TAFOA
Trend and Future of Agribusiness
TAFOA 3(1): 39–57
ISSN 3063-1785

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Integrating land suitability assessment and socioeconomic indicators for robusta coffee development

Suko Irawan[1,*]
[1] *Department of Soil Science, Faculty of Agriculture, Universitas Sebelas Maret, Surakarta, Central Java 57126, Indonesia.*
*Correspondence: sukoirawan9@gmail.com

Received Date: December 21, 2025 Revised Date: February 9, 2026 Accepted Date: February 27, 2026

ABSTRACT

Background: Robusta coffee is a strategic commodity supporting rural livelihoods and the national economy. However, average productivity (≈0.7 t/ha/year) remains far below its potential (2.5–3.0 t/ha/year). This gap reflects not only biophysical land constraints but also socio-economic limitations. An integrated assessment combining land suitability and socio-economic conditions is therefore necessary for sustainable development planning. **Methods:** This study was conducted from September 2020 to March 2021 using a descriptive-exploratory and survey approach. Soil samples were analyzed in university laboratories, and biophysical conditions were evaluated using Land Suitability Classification (LSC) through a matching method based on crop requirements. Socio-economic conditions were measured using a Socio-Economic Index (SEI) calculated through min–max normalization (0–1 scale) with equal indicator weighting. LSC and SEI were integrated to assess development potential and readiness. **Findings:** All study sites were classified as S3 (marginally suitable), limited by low organic carbon, poor drainage, and shallow soil depth. SEI values ranged from 0.15 to 0.63, indicating varying socio-economic readiness across villages. The integrated analysis shows that development feasibility depends not only on land characteristics but also on farmers' socio-economic capacity, influencing the sustainability and productivity of robusta cultivation. **Conclusion:** Integrating LSC and SEI provides a comprehensive framework for evaluating regional development potential. Sustainable robusta expansion requires addressing both land limitations and socio-economic empowerment to reduce the productivity gap. **Novelty/Originality of this article:** This study proposes a multidimensional LSC–SEI framework that bridges biophysical and socio-economic dimensions, offering a strategic decision-support model for sustainable agricultural planning.

KEYWORDS: integrated assessment; land suitability class; robusta coffee; socio-economic indicators; sustainability.

1. Introduction

Coffee is a leading plantation commodity that significantly contributes to the national economy, both through job creation, increased export foreign exchange earnings, and strengthening the rural economic structure (International Coffee Organization, 2023). According to data from the Central Statistics Agency (2023a), Indonesian coffee production reached 729,000 tons in 2018, or approximately 8% of total global coffee production. Of this total, 534,000 tons were robusta coffee, while 194,000 tons were arabica coffee. Based on data from the Ministry of Agriculture (2023), the structure of coffee plantation businesses in Indonesia is still dominated by smallholder plantations, which cover approximately 98% of the total national coffee area or equivalent to 1.25 million hectares, with a production

Cite This Article:
Irawan, S. (2026). Integrating land suitability assessment and socioeconomic indicators for robusta coffee development. *Trend and Future of Agribusiness, 3*(1), 39-57. https://doi.org/10.61511/tafoa.v3i1.2026.3125

