Available at : https://ejournal.unib.ac.id/index.php/terrajournal ISSN 2621-0207
DOI : https://doi.org/10.31186/terra.8.1.10-19

TERRA
Journal of Land Restoration

Evaluation of Land Suitability and Potential Development of Cardamom (*Amomum compactum L.*) in Padang Jaya Subdistrict, North Bengkulu Regency

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ABSTRACT

*Cardamom (Amomum compactum) is a high-value spice with significant applications in the pharmaceutical, food, and cosmetics industries. The increasing global demand makes cardamom a promising commodity for agricultural expansion. However, limited information on land suitability in Padang Jaya Subdistrict poses a challenge to optimizing cultivation. This study aimed to map the land suitability classes for cardamom cultivation and assess the potential for cardamom development in Padang Jaya Subdistrict, North Bengkulu. The research involved in field surveys, soil sampling, laboratory analysis, and GIS-based land suitability evaluation using the FAO framework. Key parameters assessed included rooting media, nutrient retention, slope, and climate condition in the past 10 years. The FAO classification system categorized land into four suitability classes, namely: S1 (high suitable), S2 (moderately suitable), S3 (marginally suitable), and N (not suitable). The result indicate the actual land suitability is predominantly S3nrnaeh and **S2nrnaeh**, with major limiting factors including rooting media, nutrient retention, nutrient availability, and slope. Land improvement efforts such as liming, organic matter applications, fertilization, and soil conservation techniques led to an increase in land suitability, with 62.3% of S3 land upgraded to S2 and 37.7% of S2 land reached S1. Furthermore, GIS-based analysis identified four land cover types suitable for extensification: mixed gardens, seasonal crops, plantations, and bare land, totaling 8,747.71 hectares. These findings provide valuable insights for optimizing land-use planning, improving productivity, and promoting sustainable agricultural development. Integrating GIS and remote sensing in future studies could enhance land suitability assessments with a more refined spatial scale. The results also serve as a scientific reference for policymakers and farmers in designing sustainable land management strategies and minimizing environmental degradation.*

Keywords: *cardamom, land extensification, land suitability*

INTRODUCTION

Cardamom (*Amomum compactum*) is a type of spice plant of *Zingiberaceae* family, commonly known as the ginger family. This plant has numerous benefits, serving as a raw material in the pharmaceutical, culinary and cosmetic industries, making cardamom highly valuable economically. After saffron and vanilla, cardamom is the third most expensive spice in the world (Abdurahim *et al*., 2022). The global demand for cardamom continues to increase due to its diverse applications, particularly in food preservation and traditional medicine. Cardamom thrives in various soil types but grows optimally in high-humidity soils with sunlight exposure (Abdurahim *et al*., 2022; Kamal, 2021; Kementrian Pertanian, 2019). However, ensuring high productivity requires proper land selection based on soil properties and environmental conditions.

Padang Jaya Subdistrict, located in North Bengkulu Regency, Bengkulu Province, has considerable potential for cardamom cultivation due to its favorable agroclimatic conditions, including an elevation range of 150-500 meters above sea level (masl) and an annual rainfall of approximately 3,418 mm (Badan Pusat Statistik Kabupaten Bengkulu Utara, 2021).

These factors align with the optimal growth requirements for cardamom (Kementrian Pertanian, 2019). However, to effectively implement cardamom as a sustainable agricultural commodity in this region, a land suitability study is required to evaluate the potential of the land, identify limiting factors, and develop appropriate management strategies to improve these constraints (Mazahreh *et al*., 2019). Despite its promising environmental conditions, specific information on land suitability for cardamom cultivation in Padang Jaya remains limited. A comprehensive land suitability evaluation is necessary to optimize agricultural land use while ensuring environmental sustainability. Land suitability analysis plays a crucial role in improving land-use efficiency and preventing soil degradation caused by improper crop selection and poor management practices. A deeper understanding of the biophysical characteristics of the land and its contraints is required to facilitate informed decision-making for sustainable agricultural practices in the region.

