International Journal of Design & Nature and Ecodynamics
Vol. 20, No. 12, December, 2025, pp. 2805-2819
Journal homepage: http://iieta.org/journals/ijdne

GIS-AHP Based Suitability Assessment Model for Smallholder Coffee Plantations: A Case Study from Jember, Indonesia

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https://doi.org/10.18280/ijdne.201207

Received: 19 October 2025
Revised: 12 December 2025
Accepted: 24 December 2025
Available online: 31 December 2025

Keywords:
Geographic Information System, Analytic Hierarchy Process, land suitability, smallholder coffee

ABSTRACT

This study develops models to classify the suitability of smallholder coffee plantations, aiming to strengthen the coffee agroindustry that depends on smallholder farmers as its main raw material source. Since most coffee production areas and farmers come from smallholder plantations, the supply of coffee cherries largely relies on this sector. The research integrates Geographic Information System (GIS) and Analytic Hierarchy Process (AHP) methods to map plantation suitability in Jember Regency, East Java Province. The model effectively identified and mapped 85,033.53 hectares of smallholder coffee plantations. Suitability analysis revealed that 9.32% of plantations were categorized as non-potential, 32.72% as developing, and 57.96% as potential. These results demonstrate the model's capability to visualize and evaluate the distribution and potential of smallholder coffee plantations in the region. The findings offer valuable insights for regional development planning, particularly in determining priority areas for infrastructure investment, farmer empowerment, and agroindustrial expansion. Additionally, the model supports land use policy by providing spatially detailed information to optimize plantation development while minimizing environmental risks. This framework can also be applied to other smallholder-based agricultural systems in tropical regions to promote evidence-based decision-making and sustainable agroindustrial growth.

1. INTRODUCTION

Coffee represents a strategic commodity in Indonesia, playing a vital role in generating income for stakeholders, enhancing community livelihoods, and contributing to national development [1]. The use of coffee to meet the needs of downstream industries aligns with the increasing demand from both domestic and export markets [2]. This growth is also driven by the expanding consumption and market of the coffee agro-industry, highlighting opportunities that should be further developed by stakeholders and the government to enhance coffee's value addition and sustainability. These opportunities require an integrated series of efforts, particularly in preparing high-quality raw materials.

The primary source of coffee beans in Indonesia is derived from a plantation area of approximately 1.266 million hectares [3] divided into three potential sources: smallholder plantations, state-owned estates, and private estates. Smallholder plantations serve as the dominant supplier for the downstream coffee industry, contributing 99.56% of the total coffee plantation area in the country.

Smallholder plantations face unique challenges in cultivation but offer significant economic benefits, encouraging farmers to continue expanding their coffee-growing activities. Consistent with this, Parmawati et al. [4] have stated that the supply of coffee beans heavily depends on smallholder plantations. As such, smallholder coffee plantations are a critical and strategic focus for meeting the raw material needs of the coffee agro-industry. Furthermore, the integration between upstream and downstream sectors is vital for the sustainability of coffee business processes [5].

Given the limitations of land productivity and the growing demand for coffee-based products, integrated strategies are needed to maintain raw material continuity and improve competitive performance [6]. Accordingly, the Indonesian government has initiated a coffee plantation rejuvenation program aimed at sustaining supply continuity and increasing productivity among smallholder farmers [7]. Beyond increasing productivity, the rejuvenation program is expected to expand employment opportunities, alleviate poverty, and improve farmers' economic status toward the middle-income level. It is intended to improve farmers' capacity to meet market and quality requirements, which in turn will boost the competitiveness and sustainability of coffee and its derivatives. According to literature [8], land suitability and geographic conditions are key determinants of productivity. These factors must be considered to meet market demands and enhance production yields. Geographic factors such as topography, soil fertility, slope, and water access directly influence the technical aspects of land suitability.

Strengthening the position of smallholder farmers is essential to enhance Indonesia's bargaining power and competitiveness through its natural resources and value-added products [9]. However, this effort faces challenges such as the lack of land certification, high capital requirements for rejuvenation, low competitiveness among farmers, weak farmer organizations, limited extension services, and a lack of up-to-date spatial/geographical data to support sustainable coffee downstream development [10-12].

Considering the need for an integrated approach to ensure a sustainable, high-quality coffee supply for the downstream agroindustry, an analysis of smallholder coffee plantations is essential. Their management should be directed toward improving competitiveness [13]. Further challenges include preparing smallholder farmers through enterprise development programs and the need for regulatory and facilitative support for smallholder coffee enterprises [14]. Drawing on the comprehensive review and the challenges identified, this study underscores the need for an integrated analytical model to assess the suitability of smallholder coffee plantations. The inclusion of spatial aspects in the model provides clearer guidance for improving smallholder coffee farming, as visual representation can generate a more accurate and detailed portrayal of existing conditions. Furthermore, spatial-based research on smallholder coffee plantations remains limited due to the scarcity of data and the uneven distribution of plantation locations.

Existing studies employing GIS and AHP have primarily focused on general land suitability or ecological zoning, yet they rarely address the unique characteristics of smallholder coffee systems, which are heterogeneous, fragmented, and highly influenced by socioeconomic and infrastructural factors [15, 16]. Moreover, previous GIS-AHP approaches often rely on coarse spatial datasets or simplified biophysical indicators, resulting in suitability classifications that are insufficiently refined for operational decision making at the smallholder level [17]. These gaps highlight the need for a more comprehensive model that combines spatial detail, multi-criteria weighting, and contextual attributes of smallholder coffee farming. Therefore, this study proposes an integrated GIS-AHP suitability assessment specifically tailored for smallholder coffee plantations, addressing both the limitations of spatial data availability and the shortcomings of existing methodological approaches.

In light of these considerations, the primary objective of this research is to develop an integrated model for assessing land suitability for smallholder coffee plantations using a combined GIS and AHP approach. The model evaluates eight key criteria: soil type, elevation, slope gradient, distance from roads, distance from rivers, proximity to settlements, distance to coffee agroindustry, and forest area classification to generate a spatially explicit suitability rating. The ultimate objective is to support decision-making by identifying priority areas that require improvement, intervention, or strategic development to strengthen smallholder coffee supply for the downstream agroindustry.

2. METHOD

2.1 Conceptual framework

This study's conceptual framework was formulated based on a situational analysis of key factors affecting coffee supply from smallholder farmers. The supply gap is identified as a result of the misalignment between plantation conditions and the bargaining position of smallholder coffee enterprises.

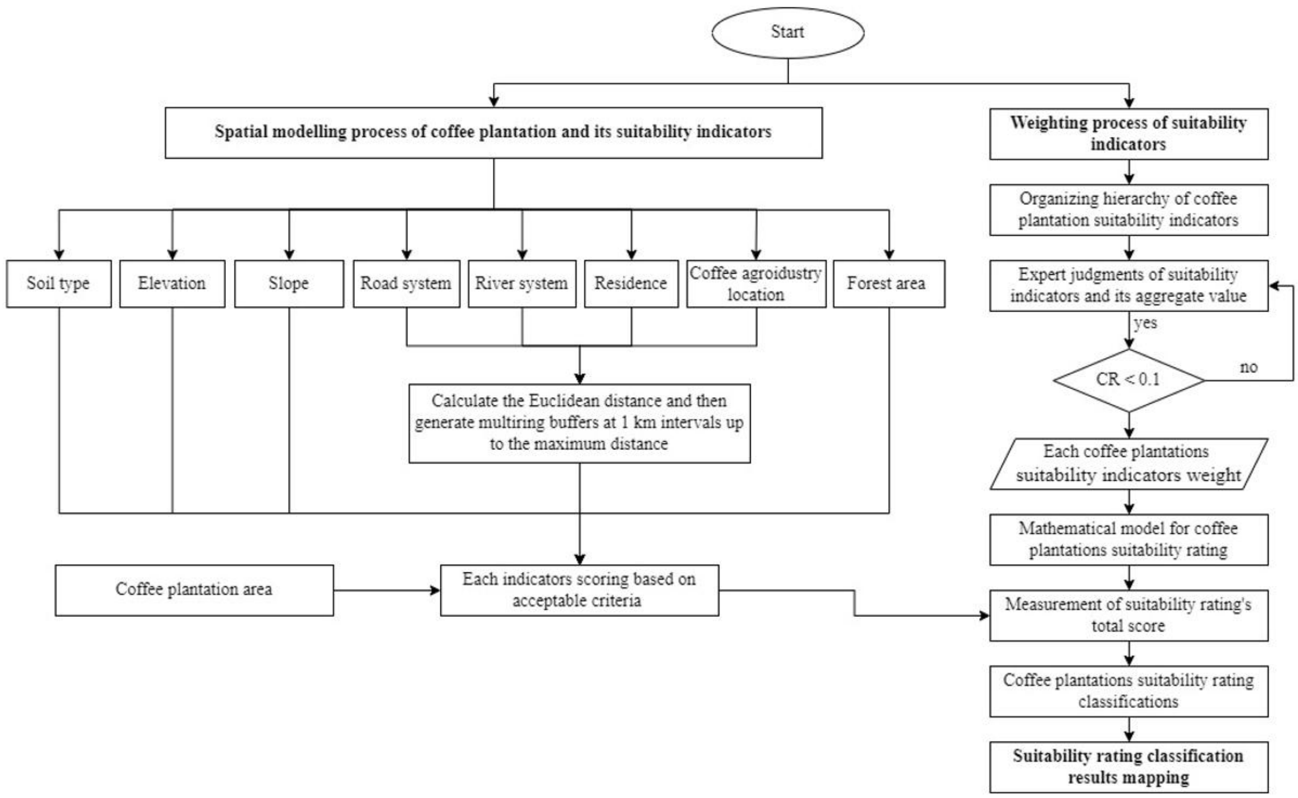

Figure 1. Conceptual framework
Modification from research [18]

