (iii) 5 to 10 degrees, (iv) 10 to 20 degrees, and (v) more than 20 degrees. Water management in rice crop cultivation is one of the prime factors. Aspects play various roles in preparing land for crop cultivation. Cultivating rice crops in diverse landscapes and topographies is challenging (Bhattarai et al. 2020). Aspects also influence the climatic variable. Sunlight and temperature may vary in different areas. That is concerning the angle at which they are exposed to the sun. It is easy to determine the places where the rice crop may be affected (Duveiller et al. 2007). Both the slope and aspect databases were generated from the elevation data by the Shuttle Radar Topographic Mission (SRTM). The raster file was resampled from 90 m to 30 m using the surface tool available in the Spatial Analysis Tools.

The digital elevation model (DEM) also generates the topographic wetness index. Considering rice crop cultivation in areas with distinct topography and varying hydrological conditions is vital. TWI is determined by the characteristics of the slope, which influence moisture and water availability (Talebi Khiavi and Mostafazadeh, 2022). TWI assists in identifying areas with water that are affected by the soil's drainage level. A higher topographic Index (TWI) value indicates a greater water availability. A place with more moisture is perfectly suitable for rice cultivation.

Land use land cover (LULC) is pivotal in rice crop cultivation. It influences sustainable productivity, environmental management, and socio-economic factors. Information provided on the LULC helps to identify suitable areas based on the type of land cover identified. It may be bare land, grassland, savannah grassland, or shrubland. The better consideration is the soil type, soil moisture availability, and the physiographic setting of the area. Information provided on the LULC map may assist farmers and investors. They may make better decisions that can help them choose the land carefully (Dargains and Cabral 2021). The Landsat satellite image was used to classify land use and cover. Classification was done using the Erdas Image. A total of 6 classes were extracted through maximum likelihood classification, namely (i) shrubland, (ii) built-up, (iii) water bodies, (iv) dense forest, (v) grassland, and (vi) less dense forest.

Rice crop cultivation requires water and optimal soil moisture to thrive well (Prasad 2005). Rice is a semiaquatic crop, with 10 to 20 centimeters of its stem submerged in water (Yamuna and Ashwini 2016). The rice crop requires substantial water for grain filling and spikelet development. A constant water supply can replenish and maintain soil moisture for extended periods. Without irrigation facilities, adequate rainfall is necessary for rice cultivation. PNGRIS data provides nine classes of rainfall class, namely (i) 1000 – 1500 mm, (ii) 1500 – 2000 mm, (iii) 2000 – 2500 mm, (iv) 2500 – 3000 mm, (v) 3000 – 3500 mm, (vi) 3500 – 4000 mm, (vii) 4000 – 5000 mm, (viii) 5000 – 7000 mm, and (ix) >7000 mm. Temperature is a factor that has no alternative source, such as water. The rice crop requires a suitable environment to ensure effective and healthy growth and germination of the seeds. The ideal temperature allows the rice crop seedlings to germinate on time. The germination can be affected if the temperature in the area is too cold. Higher temperatures may prevent germination and negatively impact crop growth. Temperature also regulates the vegetative stages of the rice crop. Also enhances the production of lateral shoots (Jagadish et al. 2015). Very low temperatures can affect crop growth and slow maturation. Temperature also modulates the production of flowers and the transfer of pollen grains. The ideal temperature enables the rice crop to produce flowers and effectively produce grain. The mean average temperature varies from 4 to 18 degrees centigrade in the study area. Both the rainfall and temperature data were extracted from the PNGRIS database, which is available in vector format. The vector-to-raster conversion was initiated to create a raster database in 30m spatial resolution. Like all other databases, the spatial reference system, UTM WGS 1984 zone 55 South, was adopted to maintain uniformity.

4.2 Multi-Criteria Decision Analysis

Multi-criteria decision analysis (MCDA) was vital in cropland suitability analysis. It provides a well-structured framework for making comparisons across multiple factors. MCDA enables the researcher to consolidate various criteria simultaneously. They are topographical, climatic, soil physical and chemical factors, and satellite images. Various parameters are incorporated into the analysis of rice crop suitability. MCDA is used to handle multiple criteria for agricultural land cultivation of the rice crop (Zolfaghary et al., 2021). The decision-makers then evaluated it based on their foreknowledge of identifying crop suitability. MCDA helps decision-makers choose among various options by determining a ranking, comparing all parameters in pairs, and assigning a preference value to each. This process, known as pairwise comparison, is beneficial for decision-making (Kou et al., 2016). A pairwise comparison matrix was generated by comparing the factors against which one is more important than the other. The comparison is performed in square metrics, where the row elements are divided by column elements. The assigned importance values were adopted from Saaty's scale (Saaty 2005) (Table 2). Once all pairwise comparison matrices were generated, a vector of weights was denoted and determined using Saaty's eigenvector method (Ramik 2017). This was accomplished through a two-step process, specifically (i) normalizing a pairwise comparison matrix and (ii) generating a weighted matrix. A normalizing operation was performed on the pairwise comparison matrix by dividing each matrix element by the column sum of the pairwise comparison matrix, ensuring that the sum of each row's elements equals 1 (Temesi, 2019). Weights were calculated using the normalized pairwise comparison matrix. Normalized pairwise comparison matrices were generated using the value evaluated from the comparison criteria by dividing it by the sum of the columns of the pairwise comparison matrix. The sum of each column in the matrix was divided by the number of elements used to obtain a weight matrix. A consistency check is performed to determine whether the value is consistent for further decision-making purposes (Garg et al., 2022). Consistency ratio (CR) is calculated by dividing the consistency index (CI) by the random index (RI).

Table 2: Comparison of importance adopted from Sasty's scale

Importance of comparison	Description
1	Equally important
3	Moderately important
5	Strong important
7	Very strongly important
9	Extreme importance
2, 4, 6, 8,	Intermediate values between adjacent judgments
1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	Inverse comparison

The flowchart (Figure 2) illustrates the workflow hierarchy for creating a suitable map for rice crop cultivation. Different maps were generated for all the conditioning parameters, maintaining the maximum class number of five. They are from not suitable to very highly suitable. All of them are rasterized to maintain the homogeneity of their spatial resolution and the reference system. They are all resampled to the exact spatial resolution for better output. Multiple factors have been standardized to prepare for establishing factor weights. This is to prepare for a weighted overlay. Finally, the suitability map for the rice crop was produced, as shown in the final steps of the flowcharts (Figure 2).