Several studies have analyzed land suitability for cardamom in different regions. Kuswara *et al*., (2024) assessed land suitability in Topos Subdistrict, Bengkulu Province, revealing that nutrient limitations and *steep* slopes were major constraints. Harist *et al*., (2021) in West Sumatra and found that 53% of the land was highly suitable for cardamom cultivation based on rainfall, soil type, and elevation. However, Gahlod *et al*., (2017) evaluated land suitability in Wayanad, India, for cardamom, tea, and rubber, highlighting the importance of soil pH, cation exchange capacity (CEC), and topographic variations. Although these studies provide valuable insights, they are region-spesific and may not reflect the unique biophysical characteristics of Padang Jaya. Furthermore, many existing studies lack an integrated approach that combines multiple factors such as soil properties, topography variations, rooting medium, climate conditions, and land resource evaluation into a comprehensive suitability assessment to generate specific recommendations for land use and management in this area (Abdelrahman *et al*., 2016; Mugiyo *et al*., 2021; Taghizadeh-Mehrjardi *et al*., 2020).

This study aimed to map the land suitability classes for cardamom cultivation and assess the potential for cardamom development in Padang Jaya Subdistrict, North Bengkulu. We hypothesize that topography, nutrient availability, erosion risk, and drainage conditions are the primary limiting factors affecting land suitability for cardamom cultivation. To achieve this objective we applied the FAO land evaluation, integrating GIS analysis and soil laboratory to assess key soil properties. The FAO land evaluation system is applied to classify land into suitability categories: *highly suitable* (S1), *moderately suitable* (S2), *marginally suitable* (S3), and *not suitable* (N). In this classification, optimal land quality align with the highest suitability class (S1), whereas suboptimal land quality falls into lower suitability classes (S2 and S3). Land that does not meet the minimum threshold is classified as unsuitable (N) (Mugiyo *et al*., 2021).

The findings of this study contribute to the development of high-value commodity based agriculture and promote sustainable land management practices. By providing empirical data on land suitability for cardamom in Padang Jaya, this research offers valuable insights for improving land-use efficiency and supporting data-driven decision-making among stakeholders. Furthermore, the results will assist local farmers in identifying the most suitable cultivation areas while minimizing environmental risks associated with unsustainable agricultural practices. Ultimately, this study supports economic growth and sustainable agricultural development by ensuring that land resources are utilized efficiently and responsibly.

MATERIALS AND METHODS

Study area

This study was conducted in the Padang Jaya Subdistrict, North Bengkulu Regency, Bengkulu Province. Geographically, the study area is located between 3° 13’40”-3°25’55” South Latitude and 102°1’55”- 102° 14’50” East Longitude. The research area covers 20.020,38 ha. The map of study area is presented in Figure 1.

The topography of Padang Jaya District is diverse (Figure 2), predominantly characterized by gentle slopes (8-15%), as further detailed in Table 1. This area is divided into three zones: 1) the Other Land Use Area (OLUA), 2) the Production Conservation Forest Area (CFA), and 3) the Protected Forest Area (PFA). The OLUA zone covers an area of 16,942.22 hectares (84.62%), consisting of secondary forests, plantations, settlements, seasonal crops, open land, and rice fields.

Most of the population in Padang Jaya District is engaged in the agricultural sector, particularly in plantations, rice farming, seasonal crops, horticulture, and fisheries. Plantations are the dominant activity. Additionally, farmers' income comes from the production of cardamom, which has been cultivated in the area, although its production percentage remains relatively small as many people grow cardamom for personal consumption. The distribution of land use and its extent can be seen in Figure 3 and Table 1.

Data collection

This study was conducted through several stages, namely: 1) preparation of a working map, 2) field survey and soil sampling, 3) laboratory analysis and data analysis, and 4) land suitability evaluation and mapping. The research stages are illustrated in Figure 4. The study began with the creation of land mapping units as a reference for soil sampling. These units were obtained by overlaying the slope map, soil type map, and land cover map, resulting in a total of 16 land mapping units. Based on these units, 16 soil samples were collected using purposive sampling, ensuring that each land mapping unit was adequately represented. This sampling approach was chosen to capture the spatial variability of soil characteristics across different land conditions, providing a representative dataset for land suitability evaluation.