In response to these issues, an integrated model is required that considers both the current conditions and future opportunities of smallholder farmers in sustaining the coffee agroindustry and downstream activities. Mapping the suitability of smallholder coffee plantations is essential to identify the spatial relationships and geographic components of such plantations. In this study, the analysis is focused on developing a spatial-based suitability assessment model for smallholder coffee plantations. The conceptual framework has been refined to eliminate components unrelated to the suitability assessment, ensuring that the model concentrates on evaluating key biophysical and infrastructural factors that influence plantation conditions. This refinement aligns the entire research flow objectives, methods, and outputs strictly with the land suitability assessment using GIS and AHP. The study's conceptual framework is presented in Figure 1.

Model development and analysis were conducted for smallholder coffee plantations in Jember Regency, East Java Province, chosen for its extensive plantation coverage and one of the highest concentrations of smallholder coffee farmers in the province. The regency comprises 31 districts, with a total plantation area of 6,382.45 hectares and 14,034 smallholder coffee farmers. The suitability model was developed to cover the entire region of Jember Regency.

2.2 Data collection

This study utilizes both primary and secondary data to achieve the research objectives and support model development. Primary data were gathered through field observations, interviews, focus group discussions, and expert judgment. Secondary data were obtained from various sources, including scientific journals, relevant previous studies, institutional reports, symposium proceedings, and official documentation. To strengthen the analytical framework, additional secondary data were derived from stakeholder analysis of the coffee business process and findings from earlier research. A detailed summary of the collected data is presented in Table 1.

Table 1. Research data collection methods

No.	Data	Data Source	Expert Background and Institutional Affiliation of Respondents
1	Spatial data of the coffee plantation area	-Field observation and Google image -Government documents (coffee agroindustry position, road network data, river network data, etc.)	-Smalholder coffee association -Jember regency government
2	Attribute data of the coffee plantation	-Interview and discussion -Literature review	-Smalholder coffee association -Academician and researcher in the coffee field -Jember regency government
3	Suitability indicators for coffee plantation assessment	-Literature review Interview and discussion -Expert opinion	-Smalholder coffee association -Academician and researcher in the coffee field -Jember regency government
4	Weights of suitability criteria based on importance levels	-Expert judgment	-Smalholder coffee association -Academician and researcher in the coffee field -Jember regency government
5	Coordinate of smallholder coffee plantation	-Field observation	-Smalholder coffee association

Developed by the authors

2.3 Smallholder coffee plantations suitability mapping

The mapping of smallholder coffee plantations was conducted using ArcGIS 10.3 software. The initial stage involved data extraction and correction to evaluate data completeness and produce standardized, corrected datasets. Satellite imagery utilized in this study was derived from Sentinel-2 time-series data acquired between April 1 and September 30, 2025, with a minimum cloud cover of 10%. Sentinel-2 is a multispectral imaging mission based on a constellation of two high-resolution satellites launched in the sun-synchronous orbit [19]. Image processing was conducted using the Google Earth Engine (GEE) platform, which offers a suite of pixel-based classification algorithms for crop-type mapping [20]. This was followed by the implementation of feature selection for smallholder coffee plantations in Jember Regency, along with the corresponding indicators. The second stage comprised data transformation and spatial analysis to generate attribute data informed by geographic information. In this stage, the characteristics of each factor were defined and spatially transformed based on their geographic location. The factors incorporated in mapping smallholder coffee plantation potential included soil type, altitude, slope gradient, road networks, river networks, settlements, coffee agroindustry, and forest areas. Each class was classified for subsequent ranking processes. The ranking results of each class were then utilized to classify smallholder coffee plantation areas according to their potential levels.

Table 2. List of experts participating in this study

No.	Name	Institution/Profession
1	Expert 1	Smallholder Coffee Farmers in Jember Regency
2	Expert 2	Coffee Agroindustry Practitioners in Jember Regency
3	Expert 3	Food Crops, Horticulture, and Plantation Service, Jember Regency
4	Expert 4	Lead Auditor Rainforest Alliance
5	Expert 5	Indonesian Coffee and Cocoa Research Institute

Developed by the authors

The third stage, spatial modeling, was conducted by weighting the determinants of plantation suitability based on the relationships between indicators and factors using the AHP method [21]. The AHP process was conducted through structured interviews and pairwise comparison questionnaires.

Expert judgments were employed to assess the relative importance of eight suitability criteria for coffee plantations. Details of the participating experts are provided in Table 2.

The pairwise comparison matrix for each expert was developed using Saaty's 1–9 fundamental scale, where a value of 1 represents equal importance and a value of 9 represents extreme importance of one criterion relative to another [22]. Priority weights were derived from expert judgments based on this pairwise comparison scale, as presented in Table 3.

Table 3. Rating scale in pairwise comparisons

Level of Interest	Definition
1	Equal importance
3	Moderate importance
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	If in doubt between two adjacent values
1 / (1-9)	The inverse of importance values on a scale of 1-9

Adapted from research [22]

Individual matrices were then combined using the geometric mean aggregation method, consistent with AHP standard procedures for synthesizing multiple expert judgments. The priority weights for each criterion were calculated using the principal eigenvector approach, where the normalized eigenvector corresponding to the maximum eigenvalue (λ_{max}) represents the final weight vector. To ensure the reliability of expert judgments, a consistency assessment was performed by calculating the Consistency Index (CI) and Consistency Ratio (CR):

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

$$CR = \frac{CI}{RI} \quad (2)$$

The fourth stage involved mathematical modeling to classify the suitability ranking of plantations. The mathematical formulation was developed using the derived hierarchical weights, as expressed in the following equation [23]:

$$X_i = \sum a_i b_i \quad (3)$$

X_i represents the suitability ranking of coffee plantations, a refers to the indicator weight, b represents the indicator score, and i indicates the number of plantation clusters assessed. Based on this formulation, the mathematical model enables spatially based measurements to compute plantation suitability rankings [18]. The aggregated results of X_i were subsequently classified into three interval classes using the Classification Interval Width (CID), that is:

CID = ((maximum score of X_i – minimum score of X_i) / number of class)

In the final stage, the suitability rankings of smallholder coffee plantations were categorized according to the CID value ranges and the specified number of classes. The suitability classification was divided into three classes, with corresponding interval ranges and class labels presented in Table 4.

Table 4. Suitability classification of smallholder coffee plantations

Interval Value (IV)	Classification
A minimum score of $X_i \leq$ IV $\leq$ A*	Non-potential coffee plantation
A* Value < IV $\leq$ B** Value	Developing a coffee plantation
IV > A maximum score of X_i	Potential coffee plantation

Notes: A* Value = Minimum score of X_i + CID; B** Value = A Value + CID. Adapted from research [18]

3. RESULT AND DISCUSSION

3.1 Spatial model of smallholder coffee plantation areas

The spatial model of coffee plantation areas in Jember Regency was developed through spatial mapping using a visual interpretation approach that integrated land-use attributes, state-owned and privately owned plantation data, and satellite imagery to delineate coffee plantation zones. The initial mapping stage involved data separation and correction through a feature selection process. This procedure generated a spatial delineation of scattered smallholder coffee plantation areas, as illustrated in Figure 2 and Figure 3.

Attribute and geographic data selection and elimination were performed using satellite imagery (as described in the methodology section) to obtain the results that served as the initial area for assessing the suitability of smallholder coffee plantations. This initial step is essential to the spatial model, serving as the foundation for land suitability evaluation, as it functions as the foundational basis for suitability assessment. The process was necessary due to the unavailability of spatial data on the cultivation areas of smallholder coffee plantations. Specifically, the spatial pattern data revealed that the cultivation area of smallholder coffee plantations covered 6,393.2 ha. The resulting plantation area differs slightly from the 2025 data reported by the Central Statistics Agency of Jember Regency [24], which recorded an area of 6,382.45 ha. These discrepancies arise from variations in digitization accuracy, differences in analysis periods, conceptual definitions, and constraints applied to plantation land, data sources, and scales, mapping techniques, and the spatial extent of the analysis [25].

3.2 Analysis of suitability criteria and indicators for smallholder coffee plantations

Assessing land suitability for coffee plantations requires the identification of factors that directly affect land conditions and nutrient availability for plant growth [26, 27]. The availability of plant nutrients is determined by the crop's genetic characteristics and the agronomic practices employed by farmers. Concurrently, the physical land conditions that affect suitability are evaluated based on eight key indicators: soil type, elevation, slope gradient, road network, river network, residential areas, location of agro-industries, and forest areas.