contribution reaching 99.3% of the total national output of 780 thousand tons, unfortunately, the competitiveness of coffee productivity in Indonesia is still relatively low, which is around 0.7 tons per hectare, far below coffee productivity in neighboring countries such as Vietnam which is able to reach 2.7 tons per hectare (International Coffee Organization, 2023). The low productivity of Indonesian coffee is not solely due to one dominant factor but is caused by multidimensional factors that include the biophysical conditions of the land, cultivation systems and the socio-economic structure of farmers who are still conventional. This factor then becomes the dominant obstacle in efforts to increase Indonesian coffee productivity, Septiani & Kawuryan (2021) added that cultivation by smallholder plantations relying on local seeds (native seeds) and minimal rejuvenation of coffee plants has an impact on production which tends to stagnate or even decline. This low productivity reflects a structural gap between the potential of land resources and the technical, social, and economic capabilities of farmers in managing coffee farming. This situation demonstrates that efforts to increase national coffee productivity and quality cannot be carried out partially but must be integrated with other factors such as strengthening institutional capacity, financing systems, and transparency within the national coffee value chain. Slob (2006) explains that weak institutional roles and supply chain governance are often the main sources of inefficiency and disparities in economic value received by farmers, which has implications for declining farmer interest in improving coffee farming management. Zailani & Ibrahim (2010) add that the final quality of an agricultural product is determined by complex interactions between actors in the value chain, from farmers, collectors, exporters, to the processing industry. Each actor in the chain plays a role in establishing quality standards, distribution efficiency, and price stability at the farm level. Furthermore, technical factors such as land degradation and limited farmer access to capital, technology, and markets also exacerbate coffee farming (Irawan et al., 2022). This situation demonstrates that sustainable coffee production cannot be achieved solely through increased land productivity, but also requires socio-economic and institutional interventions capable of strengthening the position of smallholder farmers in the coffee supply chain. Therefore, coffee development, particularly robusta, in areas such as Nawangan District is crucial to strengthen the local economic base and increase the competitiveness of Indonesian commodities in the local market.

Robusta coffee (Coffea canephora) has comparative advantages over Arabica coffee, particularly in terms of ecological adaptability and production efficiency. This variety is known for its high tolerance to hot temperatures, relatively higher productivity, and natural resistance to leaf rust (Hemileia vastatrix), a frequent threat to Arabica coffee plantations (Acihmah et al., 2024; Amrulloh et al., 2024). These advantages make robusta more suitable for cultivation in humid tropical regions at mid-altitudes such as East Java and southern Sumatra. Increasing the productivity and sustainability of robusta coffee cultivation systems is a strategic step in strengthening regional economic resilience and the welfare of smallholder farmers. The development of robusta coffee also has an accelerative function to provide employment and sources of income for rural communities, thereby encouraging local economic growth, strengthening agricultural-based industries, and alleviating structural poverty (Beenhouwer et al., 2013; Singer & Thorbecke, 1971).

Among the robusta coffee-producing regions in Indonesia, Pacitan Regency in East Java Province is one of the centers, with Nawangan District as a major producer. Agro-ecologically, this region has characteristics that support coffee growth, such as an altitude of 400–800 meters above sea level and relatively high annual rainfall (Central Statistics Agency, 2019, 2025). Data on land area and coffee production in Pacitan Regency, particularly in Nawangan District, are presented in figure 1, which illustrates the region's strategic position as a regional center for robusta coffee development.

Based on figure 1, Nawangan District has dominated both planted area and coffee production in past two years. In 2023, Nawangan's coffee area reached approximately 700 hectares, producing over 130 tons. In 2024, the planted area remained relatively stable with a slight increase in productivity. This achievement places Nawangan far ahead of other districts, such as Bandar (approximately 520 hectares) and Kebonagung (250 hectares), which rank second and third in terms of coffee production contribution in Pacitan (Central Statistics Agency, 2020, 2023b). Sarvina et al. (2023) stated that changes in environmental factors, such as temperature, rainfall patterns, and coffee plant root conditions, significantly affect land suitability classes.