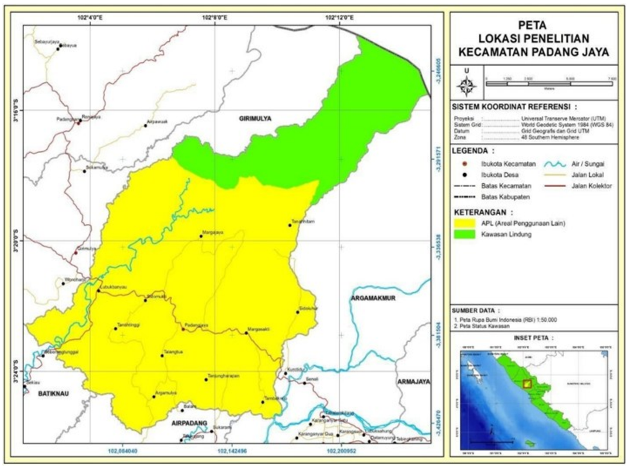

Figure 1. Map of study area

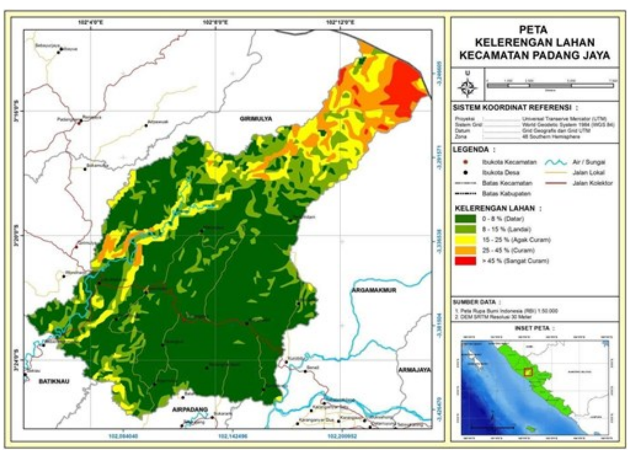

Figure 2. Map of slope

Field surveys were conducted to obtain direct observations of soil properties, including effective soil depth and drainage conditions. Disturbed soil sampling were collected to analyze soil physical and chemical properties in the laboratory. Standard laboratory procedures were followed, including calibration of instruments and adherence to quality control measures during sample preparation and analysis. The variables observed in this study were determined based on the FAO land evaluation framework, which consider multiple factors affecting land suitability for cardamom cultivation. The key variables assessed include: 1) rooting media, which consists of drainage, effective soil depth, and soil texture, 2) nutrient retention, represented by cation exchange capacity (CEC), soil pH, and organic matter content, 3) slope, as an indicator of erosion risk and land stability, and 4) climate factors, which include rainfall and temperature data. The data obtained from field surveys, laboratory data, and GIS analysis were then processed using descriptive analysis to evaluate the soil physical and chemical properties. The land suitability assessment was carried out based on the FAO land evaluation framework, where soil properties were matched with crop requirements to classify land into *high suitable* (S1), *moderately suitable* (S2), *marginally suitable* (S3), and *not suitable* (N) categories. Additionally, subclass categories are used when the land has specific limiting factors or recommended improvements, such as climate (*tc*), rooting media (*rc*), nutrient retention (*nr*), nutrient availability (*na*), and slope (*eh*). The final results were presented as land suitability maps, which serve as a scientific basis for land-use planning and sustainable agricultural development in the study area.