The indicators selected to determine the land suitability level of coffee plantations were soil type, elevation, and slope gradient. Soil type and elevation are indicators that significantly influence the growth requirements of coffee plantation land, as they provide water, nutrients, and appropriate conditions for the development of coffee plants [28]. Coffee requires land with good drainage to prevent waterlogging around the roots. It also demands soil with a loose texture and rich in organic matter to ensure optimal aeration and nutrient supply for its growth [29, 30]. Elevation significantly impacts coffee growth and quality by influencing ambient temperature, humidity, solar radiation, and rainfall, with optimal conditions often found at specific altitudes. Higher elevations typically result in cooler temperatures, less humidity, and different sunlight exposure, which can enhance coffee bean characteristics, including flavor profiles and biochemical composition, leading to higher quality coffee [31]. Slope gradient serves as a critical topographic factor as it directly influences the soil solum, which refers to the depth of the soil profile from the surface to the parent material. Steeper slopes are typically associated with shallower soil solum due to higher erosion rates and limited soil development, which restricts root penetration and water retention capacity. Consequently, coffee plants grown on steep slopes often exhibit suboptimal growth performance [32, 33].

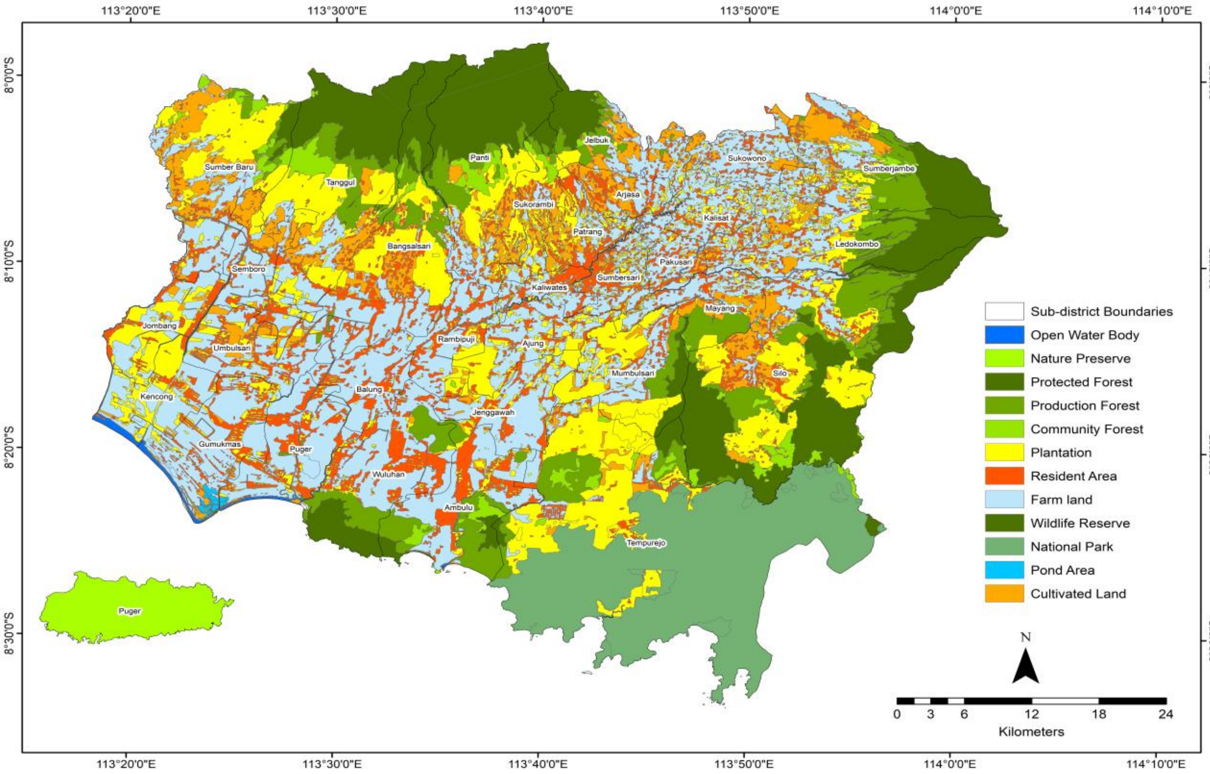

Figure 2. Jember Regency land cover
Developed by the authors

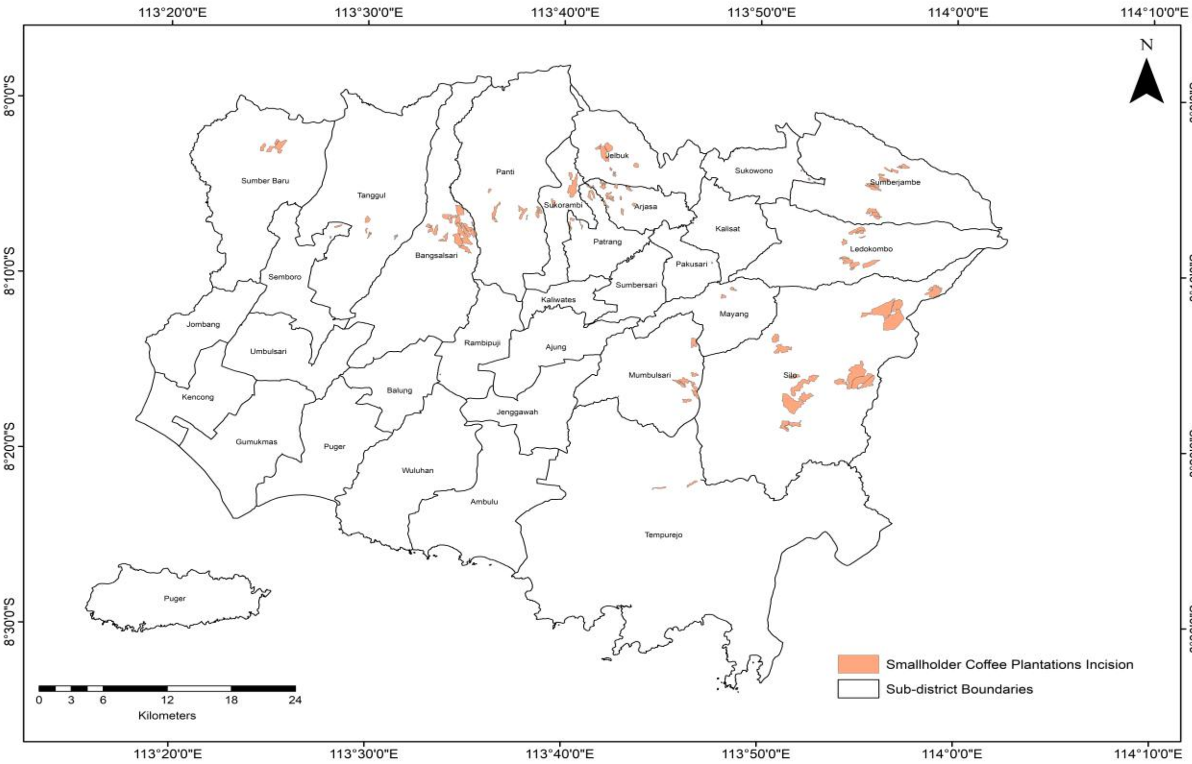

Figure 3. Smallholder coffee plantations incision
Developed by the authors

Five additional indicators influencing the coffee plantation suitability model include road networks, river networks, residential area, agroindustrial location, and forest area. Among these, road infrastructure serves as a critical determinant of plantation development, facilitating the transportation of inputs and outputs as well as market access [34]. Proximity to road networks enhances accessibility, thereby improving the efficiency of plantation operations and reducing logistical constraints [35].