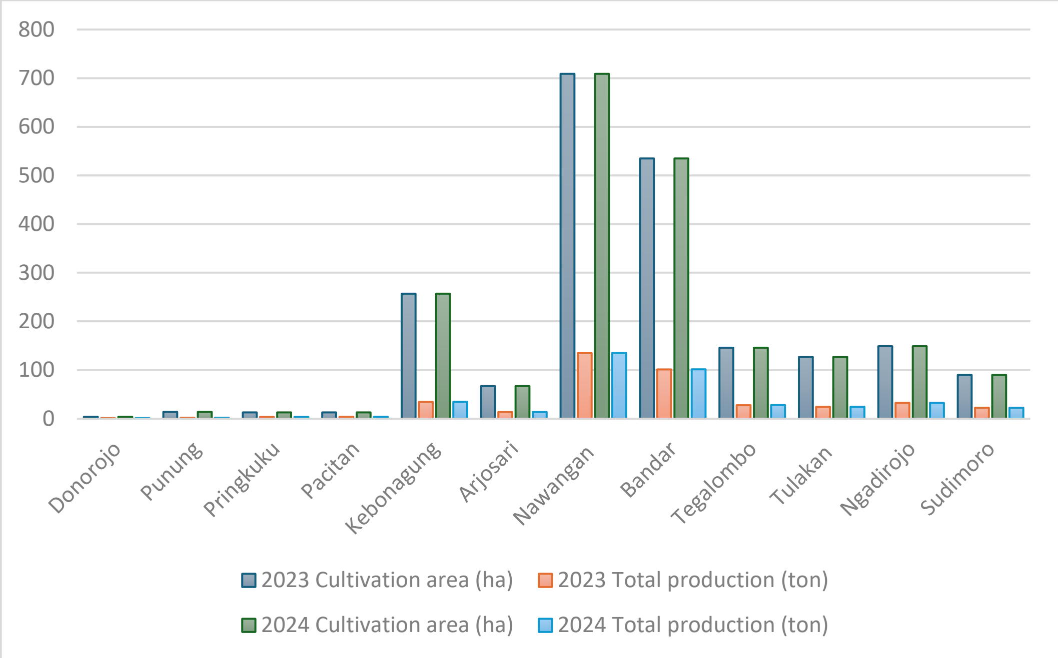

Fig 1. Coffee land area and production from 2023 to 2024
(Central Statistics Agency, 2025)

However, potential has not been fully utilized optimally due to the imbalance between land suitability and farmers' socio-economic preparedness (Pratiwi et al., 2023; Solihah et al., 2024). Domestic agricultural development is influenced not only by production factors but also by broader linkages between consumption patterns, income, and investment in non-agricultural sectors. Beyond land investment, the availability of market access, health facilities, population size, and other social factors play a crucial role in determining the extent to which the agricultural sector can transform and contribute to community welfare. Nugraha et al. (2021) add that improving land quality must go hand in hand with strengthening the social and institutional capacity of farmers, so that commodity development not only increases productivity but also strengthens the economic and social resilience of communities in a sustainable manner.

On the one hand, it cannot be denied that biophysical characteristics are a key determinant of successful coffee development. Research by Irawan et al. (2023) shows that inappropriate land use can reduce soil functionality in supporting plant growth, water regulation, and environmental buffering. Thus, this evaluation is necessary to support long-term planning for the development of superior commodities. Therefore, land suitability evaluation is applied to assess the level of compatibility between biophysical characteristics and the growth requirements of robusta coffee plants. This is crucial for developing an effective commodity development strategy to achieve optimal production results.

Furthermore, socio-economic factors also play a crucial role in determining the level of technology adoption, productivity, and sustainability of coffee farming. According to Nelson (2004) and DFID (1999), social and economic indicators need to be integrated in land suitability evaluations to assess livelihood capability and institutional readiness in a region. In the context of sustainable agricultural development, the synergy between biophysical and socio-economic factors is crucial, as the success of a production system is determined not only by soil and climate conditions but also by the community's ability to manage available resources (Heumann, 2012; Zakarya et al., 2021; OECD, 2020). Therefore, a study on the integration of land suitability and socio-economic conditions is necessary for formulating strategies in Nawangan District. Therefore, this study combines biophysical indicators (BIP) with socio-economic indicators (ISE) to develop a priority coffee development program that is realistic and contextual to the conditions of farmers in Nawangan District.

2. Methods

2.1 Study area and research period

This research was conducted in Nawangan District, Pacitan Regency, East Java. Soil analysis was carried out at the Soil Physics and Conservation Laboratory and the Soil Chemistry and Fertility Laboratory, Faculty of Agriculture, Sebelas Maret University, Surakarta. The study was conducted from September 2020 to March 2021. The research location is shown in figure 2 below. This location was selected due to its significant potential for robusta coffee development, as well as the presence of varying biophysical and socio-economic conditions that are relevant to the objectives of this study.