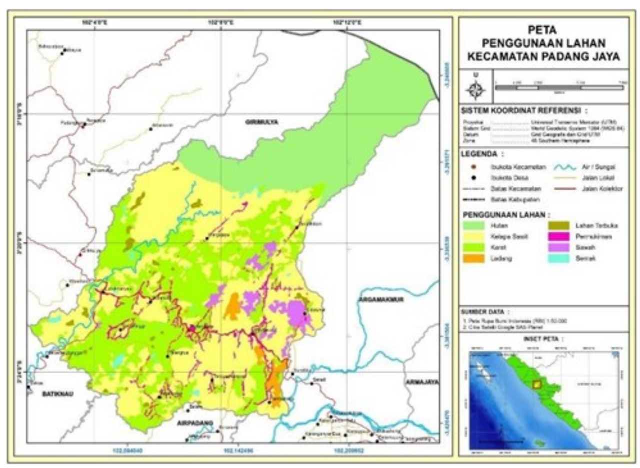

Figure 3. Map of land use

Data analysis

The data used in this study consisted of field data, laboratory analysis, and secondary data to ensure a comprehensive evaluation of land suitability for cardamom cultivation. Field observations were conducted to determine effective soil depth and drainage conditions. Effective soil depth was assessed by examining natural soil cuts, exposed soil profiles, or manually excavated soil pits using a folding ruler used in mineral soils that have a root-limiting layer at a specified depth from the mineral soil surface, following standard guidelines by Soil Survey Staff (2014). Observations were conducted in the field to evaluate the extent to which plant roots can penetrate and impact to crop productivity (Friedman *et al*., 2001). The classification of effective soil depth, which is based on its role in plant root development is presented in Table 2. Meanwhile, drainage conditions were categorized into three levels: *good, moderate,* and *poor*, based on the field observations of soil moisture influence within the soil. The field's drainage assessment was conducted by identifying specific indicators of water impact on the soil cross-section. These indicators included pale or grayish soil coloration and the presence of rust-colored mottles, which signify prolonged water saturation and poor drainage conditions (Handayani *et al*., 2021).

Table 1. Distribution of land use at Padang Jaya District

Land use	Types of Land use	Land area	
		ha	%
Primery forest	Natural forest vegetation and no interference of human	2,368.72	11.83
Secondary forest	Coffee plantation, low to medium vegetation, shrubs, hardwood plantation, agroforestry and other hardwood plantations	709.28	3.54
Plantation	Plantation crops, such as oil palm and rubber	14,297.05	71.41
Bare land	Bare land or grassland	171.89	0.85
Annual plant	Horticultural plant	279.18	1.39
Settlement	Building, yard and road	600.15	2.99
Ricefield	Ricefield	808.23	4.03
Pond	Pond and fisheries	83.84	0.41
Mixed garden	Shrubs, annual plant and fruit plant	702.04	3.50
Total		20,020.38	100.00

Laboratory analysis was conducted to soil texture, Cation Exchange Capacity (CEC), soil pH, and soil organic matter. Soil texture was determined using the hydrometer method, a widely recognized technique for measuring soil particle size distribution due to its high accuracy in quantifying sand, silt, and clay fractions (Beretta *et al*., 2014; Mozaffari *et al*., 2024). In addition, a 2 mm sieve was used to separate and quantify coarse material. Soil texture was classified following the USDA soil texture triangle classification system (Lembaga Penelitian Tanah, 1979; Soil Survey Staff, 2014). The Cation Ex-change Capacity (CEC) of the soil was analyzed using the Kjeldahl method (Balai Penelitian Tanah, 2005), a widely recognized and internationally stan-dardized technique. This method was cho-sen due to its high accuracy in determining the soil's ability to adsorb and release cations, which are essential for plant nutrient availability and its potential to support sustainable agricultural practices (Ammann, 2003; Emamgholizadeh *et al*., 2023; Sahrul *et al*., 2022).

Table 2. Category of soil depth

Soil depth (cm)	Class
>90	Very deep
60-90	Deep
30-60	Medium
<30	Low

Source: Sitorus, (1995)

Soil pH was measured electrometrically using pH meter, following established laboratory protocols to ensure data accuracy and reliability. The pH meter method is widely used for soil pH analysis as it provides high accuracy and correct values, making it a standard and reliable approach in soil evaluation (Food and Agriculture Organization of the United Nations, 2021). Soil organic matter was quantified using the Walkley and Black method, a widely applied technique for determining soil organic carbon levels. Considering its simplicity and efficiency, the Walkley and Black method is often preferred for total organic carbon analysis, as it provides a rapid and reliable estimation of soil organic matter(Hossain & Mazrin, 2023). These laboratory results were further processed and interpreted to assess the soil's ability to retain nutrients and support plant growth, forming the basis for land suitability classification for sustainable agricultural management.

In addition to primary field and laboratory data, this study utilized secondary data from various sources. Climate data, including rainfall and tempera-ture records, were obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) for the past 10 years (2011-2020). These data were analyzed to determine average monthly and annual rainfall, which are critical factors in evaluating the suitability of the study area for cardamom cultiva-tion. Slope data were derived from DEMNAS (National Digital Elevation Model), a high-resolution topographic dataset, which was classified based on Geospatial Information Agency to evaluate its influence on land suitability. Furthermore, data on available phosphorus (P) and potassium (K) were obtained from the Land Unit Information Book, Sheet 0912 (Bengkulu), which provides detailed regional soil fertility information. These secondary data sources were integrated into the land suitability assessment.