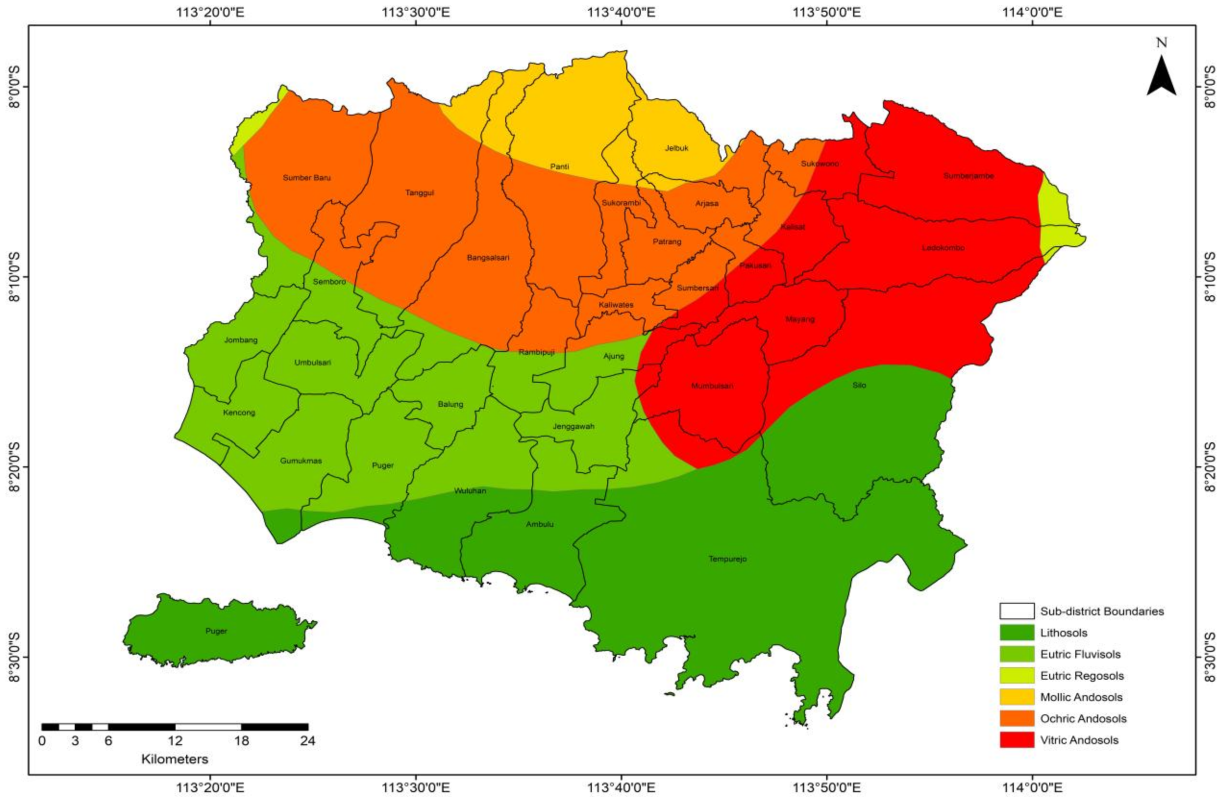

Figure 4. Soil type map
Developed by the authors

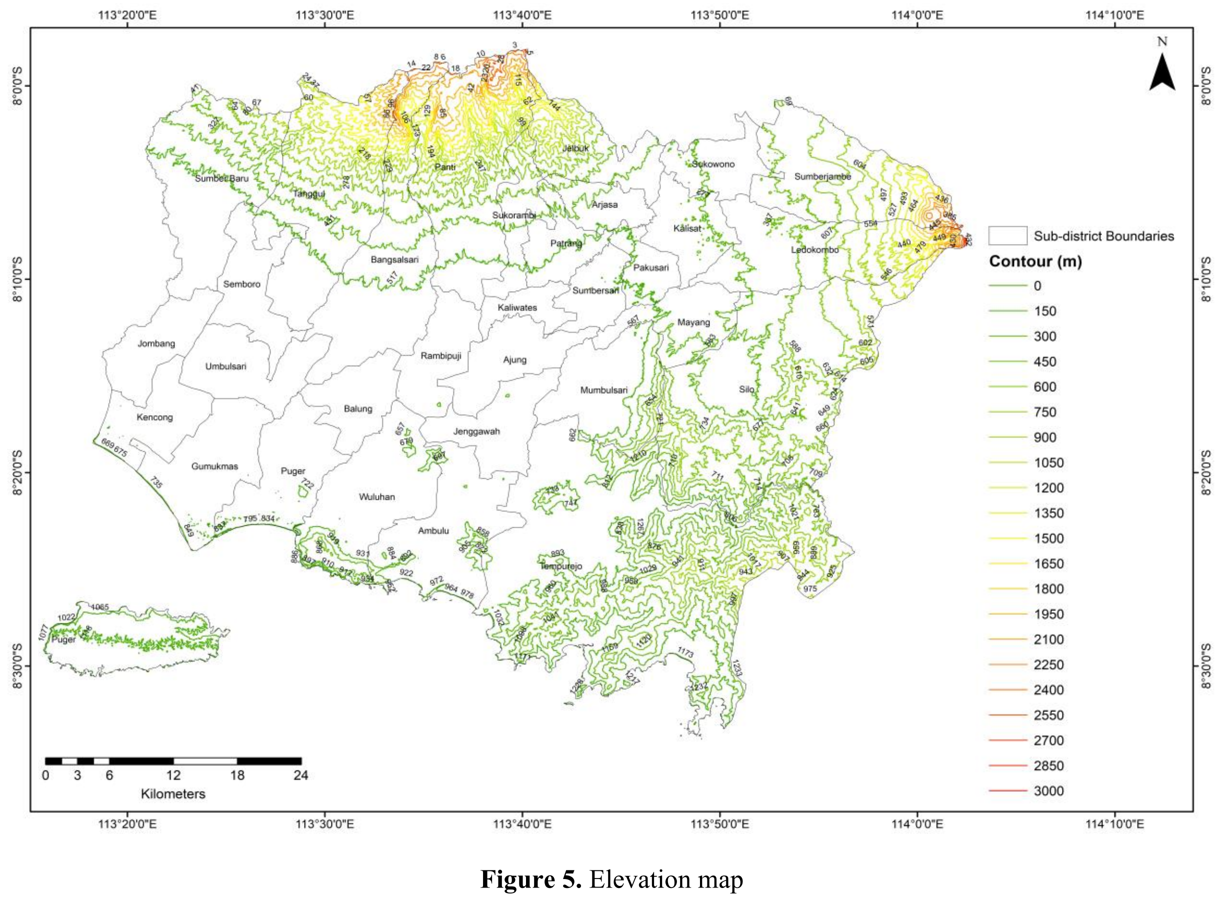

Figure 5. Elevation map
Developed by the authors

Sufficient year-round water availability from river networks is essential for sustaining plantation management and ensuring optimal crop productivity [36]. The residential area in close proximity to coffee plantations may intensify human activities that disrupt plant growth and elevate environmental and socio-economic pressures, thereby posing potential threats to the long-term sustainability of coffee cultivation systems [37]. Furthermore, the spatial location of coffee agroindustries plays a pivotal role in determining transportation efficiency and value chain dynamics, ultimately influencing the income and economic sustainability of smallholder coffee farmers [38]. Forest areas represent designated zones intended for long-term conservation and ecological balance. In practice, however, forest lands are frequently utilized for non-forestry purposes, particularly coffee cultivation [39]. Therefore, it is essential to understand the functional roles of forest areas and their suitability for coffee plantation development. The spatial representation of the indicators influencing suitability levels is shown in Figures 4-11.

3.3 Mathematical model for evaluating smallholder coffee plantation suitability

The selected suitability indicators facilitate an integrated mapping approach that captures the combined effects of biophysical conditions and anthropogenic factors arising from natural processes and human activities [40]. Each indicator was represented within a scoring classification framework, with scores ranked according to the respective land suitability classes for coffee plantations. The ranking procedure served as an analytical technique to depict varying levels of spatial relevance within the model. The assigned scores are relative measures rather than fixed values, and may vary depending on the contextual characteristics and parameters of the specific case study [41].

Soil types in Jember Regency were categorized into five categories for scoring purposes: mollic-ochric andosols, vitric andosols, eutric regosols, eutric fluvisols, and litosol. Among these categories, Andosols were identified as the most suitable soil type for coffee plantations [42]. Andosol is a type of soil found in mountainous areas, with shallow soil, a crushed structure, high porosity, and high dust and organic matter content [43]. Soil suitability scores were subsequently assigned based on literature references and expert assessments, as presented in Table 3. Subsequently, the remaining indicators were represented proportionally based on their distance from the coffee plantations. Buffer-based proximity analysis was applied to map distances between coffee plantations and key spatial networks, with road network distances reaching up to approximately 15 km in Jember Regency. This distance was then divided into five classes, each assigned a corresponding suitability score, and so forth, as presented in Table 5. All indicators were classified into five ordinal score classes, where higher scores indicate relatively more suitable conditions for coffee plantation development. The classification scores (1–5) assigned to each indicator in Table 5 were developed using a combined approach that integrates scientific literature [18], Good Agriculture Practices (GAP) on coffee document [44], expert judgment, government officers, and smallholder coffee farmers. The scoring system is therefore grounded in both empirical evidence and contextual field knowledge, ensuring that the suitability classes reflect the ecological requirements of coffee as well as the local production environment in Jember Regency.