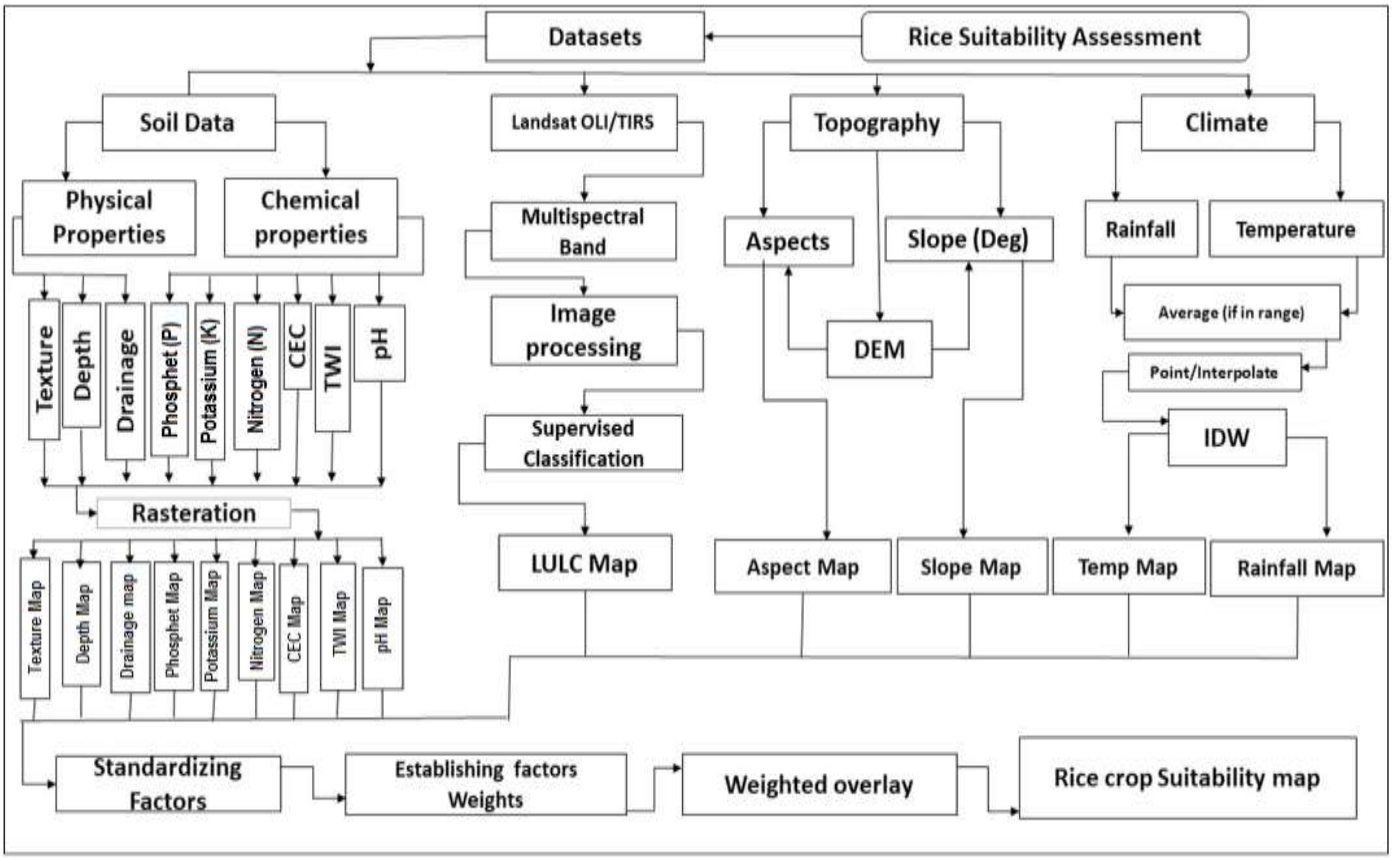

Fig. 2: The methodology flowchart for the rice land suitability analysis

5. RESULTS AND DISCUSSION

This study examined several key parameters for assessing land suitability for rice cultivation. Each of these factors holds crucial information that can significantly impact the productivity of the rice crop. These factors directly influence which pieces of land have the potential for higher and lower yields. Some of these factors are unchangeable and cannot be substituted when unavailable. For example, when there is no rainfall, it can be compensated for by irrigation. Temperature cannot be altered through other means. The factors considered in this study encompass the aspect, cation exchange capacity, soil depth, Soil drainage, temperature, soil nitrogen, soil phosphorus, soil potassium, soil pH, rainfall, soil texture, slope of the land, topographic wetness index, land use land cover, soil texture, nitrogen (N), phosphorus (P), potassium (K), soil drainage, soil depth, pH level, topographic wetness index (TWI), land use and land cover (LULC). Based on the local expert's recommendation, the suitability scale values were assigned to each subclass of the 14 parameters based on their influence in determining favourability for rice crop cultivation. This scale ranges from 1 to 5, where “1” refers to unsuitable, “2” as less suitable, “3” as moderately suitable, “4” as highly suitable, and “5” as very highly suitable. The water mask (lakes and rivers) for all the parameters was assigned a value of “0”, indicating that it was unsuitable for rice cultivation. The total area coverage for each subclass of these parameters in hectares and percentages is presented in Table 3.

5.1 Parameters and Their Suitability Rating

Rice crops cannot be cultivated in ‘coarse texture’ soil, making it unsuitable for cultivation. Therefore, it is given a ranking value of 1. It has spread over a vast area (88.66%) of the study area (Figure 3a). The ‘peat’ texture is considered less suitable for rice crops, assigned a ranking scale value of 2. The ‘medium texture’ is considered moderately suitable for rice crop cultivation, assigned a value of 3, and is found in various directions in the study region. The fine texture is regarded as highly suitable for rice crop cultivation. It is assigned a close to higher ranking value of 4. However, it is available on fewer hectares of land (1.32%) of the total land. The ‘very fine’ soil texture is highly suitable for rice cultivation, ranking at 5. It covers a total area of 2,832.17 hectares, the smallest area it covers (0.18%). The subclass ‘very stony/rocky’ is considered less suitable due to its massive amount of rock and is not suitable for cultivation; hence, a ranking value of 1 was assigned to this class. It spread over the study area's southwest, north, and southeast directions (Figure 3b). Moderately stony/rocky was denoted as 3, as it is moderately suitable for cultivation. A slightly stony/rocky area is highly suitable due to its depth characteristics. Slightly stony and rocky land was considered an alternative to rice cultivation. It received a rank value of 4 and spread over the east and northward directions of he study area. A very highly suitable area with a ranking value of 5 was assigned for the soil depth without stones or rocks (not stony/rocky) covering 51.19% of the total area. The waterlogged or swampy area was considered less suitable for the rice crop as it suffocates plants and causes them to die. It was ranked with a scale value of 1. Poorly to very poorly drained soil drainage is considered a moderately suitable area for rice cultivation. It was indicated with an intermediate ranking value of 3. Well-drained soil was considered highly suitable for rice cultivation. It was given a ranking value of 4, which covers the maximum area of the land (92.67%). Imperfectly-drained soil was considered very highly suitable for rice crops, with a ranking scale of 5. This subclass is primarily found in the eastern part and occupies a reduced land area (4.13%) (Figure 3c).