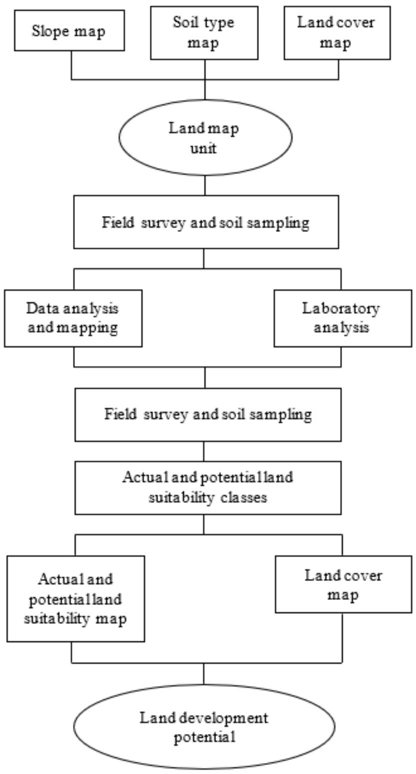

Figure 4. Flow diagram of the research

RESULTS AND DISCUSSION

Physiography of Padang Jaya District

Based on the analysis of land unit maps, slope maps and field surveys, Padang Jaya District's main landform consists of alluvial plains, hilly ares, and undulating plains. The alluvial plain is identified in land unit Af 4.1.1, representing a transitional plain toward a marine area with flat river terraces and a slope of <3%. This land unit covers an area of 78.25 hectares (0.39%). The hilly areas in this region consist of several land units with different characteristics. Land unit Hq 1.2.1 represents small hills with varied topography located on the lower slopes of the Bukit Barisan mountain range, featuring moderately steep slopes (15-25%). This land unit covers an area of 719.17 hectares (3.59%). Meanwhile, land unit Hq 2.2.2, which is formed from acidic sedimentary rocks and volcanic materials, also has a moderately steep slope (15-25%) and covers an area of 1,570.08 hectares (7.84%).

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The undulating plains are represented by land unit Pq 5.2, which is a remnant landform that has undergone geomorphic processes, featuring gentle slopes (8-15%) and covering an area of 619.19 hectares (3.09%). Additionally, land unit Pq 8.2 represents undulating plains with small hills, with slopes ranging from 8% to 25%. This unit is composed of older tuff and mafic lava parent materials, making it the most extensive area, covering 6,340.76 hectares (31.67%). The volcanic region consists of several land units, namely Vab 1.4.1, Vab 1.4.2, and Vab 1.6.2, which cover hilly and mountainous areas with young lava flow deposits. These land units are located on lower slopes and foothills, with topography varying from flat to gently sloping. The respective areas of these land units are 5,586.72 hectares (27.91%), 1,859.54 hectares (9.29%), and 168.49 hectares (0.84%). The volcanic and undulating plain areas with small hills originate from ancient volcanic activity associated with the Bukit Barisan Mountains and serve as the region's primary source of volcanic material. The land unit map of the study area can be seen in Figure 5.

Land Characteristics of Padang Jaya District

Padang Jaya District has an average annual rainfall of 3,418 mm, which falls into the high category. Additionally, the average temperature is 26.7 ° C. The total area of Padang Jaya District is 20,020.38 hectares, with cardamom plantation coverage of approximately 0.2 hectares