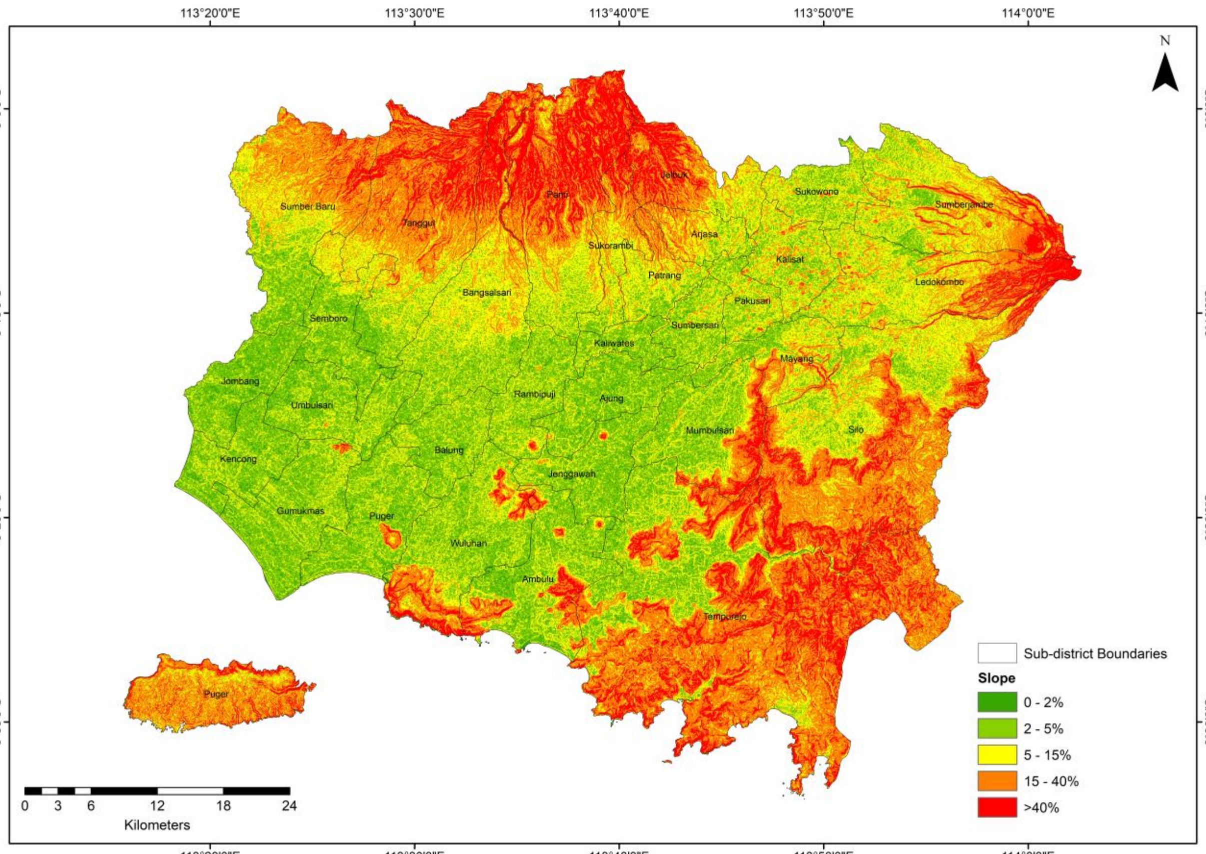

Figure 6. Slope gradient map
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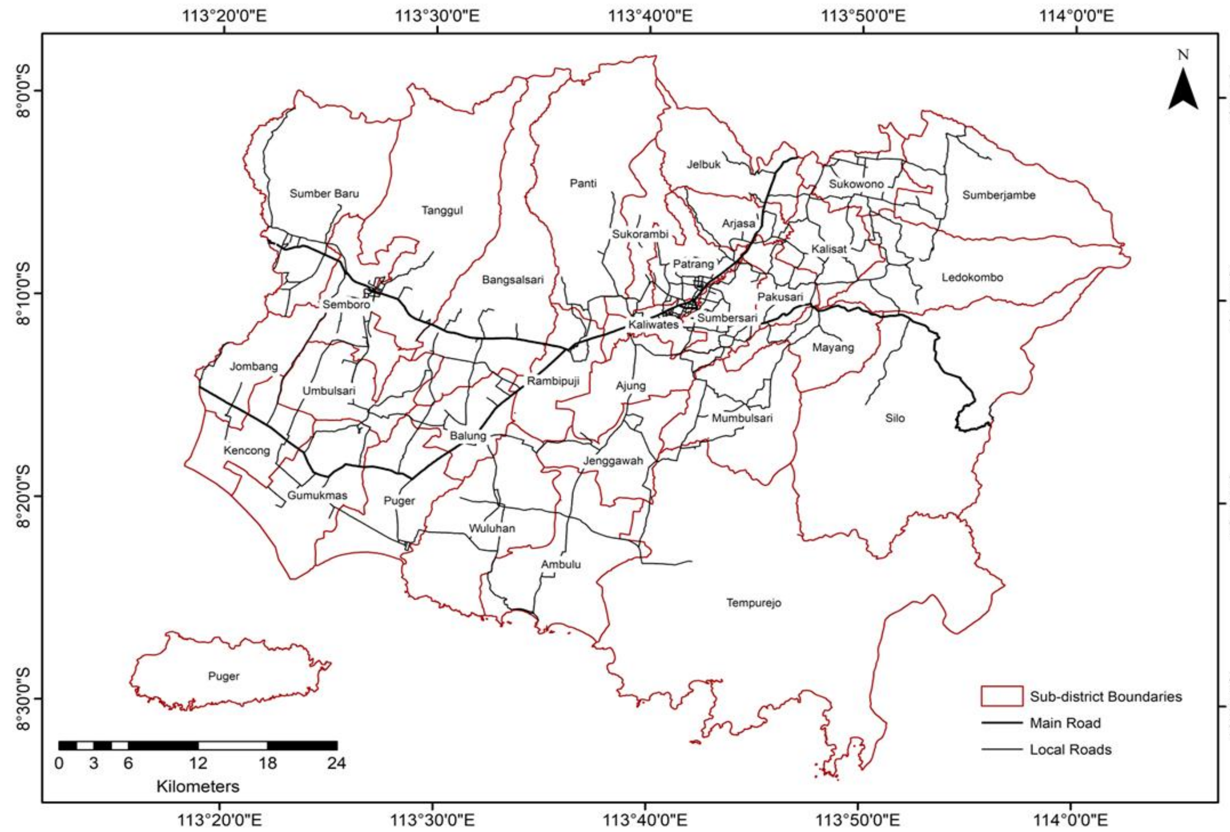

Figure 7. Road network map
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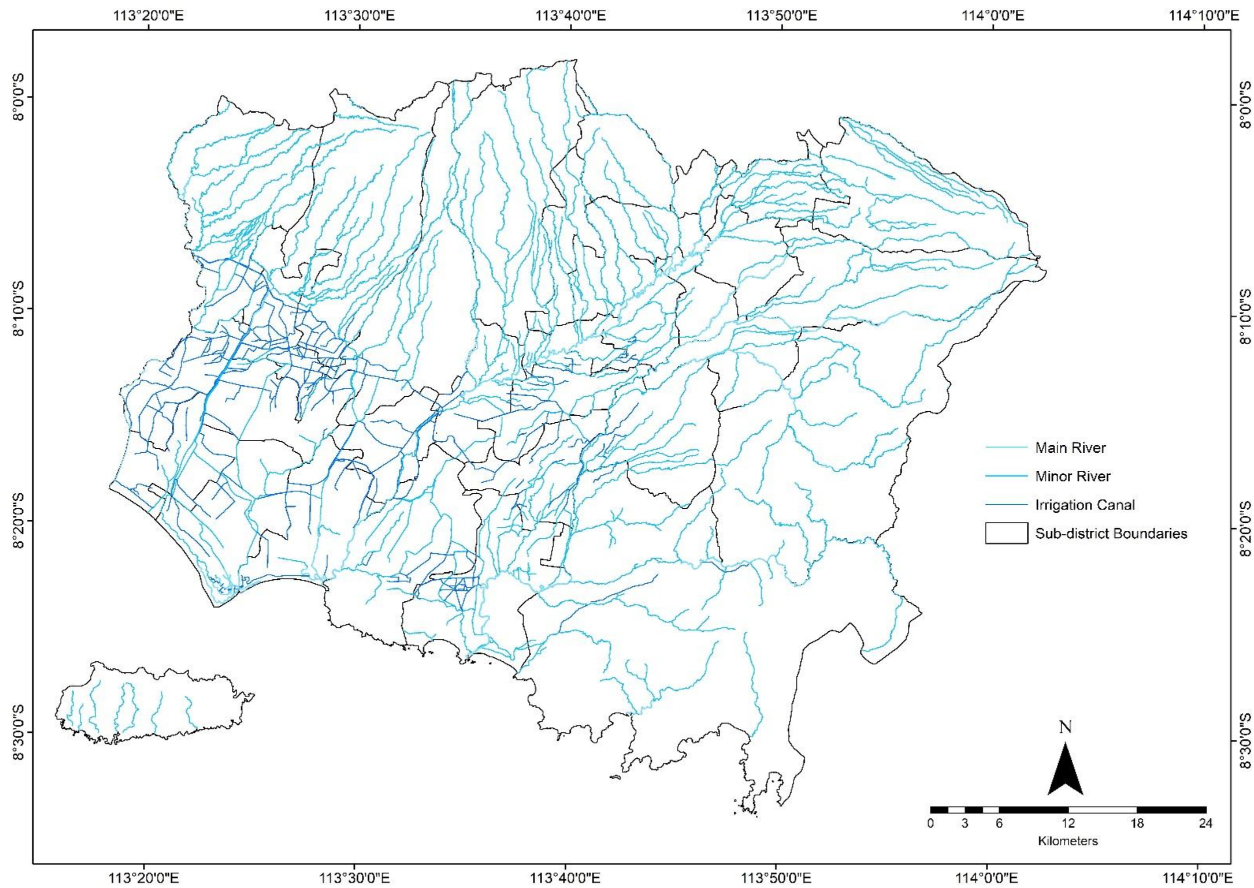