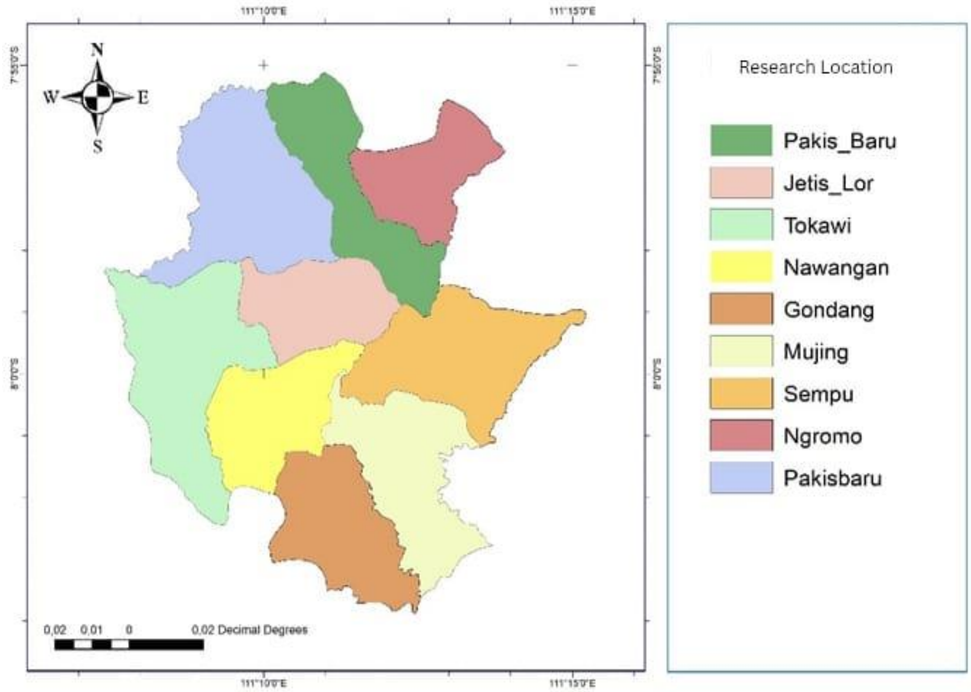

Fig 2. Research location in Nawangan District

2.2 Research design and data collection

The method used in this research was a descriptive exploratory method with a survey approach. The survey was conducted through direct field observations, followed by soil sampling for laboratory analysis. Furthermore, the analytical methods used in this study are presented in table 1 below.

Table 1. Indicators and methods

Indicator	Methods
C- organic soil	Walkey and Black
Base Saturation	Ammonium acetate extraction
KTK	Ammonium acetate extraction
pH	Electrometric
Texture	Pipettes
P_2O_5	Bray/Olsen
K_2O	Ammonium acetate extraction

Other indicators, such as temperature, soil depth, drainage, coarse material content, and slope gradient, were measured through field observations. These measurements were conducted directly at each observation point using standard field assessment techniques to ensure data accuracy and consistency. Soil depth was determined using manual probing, while slope gradient was measured using a clinometer. Drainage conditions and coarse material content were evaluated based on visual field characteristics. These indicators are essential in determining land suitability, as they directly influence root development, water availability, and overall crop productivity.

2.3 Land Suitability Evaluation (LSC)

Collected laboratory and field analysis data were then compared with specific growing requirements for robusta coffee plants (Ritung et al., 2011). This process aims to identify the extent to which land characteristics, such as physical and chemical soil properties, climate, and topography, meet optimal criteria. The next step is to justify the weighted scores for the Land Suitability Class analysis. This weighting is a critical step carried out by researchers, empirically based on the limiting factors identified as dominant at each study location. These limiting factors, such as nutrient deficiencies or poor drainage conditions, will receive higher weighting due to their significant impact on coffee productivity and sustainability. The land suitability class weighting table is presented below.