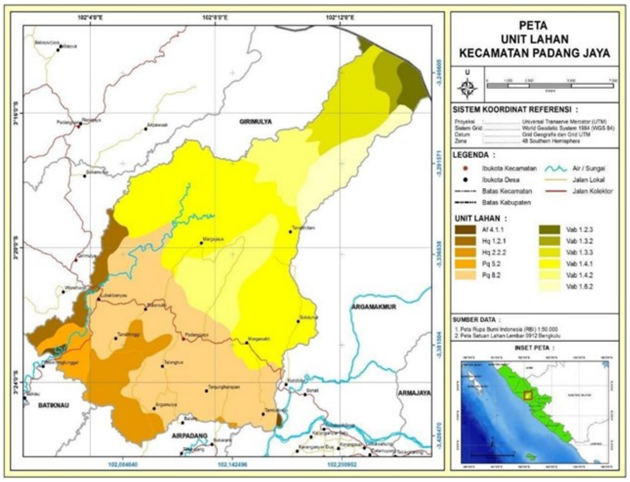

Figure 5. Land unit map in the study area

The soil texture in the study area ranges from *slightly fine* to *medium and slightly coarse*, which falls into the S1 (*highly suitable*) and S2 (*moderately suitable*) classes. *Slightly fine* to *medium* soil textures are generally favorable for cardamom growth as they can retain the soil moisture the plant needs. *Medium*-textured soils typically have good porosity, allowing roots to penetrate the soil easily and absorb nutrients efficiently. Soil texture also plays a role in supporting balanced drainage (Mustawa *et al*., 2017), soil moisture content, soil temperature, and microbial activity (Vinhal-Freitas *et al*., 2017).

According to Amsili *et al*., (2021), organic matter content can increase by up to 64% in *fine*-textured soils, which also provide high water availability for plants. Meanwhile, *slightly coarse*-textured soils can still be used for cardamom cultivation, but proper management strategies such as the application of organic mulch and efficient irrigation are necessary to maintain soil moisture. The drainage in this area is generally classified as *good*, with an effective soil depth of 60-90 cm (*deep*).

Observation of soil chemical properties includes nutrient retention, which covers soil pH, CEC, and organic matter content. The soil pH in the study area ranges from 4.0 to 5.38, which is classified as acidic. Soils with low pH can inhibit the availability of essential nutrients for plants (Penn & Camberato, 2019), particularly phosphorus, which tends to bind with aluminum and iron. Additionally, acidic soils lose cationic nutrients due to leaching, reducing plant productivity (Hong *et al*., 2018; Zhang *et al*., 2019).

The soil CEC in this area ranges from 10.33 to 21.78 (meq/100g), falling into the low to moderate category. CEC indicates the soil's ability to retain and release nutrients for plants, thus affecting plant quality and productivity (Emamgholizadeh, 2023; Jafarzadeh, 2015). The higher the CEC value, the higher the organic matter content and the finer the texture. Conversely, soils with *coarse* textures and low clay content generally have lower CEC values.

The organic matter content in the soil ranges from 3.2% to 6.4%, with variations that can affect soil fertility. Low organic matter content was found at several observation points, which can impact the soil's ability to provide essential nutrients for cardamom plants.

Padang Jaya District is located on slopes ranging from *flat* (0-8%) to *moderately steep* (15-25%). On *moderately steep* slopes, the risk of erosion and nutrient leaching can increase (Wang *et al*., 2019; Wu *et al*., 2018), especially in areas with good drainage but low organic matter content. This condition needs to be considered when developing cardamom cultivation in Padang Jaya District.

Land suitability of Cardamom

Land suitability consists of two categories: actual land suitability (Figure 6) and potential land suitability (Figure 7). Actual land suitability is assessed based on the characteristics and resources of the land that have already been developed. Meanwhile, if efforts are made to improve the land, it may result in an increase in land suitability class (Hartati *et al*., 2018; Rifki *et al*., 2023; Tjahyandari *et al*., 2024).

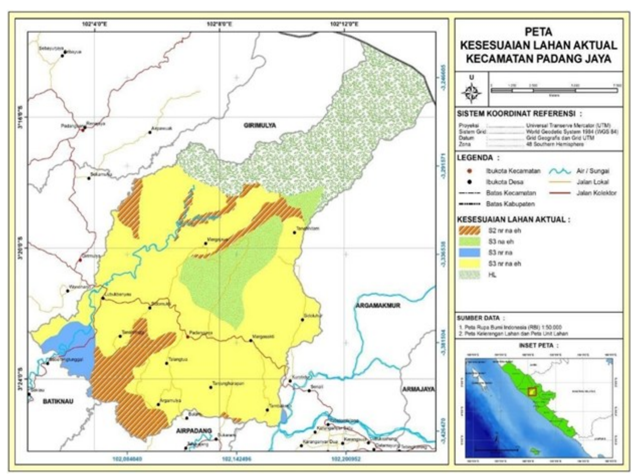

Figure 6. Actual land suitability map

The results of the land suitability class assessment for cardamom cultivation in Padang Jaya District can be seen in Table 3. The actual land suitability class **S3nrna** has limiting factors including nutrient retention (*nr*) and nutrient availability (*na*). Improvement efforts that can be made to address these limiting factors include liming and the addition of organic materials to improve nutrient retention, as well as fertilization to enhance nutrient availability in the soil. As a result, the limiting factors related to nutrient retention and availability can be improved, thus increasing its potential land suitability class to S2na.