Figure 8. River network map
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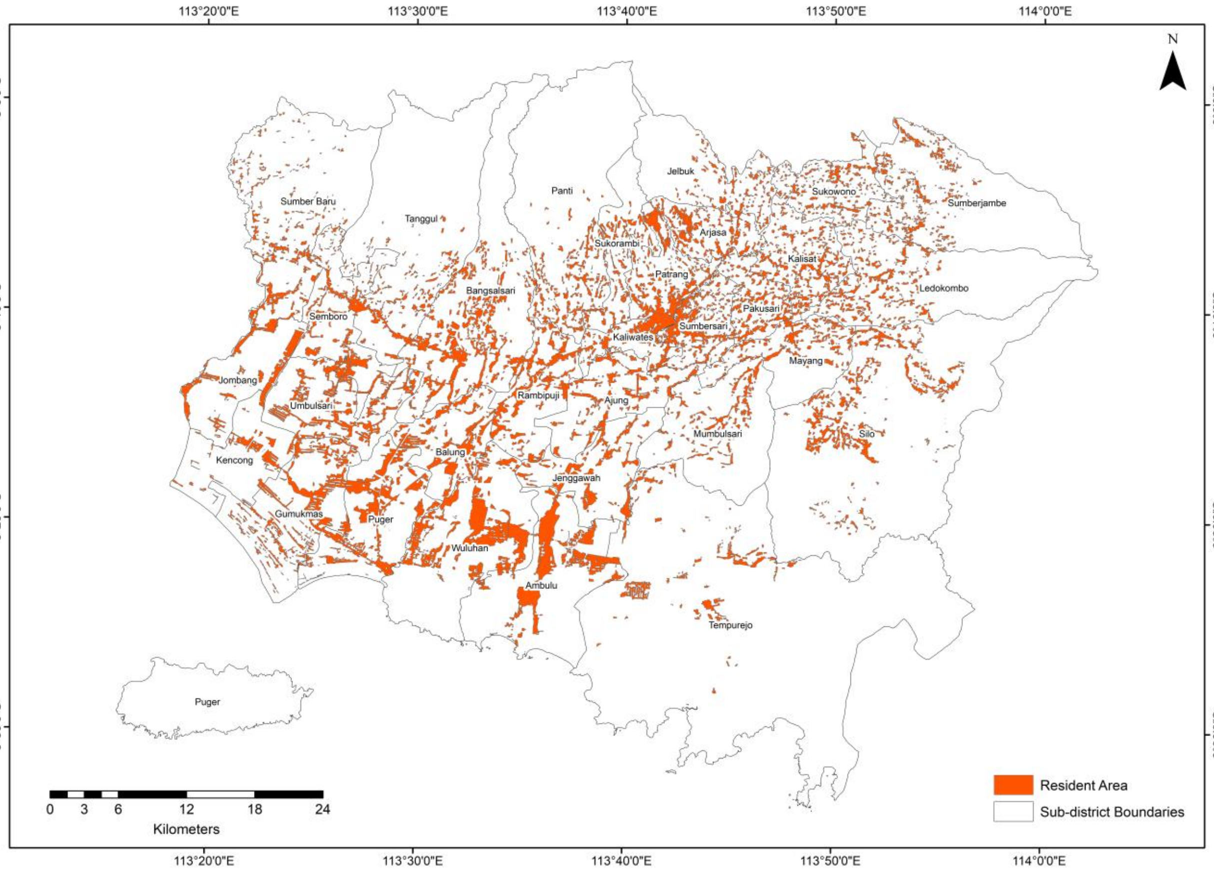