The nitrogen suitability map was created with various percentage levels of nitrogen availability (Figure 3d). The high (>0.5) nitrogen-content class, which contains more than 0.5 percent nitrogen, was considered highly suitable (value of 5) and is found in the northern part of the study area. In contrast, the moderate (0.2-0.5) class was considered moderately suitable (value of 3). It was found primarily in the western part of the study area, although it was less common in the eastern part. The low (<0.2) class was considered unsuitable (value of 1). The subclass, which has a high level of phosphorus (>20 ppm), was assigned a value of 5, which is highly suitable and is scattered in the middle portion of the study area. The moderate class of phosphorus (10 – 20 ppm) is moderately suitable for rice cultivation and was assigned a value of 3. This subclass is scattered in patches in all directions of the study area. The low-scale value of 1 was assigned to the subclass with a lower phosphorus concentration (<10 ppm), indicating that it is not necessarily optimal for rice cultivation. This unsuitable class is found in the northeast and the western end, but is scattered in a southeast direction (Figure 3e). A low potassium concentration (< 10 ppm) is primarily located in the western and eastern parts, and is scattered in a southwest direction. This region is indicated as less suitable with an assigned suitability code of 1. The second zone (10 – 20 ppm) is the most significant area (72.64%) of land it covers, compared to the other two, concentrated in the east and mid-section of the study area (Figure 3f). This zone, with medium potassium levels, is considered a moderately suitable place for rice crop cultivation. A suitability code of 3 was assigned to this moderate class. The third zone, with a potassium availability exceeding 20 ppm, has been considered highly suitable. The very highly suitable area was given a higher rank value of 5. The scale values of 2 and 4 were not assigned as only three classes were available in the N, P, and K databases.

Too much acid prevents plants from surviving, leading to aluminum toxicity and nutrient uptake. Highly alkaline soil also reduces the availability of phosphorus. The alkaline soil (7.0–8.0) was assigned a rank value of 2, whereas the strongly acidic soil (pH < 5.0) was assigned a rank value of 3, as it is relatively easy to upgrade the soil pH by applying lime. The strongly acidic soil is found in the northwestern part of the study area. The acidic soil (pH 5.0 – 6.0) was assigned a rank value of 4, as it is suitable for rice crop cultivation. This subclass is mainly found in the northeast and western parts of the study area (Figure 3g). The weakly acidic to neutral (pH 6.0–7.0) soil was considered a very highly suitable area (rank value of 5) for rice cultivation. Suitability codes 1, 3, and 5 were assigned to the low, medium, and high CEC classes. A higher CEC availability in the soil is advantageous for rice crop cultivation. It covers an area of 66.73% of the study area (Figure 3h).

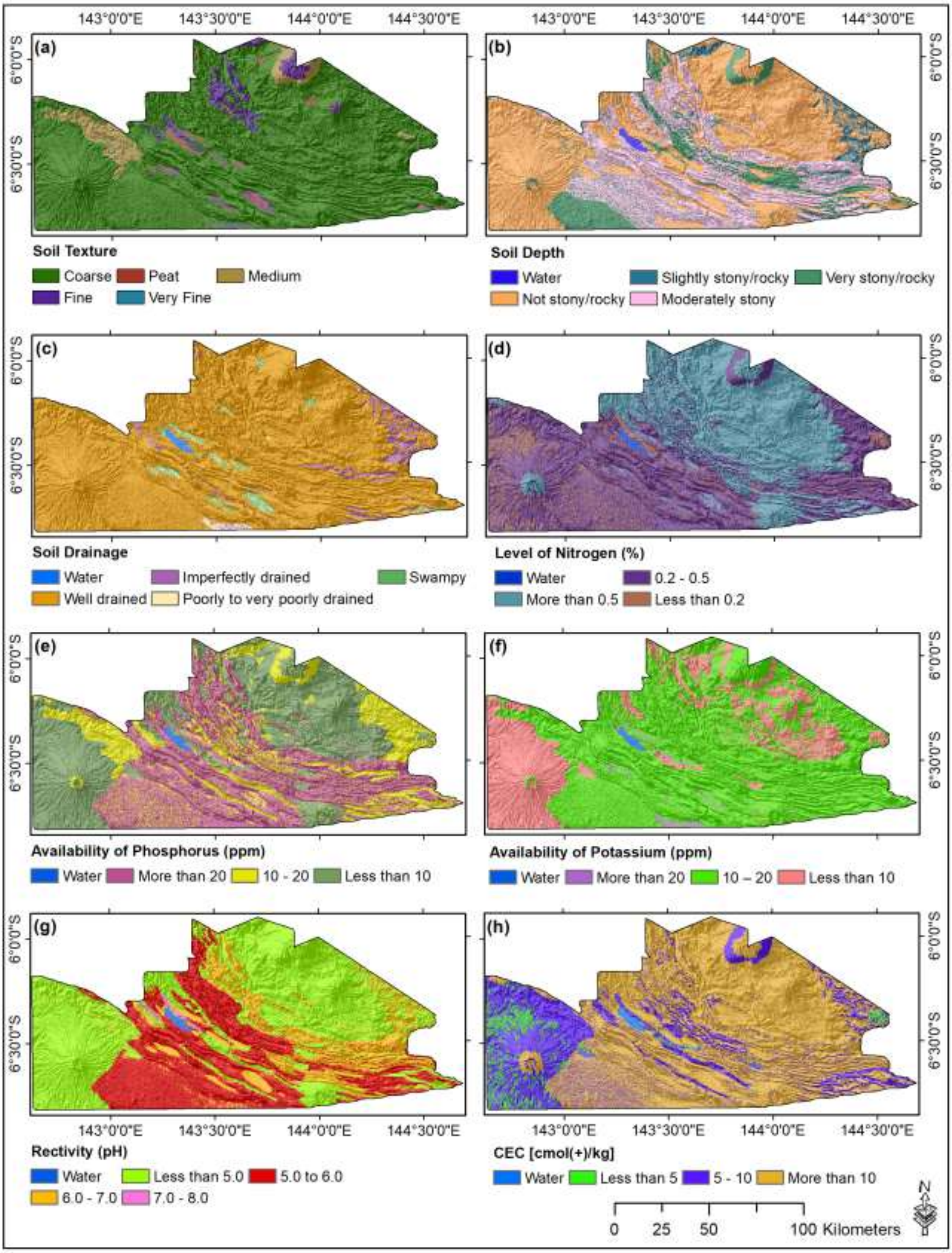

Fig. 3: Soil physical and chemical parameters for rice land suitability analysis: (a) soil texture, (b) soil depth, (c) soil drainage, (d) soil nitrogen, (e) soil phosphorus, (f) soil potassium, (g) soil pH, and (h) soil cation exchange capacity

Slopes range from less than 0 degrees to 30 degrees in the study area (Figure 4a). A higher slope value is considered unsuitable for cultivation. The slope value with the lowest degree is considered highly suitable. Since it is closer to a flat valley, it is ideal for cultivating various crops. The slope was categorised into five classes, ranked from very highly suitable to not suitable. The hill with a range of 20-30 degrees is labeled as unsuitable because it is too steep for cultivation. It was assigned a ranking value of 1. On the other hand, a slope value of less than 2 degrees was considered highly suitable for cultivating rice, and it was assigned a higher value of 5. It covers a significantly larger area than the entire region's other four classes (73.61%). The directions of slope (Aspect) facing South-East (SE), South-West (SW), and South (S) were categorised as unsuitable (value of 1) for cultivation, as these directions receive less sunlight (Figure 4b). Areas with the aspect direction of North-East (NE) and North-West (NW) were considered less suitable (value of 2). East (E) and West (W) facing aspects were assigned a value of 3, which is moderately suitable. North (N) facing slope and flat aspect were assigned values of 4 and 5, respectively, as they are favorable for rice cultivation (Table 3).