The S3naeh land suitability class, with limiting factors related to nutrient availability (*na*) and slope (*eh*), is also assessed. Limiting factors such as slope cannot be improved; however, efforts can be made to minimize the impacts of moderately steep slopes. Improvement measures include adding organic material, fertilizing, and creating terraces. Therefore, with these improvement efforts, the potential land suitability class increases to S2naeh.

Table 3. Land suitability for cardamom cultivation at Padang Jaya District

Land unit	Actual land suitability	Recommend for improvement efforts	Potential land suitability	Land area (ha)	Land area (%)
1	S3nrnaeh	Liming and organic matter application, contour planting.	S2na	906.85	4.52
2	S3nrnaeh	Liming and organic matter application, contour planting.	S2na	4,362.97	21.79
3	S3nrnaeh	Liming and organic matter application, contour planting.	S2na	276.55	1.38
4	S2nrnaeh	Liming and organic matter application, terrace planting.	S1	1,938.68	9.68
5	S2nrnaeh	Liming and organic matter application, minimize soil erosion risk	S1	425.92	2.12
6	S3nrna	Liming and organic matter application, fertilizer application	S2na	619.70	3.09
7	S3nrna	Liming and organic matter application, fertilizer application	S2na	78.27	0.39
8	S3nrnaeh	Liming and organic matter application, terrace planting	S2na	69.13	0.34
9	S3nrnaeh	Liming and organic matter application, terrace planting	S2na	429.23	2.14
10	S3nrnaeh	Liming and organic matter application, terrace planting	S2na	168.39	0.84
11	S3nrnaeh	Liming and organic matter application, terrace planting	S2na	1,908.77	9.53
12	S3nrnaeh	Liming and organic matter application, terrace planting	S2na	2,752.99	13.75
13	S2nrnaeh	Liming and organic matter application, effort for making terrace planting	S1	924.97	4.62
14	S3naeh	Organic matter and fertilizer application, terrace planting	S2naeh	1,080.55	5.39
15	S3naeh	Organic matter and fertilizer application, terrace planting	S2naeh	709.90	3.54
16	S3naeh	Organic matter and fertilizer application, terrace planting	S2na	289.92	1.44
CFA				2,368.72	11.83
PFA				709.28	3.54
		Total		20,020.38	100.00

Furthermore, the actual land suitability class S2nrnaeh has limiting factors such as root media (*nr*), nutrient retention (*na*), and slope (*eh*). Improvement efforts include liming and adding organic materials to enhance nutrient retention, as well as efforts to reduce erosion rates in order to mitigate the impact of slope on soil stability. Given that the slope is still considered gentle, these improvement measures can significantly address the existing constraints. The enhancement of root media quality, better nutrient availability, and effective erosion control make the land more optimal for cardamom plant growth. Therefore, after these improvements are made, the potential land suitability class increases to S1, meaning it is highly suitable for cardamom cultivation.

Extensification land analysis at Padang Jaya District

Land extensification is an effort to increase crop production by expanding the planting area through the opening of new land (Saharuddin & Yudianisa, 2022; Subardja *et al*., 2014). This is done to add to the area of land that will be utilized for cardamom cultivation so that the land becomes productive and results in an economic improvement for the community.