Figure 9. Resident area map
Developed by the authors

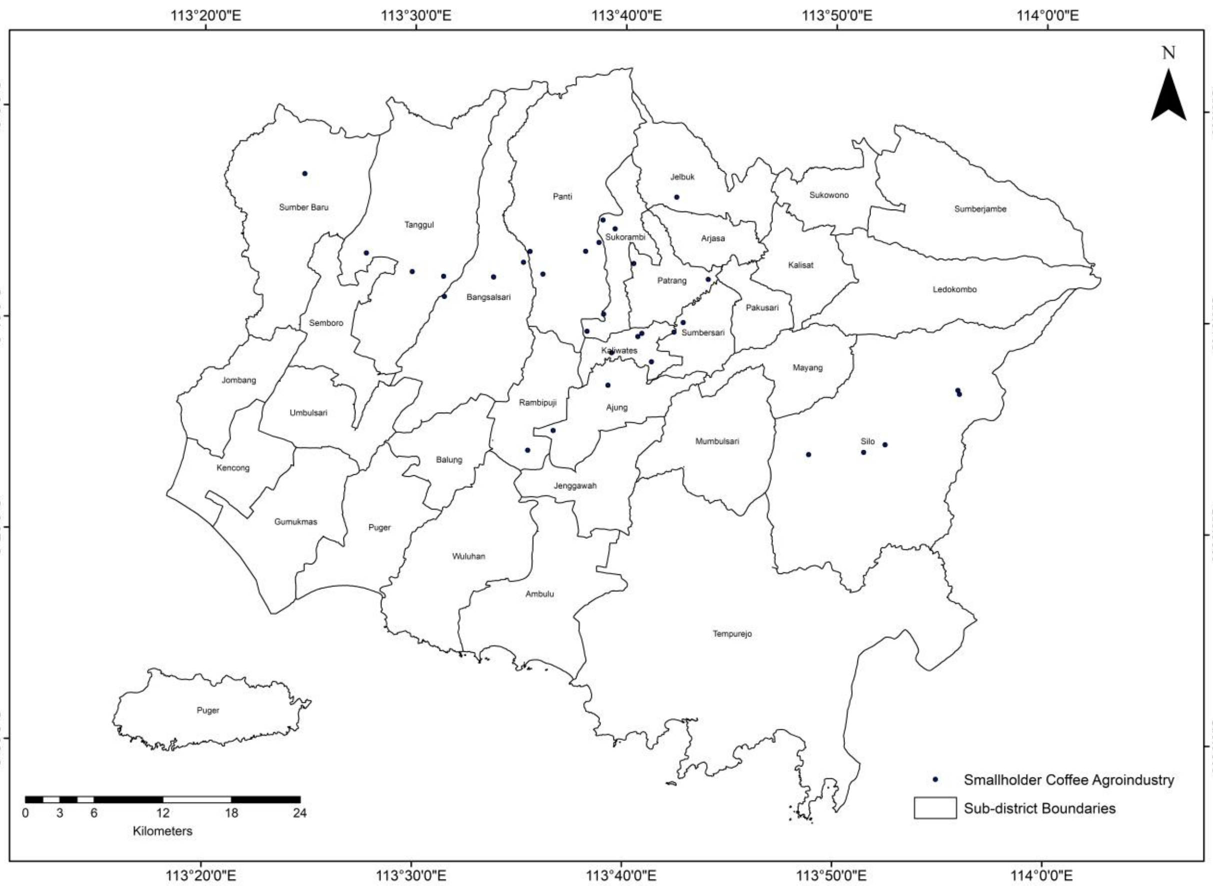

Figure 10. Smallholder coffee agroindustry map
Developed by the authors

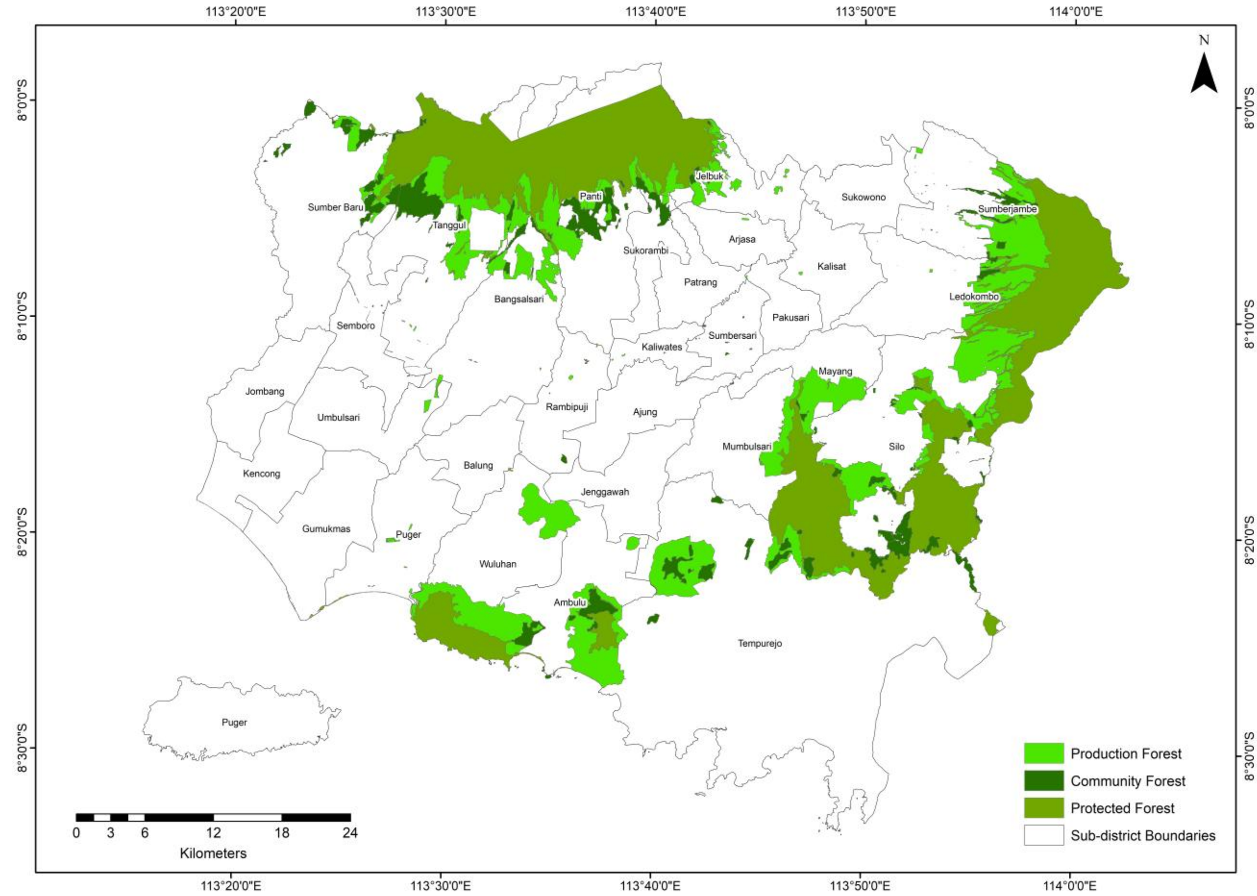

Figure 11. Forest area map
Developed by the authors

Table 5. The scoring classification of indicators' suitability and their weighting

Indicator	Classification	Classification Score	Indicator Weight	CI	CR < 0.1
Soil type	Mollic-Ochric Andosols	5	0.184	0.018	0.013
	Vitric Andosols	4			
	Eutric Regosols	3			
	Eutric Fluvisols	2			
	Litosol	1			
Elevation (masl)	> 800	5 (very suitable)	0.186		
	600-800	4 (suitable)			
	400-600	3 (moderate)			
	200-400	2 (neutral)			
	0-200	1 (unsuitable)			
Slope (%)	0%-2%	5 (flat)	0.079		
	2%-5%	4 (sloping)			
	5%-15%	3 (a little steep)			
	15%-40%	2 (steep)			
	> 40%	1 (very steep)			
Distance to road network (km)	1-3	5 (very close)	0.146		
	4-6	4 (close)			
	7-9	3 (neutral)			
	10-12	2 (far)			
	13-15	1 (very far)			
Distance to river network (km)	1-3	5 (close)	0.079		
	4-6	4 (moderate)			
	7-9	3 (neutral)			
	10-12	2 (far)			
	13-15	1 (very far)			
Distance to settlement areas (km)	1-3	5 (close)	0.083		
	4-6	4 (moderate)			
	7-9	3 (neutral)			
	10-12	2 (far)			
	13-15	1 (very far)			

Distance from coffee agroindustry (km)	1-3	5 (very close)	0.082
	4-6	4 (close)	
	7-9	3 (neutral)	
	10-12	2 (far)	
	13-15	1 (very far)	
Forest area	Other use area	5 (very suitable)	0.161
	Limited production forest	4 (suitable)	
	Production forest	3 (unsuitable)	
	Protection forest	2 (very unsuitable)	
	Nature conservation area	1 (cannot be used)	

Developed by the authors

In order to construct the mathematical model, each indicator was subsequently assigned a weight representing its relative importance. The weighting process is determined based on a priority ranking scale. Indicator and criterion comparisons relied on expert judgment and were ranked using consistent logical criteria. The resulting indicator weights are presented in Table 3. Aggregated expert assessments indicate that elevation is the most influential indicator affecting the potential of coffee plantations. These weights were then applied as coefficients in the mathematical model used to assess coffee plantation suitability. Furthermore, each indicator score is denoted as follows: STS (soil type score), ES (elevation score), SGS (slope gradient score), DFRd (distance to road network), DFRr (distance to river network), DFRt (distance to settlement areas), DFCA (distance from coffee agroindustry), and FA (forest area). The indicator evaluation process is carried out through a spatial model utilizing Geographic Information Systems (GIS). The mathematical model equation is expressed as:

$$X_i = 0.184STS + 0.186ES + 0.079SGS + 0.146DFRd + 0.079DFRr + 0.083DFRt + 0.082DFCA + 0.161FA$$

The mathematical formulation was used to calculate composite indicator scores that define the suitability level (X_i) at each location. The computation of plantation potential is conducted through a spatial overlay process. Each indicator is overlaid sequentially onto the coffee plantation map; this process produced an integrated thematic map layer containing attribute information for each indicator. Attribute values at specific locations were subsequently converted into ordinal scales, as described earlier. Based on the formulated equation, the total score is calculated to represent the overall suitability level or the potential classification of smallholder coffee plantations, as presented in the following section.

3.4 Classification of coffee plantation suitability levels

The total score analysis indicates that the mapping model was applied to 3,159 spatial records. Based on the previously established equation, the results show that the minimum total score was 1.316, whereas the maximum reached 4.678, as illustrated in Figure 12.

The aggregated total scores served as the basis for classifying the suitability levels of smallholder coffee plantations. As outlined in the Methods section, the classification was divided into three categories, with a CID value of 1.3842. Based on this CID value, the interval thresholds for each suitability class were established, as presented in Table 4. Each plantation area was subsequently assigned to a suitability class according to its calculated value. This classification reflects the number and severity of limiting land characteristics [45]. Referring to the land suitability level of coffee plantations, the classification results indicate that 57.96% of smallholder coffee plantations are located in potential plantation areas; the remaining plantation areas are classified as developing and non-potential categories, as detailed numerically in Table 6.

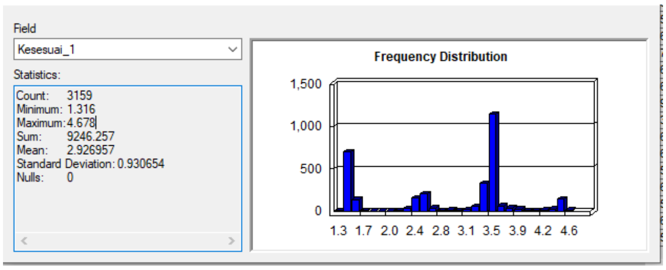

Figure 12. The total score measurement of coffee plantations
Developed by the authors

Table 6. Coffee plantations suitability rate area

Classification	Interval Value	Ares (ha)	Proportion (%)
Non-potential coffee plantation	≤ 2.247	7,925.76	9.32
Developing a coffee plantation	> 2.247-3.393	27,821.43	32.72
Potential coffee plantation	> 3.393	49,286.34	57.96
Total		85.033,53	100

Developed by the authors

Based on the obtained results, it is evident that smallholder coffee plantation areas classified as developing and non-potential require improvement and should receive attention from decision-makers to enhance their potential. Non-potential smallholder coffee plantation areas face constraining factors that hinder their productivity, whereas developing plantation areas are expected to promote better management of smallholder coffee plantations. Therefore, the evaluation of smallholder coffee plantation areas needs to be prioritized to ensure the holistic availability of coffee raw materials and support the sustainability of the coffee industry. In this regard, the role and function of the government in strengthening smallholder coffee plantation enterprises must be emphasized. Spatially appropriate directions for smallholder coffee plantation development should also be considered. Furthermore, this suitability assessment is expected to assist smallholder coffee farmers in understanding the legal status of their land. Overall, the classification map of smallholder coffee plantation suitability levels is illustrated in Figure 13. Through this spatial classification, decision-makers will be directly supported in implementing empowerment programs for smallholder coffee farmers at the right time and in the most appropriate locations.

The model results indicate that 57.96% of the assessment area falls into the "potential" suitability class. This relatively high proportion reflects the agroecological characteristics of Jember Regency, which is historically recognized as a favorable environment for Coffea robusta cultivation. A significant portion of the landscape lies above 600 masl, which aligns with optimal ecological conditions for robusta coffee as reported in regional agronomic studies. Elevation is one of the strongest positive drivers in the model, as confirmed by its high AHP weight. Much of the area is dominated by Andosols and Inceptisols, known for good drainage and organic matter content, and by moderate slope gradients (15–40%), which support perennial crop cultivation in upland regions. Although some agricultural areas are distant from processing centers, the majority remain within an economically viable accessibility range (< 12 km), supporting efficient value-chain integration. This aligns with Jember's well-established coffee processing industry and large downstream capacity. The "potential" classification is consistent with the competitive position of Jember as one of East Java's major robusta producers, supported by dense processing networks, established supply chains, and active smallholder participation. The presence of large-scale agroindustry (i.e., roasting, grinding, and export-oriented intermediaries) enhances the strategic importance of identifying zones for future expansion.