The modelled topographic wetness index (TWI) ranged from 1.50 to 26. TWI was further classified into five classes based on natural junk classification, namely (i) very low (1.56 - 5.97), (ii) low (5.98 - 8.55), (iii) medium (8.56 - 11.40), (iv) high (11.50 - 14.20), and (v) very high (14.30 – 26.00) (Figure 4c). Zones with the lowest TWI (TWI 1.50 – 5.97) were considered less suitable (value of 1), as they have lower moisture or water availability. The zone with the highest TWI value (TWI 14.30 – 26.00) was considered a higher potential class (value of 5) for rice cultivation. Grasslands and shrublands were considered highly suitable (Figure 4d), and a suitability value of 5 was assigned to this class, because farmers can easily convert these lands for cultivation with limited resources and time. Built-up and water bodies are permanently unsuitable (Suitability value of 1) because cultivation cannot be done in the middle of the town, airport, on top of house roofs, on water, or on rivers. Less dense forests and dense forests were considered moderately suitable (value 3) and less suitable (value 4).

The temperature class 4-11°C was considered unsuitable for rice crops, and the lowest ranking value of 1 was assigned to the northward direction of the study area. The temperature range from 22 to 26°C is rated as less suitable. A rank value of 2 was assigned to this class, primarily found in the eastern and western parts of the study area. Temperature ranges from 12 – 15 °C for rice crops are said to be moderately suitable, with a ranking value of 3. The second-highest suitability ranking has been assigned a score of 4 to the temperature class of 19 to 21 °C, scattered in the study area's eastern and western parts. Rice is highly suitable for cultivation in a temperature range from 16 to 18 degrees Celsius. This class is located in the middle portion of the study area, and a higher-ranking value of 5 is assigned to it (Figure 4e). The study area experiences continuous rainfall throughout the year, ranging from 1000 mm to 8000 mm (Figure 4f). A rainfall of more than 7000 mm is considered unsuitable (rank value 1) for cultivation, as these areas may experience excessive water, which prevents plants from breathing properly and suffocates them, causing them to wilt and die. This class is found mainly in the western part and is scattered in the south. The rainfall value of 4000–7000 mm was considered less suitable (rank value 2) and is predominantly found in the study area's southern, southwestern, and southeastern portions. The 3000-4000 mm rainfall value was moderately suitable (rank value 3). Rainfall classes of 1000-2000 mm and 2000-3000 mm were considered highly (rank value 4) and very highly suitable (rank value 5) for rice cultivation, respectively. Suitable rainfall areas are found in the east, partly in the north, and scattered throughout the western part. The rainfall and temperature suitability thresholds were arranged based on the experts' decisions on local conditions.

Table 3: Conditioning factors used for land suitability analysis for rice cultivation

Parameters	Sub Class	Suitability scale value	Area (ha)	Area (%)
Soil Texture	Coarse	1	1403596.49	88.66
	Peats	2	75590.78	4.78
	Medium	3	80094.02	5.06
	Fine	4	20930.81	1.32
	Very fine	5	2832.17	0.18
Soil Depth	Water	0	6072.22	0.38
	Very Stony/rocky	1	257168.57	16.25
	Moderately Stony/rocky	3	434041.46	27.42
	Slightly Stony/rocky	4	75237.59	4.76
	Not Stony/rocky	5	810524.39	51.19
Soil Drainage	Water	0	6072.22	0.38
	Waterlogged/ Swampy	1	26513.10	1.68
	Poorly to very poorly drained	3	17884.13	1.13
	Well Drained	4	1467275.10	92.68
	Imperfectly drained	5	65299.72	4.13

Nitrogen (N)	Water	0	6072.85	0.38
	Less than 0.2	1	155003.77	9.79
	0.2 – 0.5	3	790576.39	49.94
	More than 0.5	5	631391.23	39.89
Phosphorus (P)	Water	0	6072.8525	0.38
	Less than 10 ppm	1	611433.10	38.62
	10 – 20 ppm	4	410580.01	25.94
	More than 20 ppm	5	554958.28	35.06
Potassium (K)	Water	0	6072.28	0.38
	Less than 10 ppm	1	412737.38	26.06
	10 – 20 ppm	4	1149509.97	72.64
	More than 20 ppm	5	14724.64	0.92
pH	Water	0	6068.13	0.38
	Alkaline (7.0 – 8.0)	2	7525.50	0.47
	Strongly Acidic (<5.0)	3	499344.63	31.54
	Acidic (5.0 to 6.0)	4	786711.30	49.71
	Weak acidic to neutral (6.0 – 7.0)	5	283394.67	17.90
Cation Exchange Capacity (CEC)	Water	0	6153.44	0.38
	Less than 5	1	72222.41	4.56
	5 - 10	3	448494.55	28.33
	More than 10	5	1056173.86	66.73
Slope in degrees	20 - 30	1	328.80	0.02
	10 – 20	2	5891.88	0.37
	05 - 10	3	68929.32	4.35
	02 - 05	4	342897.24	21.66
	Less than 2	5	1164997.02	73.60
Aspect	SE, SW, & S	1	466278.14	29.46
	NE & NW	2	146023.48	9.22
	E & W	3	489434.12	30.92
	N	4	258984.29	16.36
	Flat	5	222324.24	14.04
Topographic Wetness Index (TWI)	1.56 - 5.97	1	995280.15	62.89
	5.98 - 8.55	2	417893.52	26.40
	8.56 - 11.40	3	147341.37	9.30
	11.50 - 14.20	4	20417.61	1.28
	14.30 – 26.00	5	2111.61	0.13

LULC	Built up	0	7542.52	0.48
	Inland Water	0	12233.69	0.77
	Shrub Land	1	49872.06	3.15
	Dense Forest	1	637257.1	40.25
	Low-Dense Forest	3	526327.3	33.25
	Grassland	5	349811.6	22.1
Rainfall (mm)	More than 7000	1	175778	25.14
	4000 - 7000	2	398004	32.49
	3000 - 4000	3	514422	12.92
	1000 - 2000	4	204485	18.34
	2000 - 3000	5	290355	11.11
Temperature (°C)	4 - 11	1	42145.52	2.66
	22 - 26	2	554854.40	35.05
	12 - 15	3	205232.38	12.96
	19 - 21	4	359457.55	22.71
	16 - 18	5	421354.41	26.62