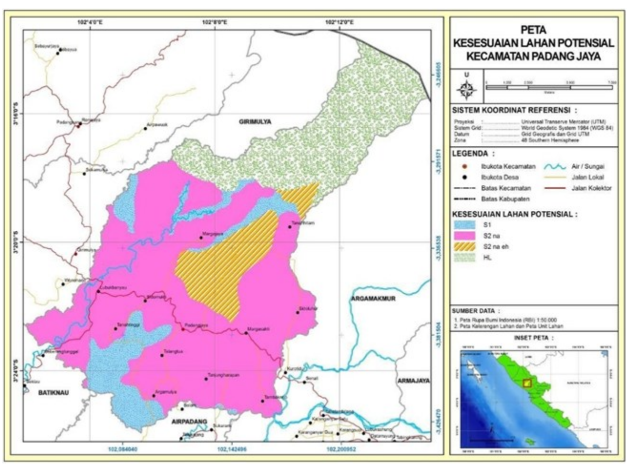

Figure 7. Potential land suitability map

Padang Jaya District has nine land cover types, with four land covers that have the potential for extensification, namely mixed gardens, annual crops, plantations, and open land. The land covers that can be subject to extensification are shown in Table 4.

Land extensification in Padang Jaya District has great potential, considering the large area of land cover that can be developed, totaling 8,747.71 ha. The utilization of this land is expected to increase cardamom production while supporting the growth of the agribusiness sector in the region. However, during the extensification process, further identification of soil characteristics and limiting factors is needed to ensure the success of cardamom cultivation in the expanded area.

Table 4. Extensification landuse potential for cardamom cultivation

Landuse	Land suitability	Land area (ha)
Mixed garden	S2nrnaeh. S3nrnaeh. S3naeh. S3nrna	770.03
Annual plants	S2nrnaeh. S3nrnaeh. S3naeh. S3nrna	452.64
Plantation	S2nrnaeh. S3nrnaeh. S3naeh	5,531.52
Empty land	S3nrnaeh. S3naeh. S3nrna	1,993.52
Total		8,747.71

Land extensification can benefit the surrounding community, particularly in improving the welfare of farmers. The increase in land area provides opportunities for higher income through greater production yields. Additionally, the development of post-harvest cardamom industries, such as processing and marketing, will have a positive impact on the regional economy.

Land extensification from an environmental sustainability perspective must be carried out with an eco-friendly approach to prevent land degradation. Uncontrolled land conversion can lead to the loss of natural vegetation cover, increased erosion risks, and a decline in soil quality due to improper management practices. Therefore, extensification will be optimal if implemented with soil and water conservation strategies, such as agroforestry, intercropping, and sustainable farming systems, to maintain ecosystem balance and achieve optimal results.

CONCLUSION

This study assessed land suitability and the potential for cardamom cultivation in Padang Jaya to support sustainable agriculture. The results indicate that the predominant land suitability classes are S3nrnaeh and S2nrnaeh, with major limiting factors including rooting media, nutrient retention, nutrient availability, and slope. However, improvements such as liming, fertilization, organic matter application, and soil conservation can enhance land suitability.

Notably, 62.3% of S3-class land can be upgraded to S2 through soil fertility enhancement and erosion control, while 37.7% of S2-class land can be improved to S1 with intensive conservation measures such as terracing and optimized nutrient management. Furthermore, land extensification analysis identifies 8,747.71 hectares with development potential in mixed gardens, seasonal crops, plantations, and bare land. Despite these insights, factors such as seasonal soil variability and sampling limitations may affect the generalizability of the findings. Further research with long-term monitoring and more detailed spatial analysis is recommended to refine land suitability assessments and management strategies. These findings have important implications for agricultural planning, policymaking, and farming practices, providing a basis for more effective land-use policies. By adopting recommended improvements, farmers can enhance productivity and sustainability, while integrating these insights into regional agricultural planning can optimize land use and mitigate soil degradation risks.

Considering the limiting factors such as slope and erosion, future research can explore the effectiveness of various soil conservation techniques, such as agroforestry implementation, organic mulching, and terracing, in enhancing cardamom productivity. Additionally, interdisciplinary approaches should be considered to improve land evaluation accuracy. Future studies could refine the existing GIS-based analysis by increasing the spatial resolution and incorporating remote sensing techniques to obtain more detailed and localized information on land suitability for cardamom cultivation. A finer-scale assessment would enable more precise spatial analysis of soil properties, microtopographic variations, and land-use dynamics, thereby improving the accuracy of land management recommendations.

Further research may also include evaluating the long-term impacts of land extensification and land suitability improvements on cardamom productivity, ecosystem sustainability, and farmers' well-being. By incorporating advanced geospatial analysis with a moe detailed spatial scale and continuous monitoring, future studies can generate more targeted and site-specific recommendations for sustainable land management and optimized agricultural planning.

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