Table 2. Land suitability class weighting

Land suitability class	Weighting
S1	1
S2	0.75
S3	0.5
N	0.25

2.4 Socio-economic data and indicators

Socio-economic indicators were selected based on the availability of secondary data and their relevance to robusta coffee development (Tatis Diaz et al., 2022). The types of secondary data used in this study are presented in table 3 below. These data include various indicators that reflect demographic conditions, economic capacity, and institutional support relevant to agricultural development.

Table 3. Social and economic indicator aspects

Social Aspects	Indicators	Characteristic
Social	Number of residents	POS (+)
Social	Number of farmer groups	POS (+)
Economic	Number of health facilities	POS (+)
Economic	Distance to market (km)	NEG (−)
Economic	Number of markets	POS (+)
Economic	Number of agricultural shops	POS (+)
Economic	Number of financial institutions	POS (+)
Social Aspects	Coffee productivity (tons/ha)	POS (+)
Social	Coffee area (ha)	POS (+)

Each indicator was categorized as positive (+) or negative (−). Positive indicators indicate that higher values improve socio-economic conditions, while negative indicators (e.g., distance to market) indicate that lower values are more favorable. This classification ensures that all indicators are interpreted consistently during the normalization process, allowing for a more accurate comparison across variables. By distinguishing the direction of influence, the analysis can better reflect real socio-economic conditions and avoid bias in the calculation of the Socio-Economic Index (SEI).

2.5 Data normalization and weighting

Data normalization was performed to standardize different units and scales of indicators into a comparable range (0–1). This process used the min–max normalization method (Jain et al., 2005). This approach transforms all indicator values into a uniform scale, enabling proportional comparison and integration across variables with different measurement units, such as kilometers, hectares, and population size. As a result, no single indicator disproportionately influences the analysis due to differences in magnitude, ensuring a more balanced and objective calculation of the Socio-Economic Index (SEI). As a result, no single indicator disproportionately influences the analysis due to differences in magnitude, ensuring a more balanced and objective calculation of the Socio-Economic Index (SEI), where positive indicators (+) use Equation (1) and negative indicators (−) use Equation (2).

$$Xi = \frac{Xij - Xjmin}{Xjmax - Xjmin} \quad \text{(Eq. 1)}$$

$$Xi = \frac{Xjmax - Xij}{Xjmax - Xjmin} \quad \text{(Eq. 2)}$$

Where Xi is the normalized value, Xij is the value of indicator j in village i, $Xjmin$ is the minimum value, and $Xjmax$ is the maximum value. This formulation ensures that all indicator values are proportionally rescaled within the same range, facilitating consistent comparison across different variables. Each indicator was assigned equal weight to maintain objectivity: this approach assumes that all selected indicators have an equal level of importance in influencing socio-economic conditions, thereby minimizing subjectivity in the weighting process and ensuring a fair representation of each variable in the overall analysis.

$$w = \frac{1}{n} \quad \text{(Eq. 3)}$$

Where n is the number of indicators. This means that the total weight is evenly distributed among all variables, so that each indicator contributes equally to the final Socio-Economic Index (SEI) calculation without prioritizing any specific factor. Furthermore, this method enhances the transparency and reproducibility of the analysis by applying a simple and consistent weighting scheme across all indicators.

2.6 Socio-Economic Index (SEI) calculation

The Socio-Economic Index (SEI) was calculated using a weighted aggregation of normalized indicators. This approach allows multiple socio-economic variables to be integrated into a single composite value that represents overall conditions at the village level. It also simplifies the comparison between different villages by providing a standardized index score.

$$ISE_i = \sum_{j=1}^{n} Wj \; x \; Xij \quad \text{(Eq. 4)}$$

where ISE_i is the socio-economic index of village i, Wj is the weight of indicator j, and Xij is the normalized value. This formulation ensures that each indicator contributes proportionally according to its assigned weight in the aggregation process. As a result, the final SEI value reflects the combined influence of all indicators in a balanced and systematic manner.