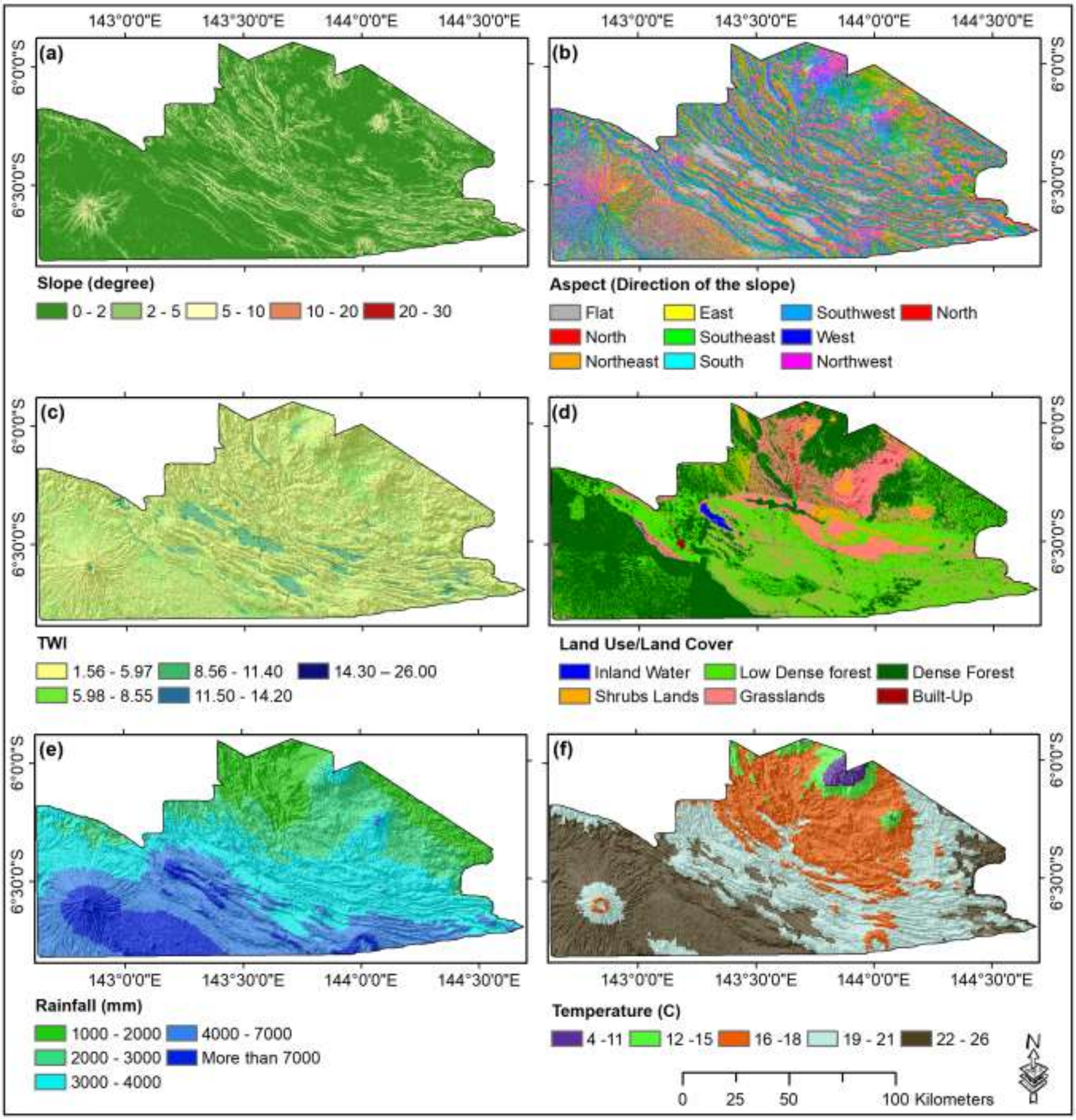

Fig. 4: Topographic and climatic parameters for rice land suitability analysis: (a) slope, (b) aspect, (c) topographic wetness index, (d) land use/land cover, (e) rainfall, and (f) temperature.

5.2 The Pairwise Comparison Matrix

Specific symbols were assigned to each parameter for the pairwise comparison matrix (Table 4). These parameters were integrated into the GIS platform and overlaid to identify suitable areas for cultivating rice in SHP through the MCDA.

Table 4: Conditioning factors used for rice crop suitability analysis

Sl. No.	Rice crop suitability Factors	Symbol	Data type / Conversion	Alternative availability
01	Aspect	AS	Raster	No
02	Cation exchange capacity	CEC	Vector - Raster	Yes
03	Soil depth	DPT	Vector - Raster	No
04	Soil drainage	DR	Vector - Raster	No
05	Temperature	TEM	Vector - Raster	No
06	Nitrogen (N)	N	Vector - Raster	Yes
07	Phosphorus (P)	P	Vector - Raster	Yes
08	Potassium (P)	K	Vector - Raster	Yes
09	Soil pH	pH	Vector - Raster	Yes
10	Rainfall	RFL	Vector - Raster	Yes
11	Soil texture	TXT	Vector - Raster	No
12	Slope	SLP	Raster	No
13	Topographic wetness index	TWI	Raster	No
14	Land use land cover	LULC	Raster	Yes

The Analytical Hierarchy Process (AHP) was employed to evaluate land suitability for rice cultivation. The methods include calculating the pairwise comparison matrix, the normalized pairwise comparison matrix, the weighted sum, the criteria weights, the ratio, the consistency index, and finally, the consistency ratio. Pairwise comparisons are performed using a relative importance scale. The first stage involves calculating the comparison matrix. The value of 1 is considered equally important, and the value of 9 is highly significant. The intermediate values are 2, 4, 6, 8, and 1/3, 1/5, 1/7, 1/9, which are the inverse comparison values. The number of used criteria determines the pairwise matrix table. In this instance, a 14-by-14 matrix represents 14 criteria for the rice crop suitability analysis (Table 5). The value assigned in the individual matrix cell wholly depends on the local expert knowledge and the researcher's preferences.

The suggestions from six experts, two from each institution, were incorporated. The expert identified the pairs by considering the critical pair compared to the others. The inconsistencies were resolved by measuring the consistency ratio analysis through the minor adjustment of the matrix elements.

The question in the researcher's mind is, how important is, for instance, the aspect and the cation exchange capacity (CEC) concerning rice growth? In this case, the user decided this aspect is more critical than CEC. The moderate importance value is three (3); therefore, CEC was assigned a value of 1x and aspect 3x. Similarly, the CEC-to-Aspect ratio is achieved by multiplying the CEC by 3 and the Aspect by 1. It is done likewise to all the pairwise comparison matrices. In the pairwise comparison matrix, the diagonal elements remain "1" since all individual factors are equally important when compared to themselves. All column sums were calculated and listed in the final row of the pairwise comparison matrix. This sum value was used to calculate the normalized pairwise comparison matrix.