Non-potential coffee plantation covers only 9.32% of the total area. A cross-analysis of spatial overlays indicates that these areas have extreme slopes (> 40%), which are associated with erosion risks, shallow rooting depths, and low mechanization feasibility. The protected forest classification also influences land-use conversions, which are restricted by regulations, thus eliminating the possibility of plantation development regardless of biophysical suitability. Very low accessibility, including areas located >12 km from roads or coffee agro-industry centers, increases production and transportation costs.

A spatial overlay of the eight individual indicator maps (Figures 4-11) confirms that "non-potential" areas tend to show multiple interacting constraints rather than a single limiting factor. Conversely, "potential" areas typically show at least four high-scoring indicators in combination, most commonly: favorable elevation, moderate slopes, suitable soil types, and reasonable proximity to transport and processing facilities. This multi-criteria convergence explains the high proportion of "potential" areas and supports the validity of the classification results.

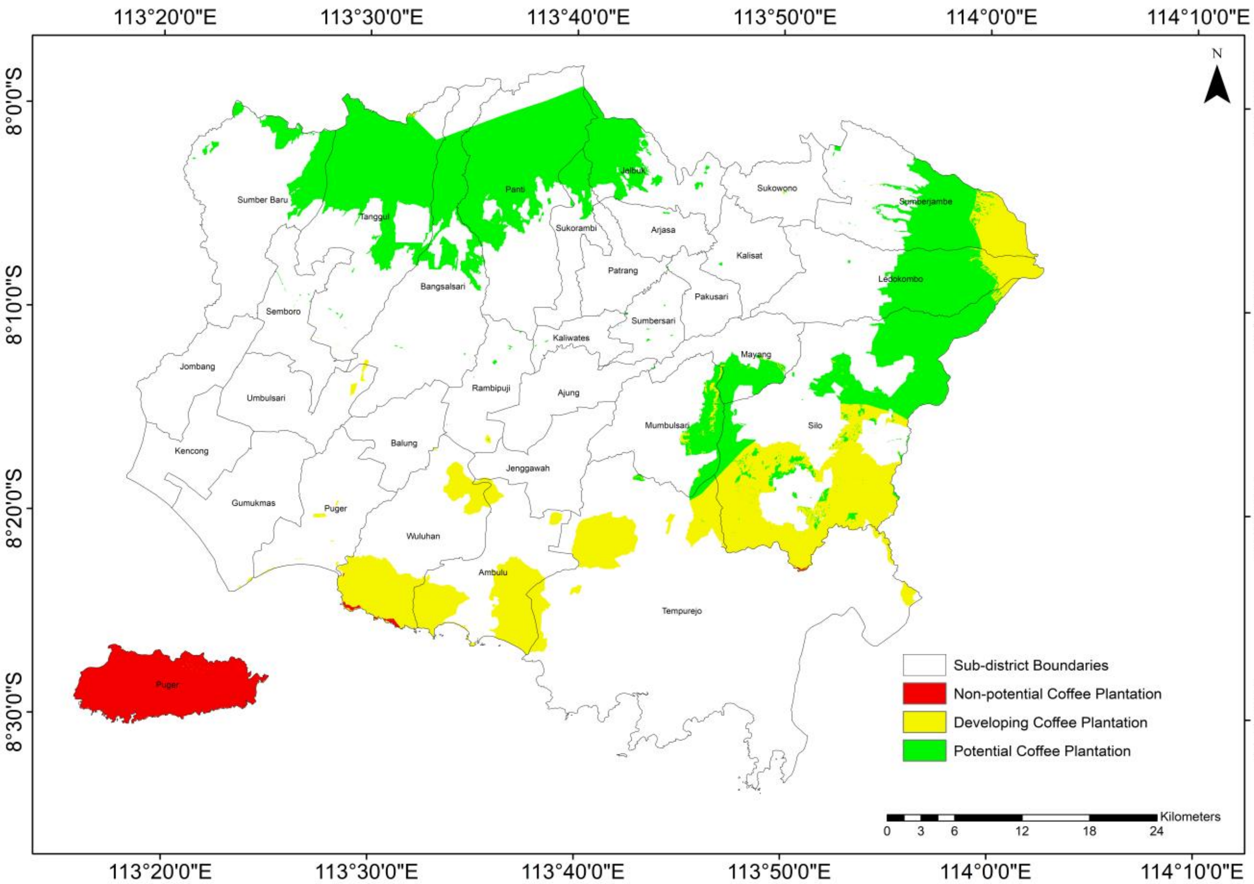

Figure 13. The suitability rate map of smallholder coffee plantations
Developed by the authors

3.5 Managerial implications

The findings of this smallholder coffee plantation suitability assessment are expected to support the strategic development and positioning of smallholder farmers in advancing sustainable coffee production. The spatial-based suitability analysis of smallholder coffee plantations provides a visual representation of plantation conditions with geographic coordinates, which facilitates decision-makers in identifying priorities across key aspects. Considering these critical aspects can help decision makers, particularly local governments, allocate resources more effectively and efficiently toward issues with the greatest potential for improvement. Furthermore, the certification or categorization of smallholder coffee farmers based on land suitability would also be beneficial. Such categorization can provide a foundation for designing targeted or customized intervention programs that more effectively address the specific constraints and criteria associated with each category. These classifications should also be considered within smallholder coffee plantation certification schemes, enabling more structured and well-directed regulatory frameworks for smallholder farmers.

The synergy among various stakeholders needs to become a primary focus through a series of processes aimed at ensuring and strengthening the bargaining position of smallholder coffee farmers. The improvement of smallholder coffee plantation suitability relies on joint support and coordination between private-sector actors and local governments, which ultimately should empower the functions of guidance, facilitation, and supervision. In summary, the current conditions can serve as a foundation for formulating directives to strengthen and enhance the capacity of smallholder coffee farmers at both managerial and strategic levels. At the managerial level, smallholder coffee farmers may need to plan improvements to their plantation profiles and status in order to meet competency standards. In the near term, these efforts can directly improve bargaining capacity and social welfare. Strategically, local governments need to design targeted strengthening measures and objectives based on defined categories. Robust governance mechanisms and cross-sectoral collaboration are critical for addressing the challenges of smallholder coffee farmers through timely and location-specific solutions.

3.6 Limitations and future research

The suitability mapping framework for smallholder coffee plantations remains limited by the exclusion of productivity-related indicators, such as crop age and yield potential. These aspects could not be integrated into the analysis because of data availability limitations. Future research should incorporate such aspects, particularly those that directly influence the suitability of smallholder coffee plantations, through the use of adaptive and continuous data. Subsequent research could generate more comprehensive insights by integrating competitiveness assessments of smallholder coffee farmers supported by quantifiable indicator scales, in order to integrate plantation location suitability with the competitiveness conditions of the farmers. Strategic planning studies are also needed to facilitate informed decision-making and policy formulation focused on empowering smallholder coffee farmers. Further development is needed to embed the complete model within a spatially intelligent decision support system to support adaptive and flexible decision-making processes.

4. CONCLUSIONS

This study introduces an integrated GIS–AHP multi-factor suitability assessment model specifically designed for supporting smallholder coffee production systems in Jember Regency. The key contribution of this study lies in the comprehensive integration of eight spatial indicators: soil type, elevation, slope gradient, road networks, river networks, residential areas, coffee agroindustry locations, and forest area classification into a weighted decision support framework that reflects both scientific knowledge and local expert judgment. The results were classified into three categories of potential levels. The findings indicate that only 57.96% of smallholder coffee plantations are categorized as potential, 32.72% as developing, and 9.32% as non-potential.

The spatial suitability results offer practical, actionable value for regional planners, agricultural agencies, and coffee sector stakeholders. The model identifies clear priority intervention zones where targeted support, infrastructure improvement, or cultivation expansion would yield the greatest benefits for strengthening the downstream coffee value chain. Likewise, the identification of non-potential and developing areas provides essential guidance for resource allocation, risk mitigation, and land use planning aligned with environmental and regulatory constraints.

Future research should prioritize the continuous updating of data used in suitability mapping to reflect dynamic changes in plantation land conditions. In addition, strategic planning studies are needed to support evidence-based decision-making and policy formulation aimed at strengthening smallholder coffee farmers. Furthermore, integrating the complete model into a spatially intelligent decision support system is essential to enhance decision-making efficiency within an adaptive and flexible framework.

ACKNOWLEDGMENT

The author extends sincere gratitude to the Department of Food Crops, Horticulture, and Plantation of Jember Regency; the smallholder coffee farmers of Jember Regency; the Doctor of Agricultural Science Study Program, Faculty of Agriculture, University of Jember; and the University of Muhammadiyah Jember for their invaluable support and contributions to the completion of this research.

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