2.7 Integration of LSC and SEI

The integration of land suitability and socio-economic conditions was conducted using linear weighting. This method enables the combination of different dimensions into a single composite score that reflects overall development potential. It also allows for a more systematic comparison between areas by incorporating both environmental and socio-economic factors simultaneously.

$$Score = 0.65 \times KKL + 0.35 \times ISE \quad \text{(Eq. 5)}$$

Where KKL represents the Land Suitability Class and ISE represents the Socio-Economic Index. This integration provides a comprehensive assessment by combining biophysical and socio-economic aspects. The higher proportion assigned to KKL reflects the dominant role of land characteristics in determining agricultural feasibility, while the ISE captures the supporting capacity of local communities. As a result, the final score can be used as a basis for prioritizing areas for sustainable robusta coffee development.

2.8 Classification and interpretation

The integration results were classified into three categories based on score ranges, as shown in table 4. This classification aims to simplify the interpretation of composite scores and facilitate decision-making in determining development priorities. It also helps stakeholders identify areas with high potential, moderate readiness, and those requiring significant intervention.

Table 4. Classification and interpretation of integration results

Category	Range	Interpretation
High	≥ 0.75	High socio-economic readiness
Medium	0.50 – 0.74	Potential, but still requires institutional and infrastructure intervention
Low	< 0.50	Low socio-economic capacity; requires empowerment programs and improvements to basic facilities

2.9 Weighting justification

The weighting proportion of 65% for land suitability and 35% for socio-economic factors is based on multi-criteria evaluation principles. Land suitability is considered the primary determinant of agricultural success, while socio-economic factors support technology adoption and sustainability (Bazkiaee et al., 2024; Chari et al., 2023). This approach enables a balanced assessment of land potential and socio-economic readiness for robusta coffee development in Nawangan District.

3. Results and Discussion

3.1 Social and economic characteristics

The social and economic characteristics of farmers in Nawangan District are presented in the table below. In developing coffee farming businesses, the socio-economic factors used are based on the aspects of secondary data availability and relevance to coffee farming business development. These factors help identify key constraints and opportunities for improving farmers' productivity and livelihoods.

Table 5. Social and economic indicators

Village	Market Distance (km)	Wide (ha)	Production (ton)	Resident	Farmer groups	Farm shop	Market	Financial institutions	Health facilities
Gondang	6.3	41	6.4	4,784	1	0	3	2	0
Jetis Lor	1.9	130	21.7	7,544	4	0	0	0	1
Mujing	1.6	41	5.4	6,380	1	0	4	3	0
Nawangan	1	38	7.8	6,194	1	2	4	1	2
Ngromo	8.2	91	19	6,151	2	0	1	0	0
Pakisbaru	7.6	100	18.5	4,501	3	0	3	1	0
Penggung	8.6	85	15.9	6,894	3	0	2	2	0
Sempu	2.4	34	8	5,406	1	0	1	0	0
Tokawi	10.3	127	20.5	4,494	3	0	4	0	0

Market distance (km) is a crucial aspect in socio-economic analysis. It directly impacts the efficiency of product distribution, transportation costs, and farmers' access to the market value chain. The closer the distance between farmland and the main market, the lower the logistics costs incurred by farmers, thus increasing their profit margins. Nawangan has the shortest distance (1 km) compared to other villages, while Tokawi and Penggung villages have the longest distances, with over 8 km to reach the sub-district center. Long market distances can be a major limitation in the development of commodities like coffee, especially in areas with inadequate transportation infrastructure. This condition often leads to price disparities between farmers and traders due to high transportation costs and limited and uneven distribution of harvested produce.