Table 5: Pairwise comparisons matrix for rice crop suitability factors for the first stage calculation

Symbol	AS	CEC	DPT	DR	TEM	N	P	K	pH	RFL	TXT	SLP	TWI	LULC
AS	1.00	0.33	0.14	0.14	0.50	0.33	0.50	0.50	0.14	0.33	0.33	0.33	0.20	0.14
CEC	3.00	1.00	0.14	1.00	3.00	1.00	5.00	5.00	1.00	1.00	0.50	0.25	0.50	0.11
DPT	7.00	7.00	1.00	5.00	9.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	3.00	1.00
DR	7.00	1.00	0.20	1.00	4.00	2.00	7.00	7.00	1.00	2.00	0.33	0.50	0.33	0.11
TEM	2.00	0.33	0.11	0.25	1.00	0.20	1.00	1.00	0.20	0.33	0.25	0.20	0.14	0.11
N	3.00	1.00	0.14	0.50	5.00	1.00	3.00	6.00	0.33	2.00	0.33	0.25	0.17	0.20
P	2.00	0.20	0.14	0.14	1.00	0.33	1.00	1.00	0.25	0.50	0.20	0.20	0.33	0.14
K	2.00	0.20	0.14	0.14	1.00	0.17	1.00	1.00	0.20	0.20	0.14	0.33	0.33	0.11
pH	7.00	1.00	0.14	1.00	5.00	3.00	4.00	5.00	1.00	2.00	0.50	0.33	0.20	0.11
RFL	3.00	1.00	0.20	0.50	3.00	0.50	2.00	5.00	0.50	1.00	0.14	0.17	0.20	0.11
TXT	3.00	2.00	0.20	3.00	4.00	3.00	5.00	7.00	2.00	7.00	1.00	2.00	0.33	0.50
SLP	3.00	4.00	0.20	2.00	5.00	4.00	5.00	3.00	3.00	6.00	0.50	1.00	1.00	1.00
TWI	5.00	2.00	0.33	3.00	7.00	6.00	3.00	3.00	5.00	5.00	3.00	1.00	1.00	1.00
LULC	7.00	9.00	1.00	9.00	9.00	5.00	7.00	9.00	9.00	9.00	2.00	1.00	1.00	1.00
SUM	55.00	30.07	4.10	26.68	57.50	33.53	51.50	60.50	30.63	41.37	14.24	12.57	8.74	5.65

All the column elements are divided by the sum of the column to calculate the normalized pairwise comparison matrix. The results were recorded in the column of the normalized matrix table. All the normalised values in each row were summed, and the results are recorded in the final column of the normalized matrix table (Table 5). The sum value of the normalized pairwise comparison matrix is further used to calculate the criteria weights (CW) by dividing the row sum by the total number of criteria (Table 6).

Table 6: Normalized Pairwise Comparison Matrix for rice land suitability analysis

Symbol	ASP	CEC	DPT	DR	TEM	N	P	K	pH	RFL	TXT	SLP	TWI	LULC	SUM	CW
ASP	0.02	0.01	0.03	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.02	0.03	0.02	0.02	0.21	0.0149
CEC	0.05	0.03	0.03	0.04	0.05	0.03	0.10	0.08	0.03	0.02	0.04	0.02	0.06	0.02	0.61	0.0412
DPT	0.13	0.23	0.24	0.19	0.16	0.21	0.14	0.12	0.23	0.12	0.35	0.40	0.34	0.18	3.03	0.2217
DR	0.13	0.03	0.05	0.04	0.07	0.06	0.14	0.12	0.03	0.05	0.02	0.04	0.04	0.02	0.83	0.0545
TEM	0.04	0.01	0.03	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.23	0.0151
N	0.05	0.03	0.03	0.02	0.09	0.03	0.06	0.10	0.01	0.05	0.02	0.02	0.02	0.04	0.57	0.0376
P	0.04	0.01	0.03	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.02	0.04	0.02	0.26	0.0171
K	0.04	0.01	0.03	0.01	0.02	0.01	0.02	0.02	0.01	0.00	0.01	0.03	0.04	0.02	0.25	0.0161
pH	0.13	0.03	0.03	0.04	0.09	0.09	0.08	0.08	0.03	0.05	0.04	0.03	0.02	0.02	0.75	0.0506
RFT	0.05	0.03	0.05	0.02	0.05	0.01	0.04	0.08	0.02	0.02	0.01	0.01	0.02	0.02	0.45	0.0294
XTX	0.05	0.07	0.05	0.11	0.07	0.09	0.10	0.12	0.07	0.17	0.07	0.16	0.04	0.09	1.24	0.0906
SL	0.05	0.13	0.05	0.07	0.09	0.12	0.10	0.05	0.10	0.15	0.04	0.08	0.11	0.18	1.31	0.0953
TWI	0.09	0.07	0.08	0.11	0.12	0.18	0.06	0.05	0.16	0.12	0.21	0.08	0.11	0.18	1.62	0.1206
LULC	0.13	0.30	0.24	0.34	0.16	0.15	0.14	0.15	0.29	0.22	0.14	0.08	0.11	0.18	2.62	0.1953

The consistency ratio (CR) was calculated by dividing the consistency index by a random index. The consistency ratio helps validate judgments made throughout the entire analytical hierarchy process. When a consistency ratio falls to zero, it shows perfect judgment, and consistency is accepted. However, increasing the CR value indicates inconsistency. The CR value falling between 0 and 0.10 is considered consistent (Sasikumar et al. 2022). When the CR is consistent, it is okay to proceed with further decision-making. The consistency index was calculated as 0.1368, and the random index was 1.57. Therefore, the CR was calculated as 0.087, which is acceptable. Thus, the final decision-making stage was conducted using the Analytical Hierarchy Process. The criteria weights were converted into percentage influence for suitability analysis. The resulting weights are presented in Table 6. This percentage influence was assigned to individual criteria for an overlay analysis using ArcGIS 10.5 spatial analysis tools. The total of 14 criteria was allocated a permanent percentage influence for the final suitability analysis process (Table 7).

Table 7: The resulting weight for the criteria based on pairwise comparison

Category	Factors	Priorities (%)	Rank	(+) (%)	(-) (%)
01	Aspect	1.30	14	0.90	0.90
02	CEC	7.70	8	1.70	1.70
03	Depth	6.30	1	11.00	11.00
04	Drainage	1.70	6	2.70	2.70
05	Temperature	9.00	13	0.50	0.50
06	Nitrogen	4.30	9	2.00	2.00
07	Phosphorus	9.60	11	0.80	0.80
08	Potassium	3.00	12	1.00	1.00
09	pH	3.10	7	2.50	2.50
10	Rainfall	2.50	10	1.50	1.50
11	Soil texture	5.50	5	4.60	4.60
12	Slope	3.10	4	4.70	4.70
13	TWI	8.90	3	6.60	6.60
14	LULC	32.50	2	11.50	11.50