Land area (ha) and coffee production (tons) reflect the economic capacity of agriculture and the level of land intensification. Jetis Lor, Tokawi, and Ngromo have the highest production (>18 tons) and land area of >90 ha, which is a key factor in robusta coffee development. Furthermore, population density and the number of farmer groups reflect the potential workforce and social cohesion of a community. Furthermore, population density and the number of farmer groups serve as indicators of the potential workforce and the strength of social cohesion within a farming community (Prilierdi et al., 2015; Wulandari et al., 2012). Jetis Lor Village has the largest number of farmer groups (four groups) and the highest population (7,544 people), reflecting strong social institutional capacity and the potential for faster innovation adoption. In contrast, Gondang and Sempu only have one farmer group, indicating limited farmer institutions and knowledge diffusion among members. This situation aligns with the findings of Rosanti et al. (2019), who showed that farmers with stronger economic conditions have a greater capacity to rejuvenate crops and adopt innovations, while farmers with limited capital often lag behind in accessing new technologies.

The challenges in strengthening farmer institutions are also explained by Sukayat et al. (2023), who emphasize that social capital and farmer organizations are key factors in increasing efficiency, expanding market access, and accelerating sustainable agricultural transformation. In the context of Nawangan, the existence of active farmer groups can act as collective learning institutions and bridges between farmers and external institutions, such as the agricultural office, financial institutions, and markets. Therefore, strengthening the institutional capacity of farmers in villages with low ISE is a critical priority to ensure that the entire region can move towards a more inclusive, resilient, and sustainable coffee production system. Villages that lack agricultural shops and adequate market access, such as Tokawi and Ngromo, require strategic interventions to provide production inputs and access to farm financing. Limited access to agricultural inputs and financial institutions prevents farmers in these areas from optimally intensifying and rejuvenating their crops, while successful coffee cultivation is largely determined by the availability of inputs such as superior seeds, fertilizers, pesticides, and plant maintenance support tools (Yan et al., 2016). Without this support, farmers can only maintain productivity at a subsistence level, rather than increasing the commodity's competitiveness in the market.

Furthermore, (Pratiwi et al., 2020 and Worku et al., 2022) emphasize that the sustainability of the coffee industry at the grassroots level must be integrated with the principles of sustainable agriculture, namely utilizing organic materials and local agricultural waste to reduce dependence on chemical inputs that negatively impact the environment. This approach is relevant for Nawangan, given that most farmers still have limited access to industrial fertilizers and rely more on local resources. From a socio-economic perspective, limited access to production inputs and financial institutions also hinders the role of farmer institutions as agents of change. Raharjo et al. (2020) explain that strengthening farmer capacity through capital support, extension services, and market partnerships can directly increase farmer productivity, income, and welfare. Thus, increasing the contribution of the coffee sector in Nawangan depends not only on land potential but also on the effectiveness of socio-economic support systems that bridge farmers with markets and financing sources.

In terms of health care provision, Nawangan and Jetis Lor Villages have relatively better facilities than other villages in Nawangan District. The availability of health facilities is not only an indicator of public services but also plays a direct role in determining the sustainability of the farm workforce and the social well-being of farming communities. Access to adequate health services enables farmers to maintain work productivity, reduce vulnerability to work-related diseases, and maintain family economic stability. In the context of sustainable agricultural development, the health of farming communities is an often-overlooked dimension despite its crucial role in the efficiency of agricultural systems. Furthermore, Nugraha et al. (2021) emphasize that social aspects such as health and education serve as productive social capital, accelerating technology adoption and strengthening farmer institutional networks. Therefore, differences in the quality of health facilities between villages in Nawangan could be a differentiating factor in the level of socio-economic readiness (ISE), with villages with better health services having a greater opportunity to support sustainable coffee farming transformation.

3.2 Land suitability characteristics

The characteristics of land suitability for robusta coffee plants are presented in table 6 below, and these characteristics are in accordance with FAO guidelines (FAO, 2007). These criteria include key biophysical factors such as climate conditions, soil properties, and topography that influence coffee growth and productivity. Furthermore, the use of standardized FAO guidelines ensures that the evaluation is consistent and comparable with other land suitability studies. This framework provides a reliable basis for assessing the potential of the study area for robusta coffee cultivation.