5.3 Land suitability Map for Rice Cultivation

A suitability map is paramount for policymakers, investors, and, importantly, for the provincial development plans (Kehbila et al. 2014). A total of 14 criteria, including land use land cover (LULC), were considered for rice cropland suitability analysis. The spatial factors include soil properties, both physical and chemical, topography, surface features, climatic conditions such as rainfall and temperature, and Landsat 8 satellite images for LULC classification. Land use and land cover have the highest influence, at 32%, in this suitability analysis. Suitability maps indicate the areas that are suitable and unsuitable for cultivation. This map may be informative to the provincial government. That may be utilized to equalize the distribution of services regarding agricultural grant funding. Unsuitable areas can be ignored as they are typically known to be water bodies, built-up areas, and dense forests. Cultivating a rice crop on top of water, roads, buildings, and infrastructure is impossible. That includes thick and stony mountains with higher elevations. Shrublands and grasslands are considered to have the highest potential for rice cultivation. A less dense forest is supposed to be moderately suitable for rice crop cultivation. The suitability area played a significant role in rebuilding the ecosystem, mitigating climate change impacts, and alleviating food insecurity. The resulting output was further classified into five classes. They are (i) unsuitable land with extreme limitations, (ii) unsuitable land with severe limitations, (iii) suitable land with moderate limitations, (iv) suitable land with minor limitations, and (v) suitable land with negligible limitations (Figure 5 and Table 8). The unsuitable land with extreme limitations zone covers an area of 20370.03 hectares, 1.29% of the entire study area. Unsuitable land with severe limitations covers a total area of 444971.50 hectares (28.11%). Suitable land with moderate limitations zone covers an area of 649,347.54 hectares (41.04%), whereas suitable land with minor limitations zone covers an area of 400305.16 hectares (25.29%). Finally, suitable land with a negligible limitations zone covers an area of 68050.02 hectares, which is 4.30% of the provincial area. The suitable land with a negligible limitations zone covers an adequate area compared to the rest of the suitability classes. In contrast to the vast amount of suitable land available in Asia, like 74% in Vietnam (Redfern et al. 2012), 43% in India (Pandey and Patel 2014), and 55% in Indonesia (Panuju et al. 2013), PNG has significantly less suitable land (14%) (Samanta et al. 2011; Mohamed et al. 2024). The Southern Highland province area is characterised by rough terrain, higher slopes, and rocky soils, which leads to a low percentage (4.30%) of highly suitable land for rice cultivation.

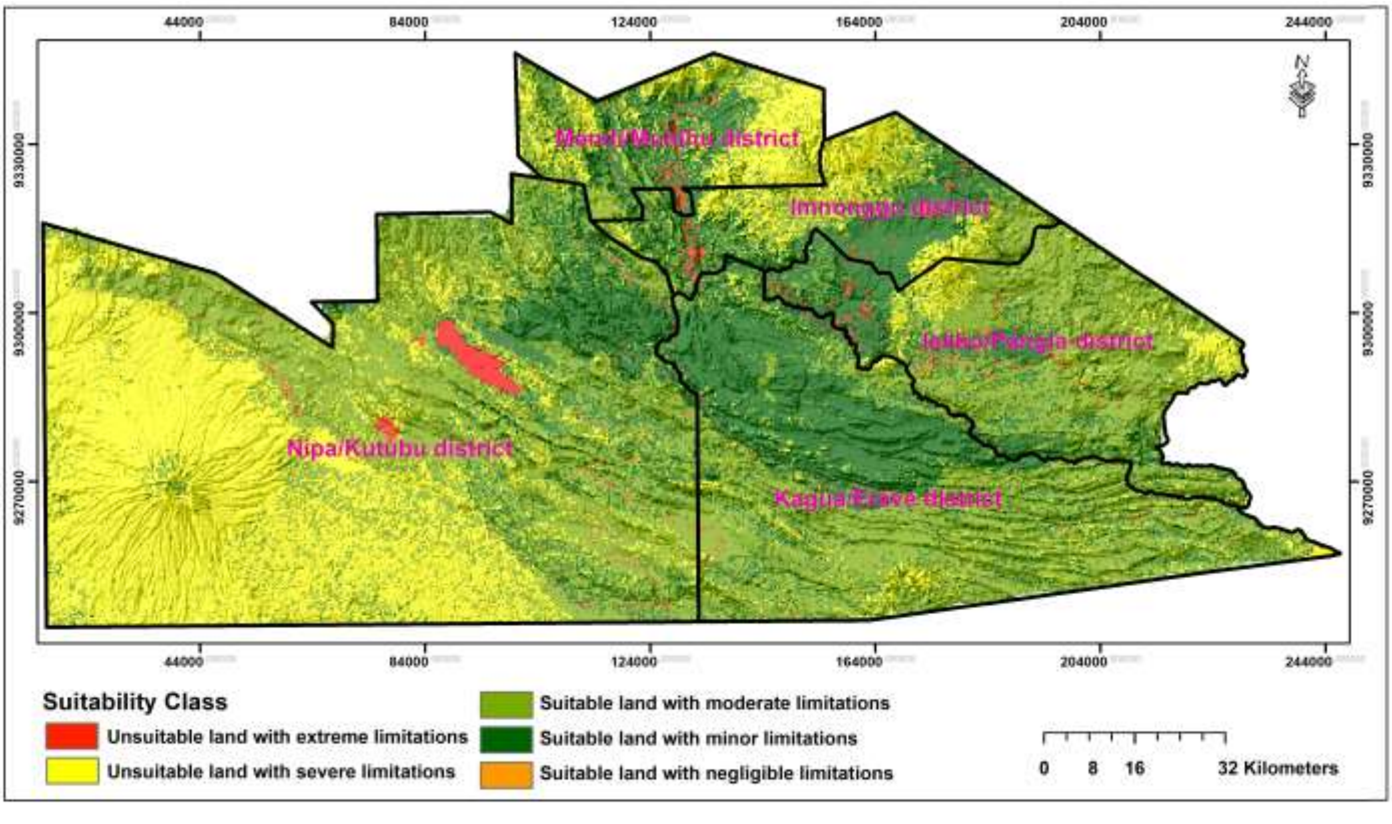

Fig. 5: Various levels of suitable land for rice cultivation with limitations in the Southern Highlands Province

Table 8: Rice suitability classes in the Southern Highlands Province in hectares and percentage

Sl. No.	Suitability Classes	Area (ha)	Area (%)
01	Unsuitable land with extreme limitations	20370.03	1.29
02	Unsuitable land with severe limitations	444971.50	28.11
03	Suitable land with moderate limitations	649347.54	41.02
04	Suitable land with minor limitations	400305.16	25.29
05	Suitable land with negligible limitations	68050.02	4.30

The rice crop suitability map for the Southern Highlands Province was further analysed at the district level. There are five districts in the Southern Highlands Province, namely (i) Imbonggu, (ii) Mendi Muniu, (iii) Nipa Kutubu, (iv) Ialibu Pangia, and (v) Kagua Erave. Kagua Erave has 51.73% of its land classified as having higher potential (Suitable land with minor to negligible limitations) for rice cultivation. In contrast, the Nipa Kutubu district covers 28.58% of the total landmass, compared to the other three districts, which have less than 10% of their land with higher potential for rice cultivation.

To cultivate rice crops, the condition of the land, basically the land slope, is vital for sowing crops. Commercial rice cultivation primarily focuses on generating a profit. Even though the land is suitable, investors must assess the vast hectares of land in advance. Therefore, the study area with a less than one degree slope had been extracted for further analysis. An area with a slope of less than one degree is suitable for large-scale mechanized farming. The less than 1-degree slope was overlaid with suitable land, having minor and negligible limitations. The result shows that massive hectares of land for rice cultivation are available in the northward and eastward direction, which can be used for mechanised large-scale commercial cultivation of rice crops (Figure 6). A total area of 10,829.34 hectares (15.91%) of land is eligible for this category.

The field interviews were conducted in five districts of the Southern Highlands Province to determine the type of crops cultivated, their harvesting techniques, accessibility, daily rice consumption, and employment patterns. Each suitability class in the Southern Highlands Province derived through the model was compared with the interview result to find the correlation between local people's concerns and involvement in cultivation. Only 12 closed-ended questions were asked. The sample size was 20 in each district, with a total sample of 100 questionnaires. The interview results indicated that 30% of the people living in the Kagua Erave district cultivated rice, while the area has 51.73% higher potential land for rice cultivation. In contrast, not a single farmer in the Imbonggu district cultivates rice, despite the district having 7.94% of its land with higher potential for rice cultivation. The Nipa Kutubu district has 28.54% of its land with high potential for rice cultivation, yet only 10% of farmers in the area grow rice. Although the Mendi Muniu and Ialibu Pangia districts have 4.43% and 7.32% of highly potential land for rice cultivation, respectively, only 5% and 10% of the population is engaged in rice cultivation.

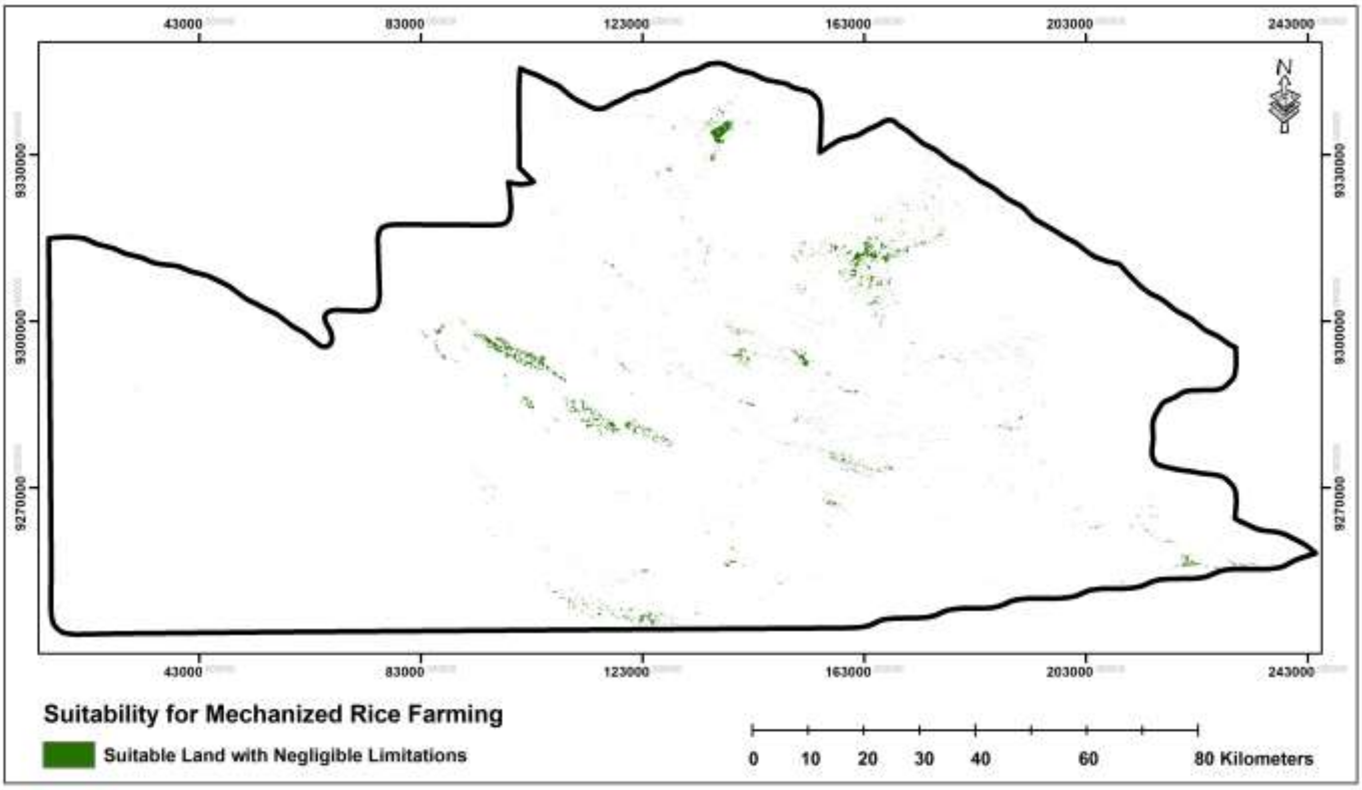

Fig. 6: Available suitable land with negligible limitations for mechanized rice cultivation in the Southern Highlands

6. CONCLUSIONS AND RECOMMENDATIONS

The study identifies potential zones for cultivating rice crops in the Southern Highlands Province by analyzing agricultural land suitability. The analysis used a GIS-integrated multi-criteria decision analysis (MCDA) method and the Analytical Hierarchy Process (AHP). This study significantly advances land evaluation procedures by combining Geographic Information Systems (GIS) with the multi-criteria decision-making approach. The study conducted a detailed analysis of more than 14 major geospatial factors. This includes soil chemical and physical properties, and climatic factors such as rainfall and temperature. Topographic elements such as slope, aspect, and the topographic wetness index (TWI) were also considered. These factors were analyzed to understand their interactions and soil nutrient and moisture requirements. All these criteria were assessed using a comparison matrix, and weights were assigned to each criterion. The pairwise comparison in AHP fully assists in determining the criteria weights and the consistency index. The final consistency ratio, which fell within the accepted range, was 8% for rice, confirming the reliability of the suitability map. The analysis successfully identified areas suitable for rice cultivation using the Analytic Hierarchy Process (AHP) method. 468,355 hectares of land out of 1,583,044 hectares are deemed appropriate, with minor to negligible issues, representing 29.59% of the total land under consideration. Among these, 10,829 hectares (15.91%) are ideal for mechanized large-scale rice farming. Cultivating rice on this scale is expected to boost productivity and economic activity in the province. This is anticipated to create employment opportunities, improve law and order, enhance food security, and mitigate starvation. The finding also addresses several United Nations (UN) Sustainable Development Goals (SDGs), including food security (SDG 2) and climate action (SDG 13) (DAL 2015; UNDP 2020). Cultivating rice in suitable zones can eradicate poverty (SDG 1), decent work and economic growth (SDG 8) for farmers, and reduce environmental impact (Benny et al. 2022).

Based on the results, citizens of the province can utilize the identified land for rice crop cultivation, which can enhance both consumption and income. Future research could include other cereal crops, such as corn, oats, rye, and millet, and other crops like sweet potatoes, taro, yams, carrots, broccoli, cabbage, and watermelon. The Southern Highlands Province has significant potential for diverse crop cultivation. While past studies have included fewer criteria, this research offers more comprehensive findings. Future studies can adopt this methodology to explore similar research in other regions. GIS and remote sensing technologies remain cutting-edge tools for long-term decision-making. The findings suggest that the SHP has considerable potential for medium to large-scale rice crop cultivation. This opens up opportunities for improving domestic food security and fostering development through agriculture. The technique employed in this study provides policymakers and planners with valuable tools to guide agricultural investments and resource allocation. Successful cultivation in the identified high-suitability zones will likely lead to improved food security, increased employment opportunities, and enhanced living standards. While also promoting sustainable farming practices and ecological restoration.

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