Rooting media (rc) criteria showed variation, particularly in texture, which was dominated by clay and silty clay loam (Tokawi), which generally has implications for optimal water and nutrient retention capacity. Research by Irawan et al. (2022) showed that rooting criteria (rc) significantly influence water availability. This is because clay texture has a greater number of micropores than other soil textures, allowing for higher water storage capacity. Coarse material in all locations is relatively low (<15), while soil depth (cm) ranges from 50-75 cm to 75-100 cm, which is quite suitable for coffee plants. Most of the land in Nawangan has a clay texture with a moderate to high cation exchange capacity (CEC), which indicates nutrient absorption capability. The soil CEC value (cmol) varies quite significantly, from 8.77 (Nawangan) to 16.14 (Pakisbaru). Furthermore, CEC indicates the soil's ability to retain and provide nutrients such as Ca^{2+}, Mg^{2+}, and K^{+} (Sato et al., 2003). The relatively high cation exchange capacity reflects optimal soil chemical fertility at the study sites, particularly in locations with higher clay and organic matter content.

Table 6. Land criteria

Criteria	Location								
	1	2	3	4	5	6	7	8	9
Temperature (tc)									
Average temperature (°C)	22.06	22.4	22.4	22.11	22.11	22.33	22.08	22.08	20.1
Water availability (wa)	1,756	1,756	1,756	1,756	1,756	1,756	1,756	1,756	1,756
Rainfall (mm)									
Dry period duration (months)	3	3	3	3	3	3	3	3	3
Humidity	81.83	81.83	81.83	81.83	81.83	81.83	81.83	81.83	81.83
Oxygen availability (oa)									
Drainage	Currently	Currently	Currently	Somewhat hampered	Somewhat hampered	Somewhat hampered	Currently	Currently	Currently
Rooting medium (rc)									
Texture	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Silty clay loam
Coarse matter (%)	<15	<15	<15	<15	<15	<15	<15	< 15	< 15
Soil depth (cm)	75-100	50-75	50-75	75-100	75-100	50-75	75-100	75-100	75-100
Nutrient retention (nr)									
Soil CEC (cmol)	14.73	12.81	13.73	8.77	10.57	16.14	15.39	14.29	14.94
Base saturation (%)	33.32	46.3	41.67	63.5	52.24	52.05	38.19	50.16	35.72
pH H2O	5.2	5.36	5.54	6.61	6.67	6.51	5.51	5.9	5.8
Organic C (%)	0.61	1.6	0.18	0.29	0.29	6	0.24	0.6	1.12
Available nutrients (na)									
Total nitrogen (%)	0.36	0.27	0.19	0.19	0.18	0.41	0.21	0.23	0.29
P2O5 (mg/100 g)	0.33	0.32	0.94	0.72	0.73	0.74	0.73	0.77	0.71
K2O (mg/100 g)	1.26	0.92	0.86	1.08	1.06	1.43	0.82	0.81	1.01
Erosion hazard (eh)									
Slope (%)	8-15%	8-15%	8-15%	8-15%	8-15%	<8	<8	<8	8-15%
Erosion hazard	Mild-Moderate	Mild-Moderate	Mild-Moderate	Mild-Moderate	Mild-Moderate	Very light	Very light	Very light	Very light

Description: 1 = Gondang; 2 = Jetis Lor; 3 = Mujing; 4 = Nawangan; 5 = Ngromo; 6 = Pakisbaru; 7 = Penggung; 8 = Sempu; 9 = Tokawi.

Base saturation (BSC) values at all sites were generally high (>30%), indicating the dominance of base cations in the soil cation exchange complex. The Nawangan (63.5%) and Ngromo (52.24%) locations had the highest base saturation, indicating that most of the exchange sites were occupied by Ca and Mg ions, thus ensuring relatively fertile soils (Juhos et al., 2019). Base saturation can also be interpreted as an indicator of the high or low levels of hydrogen ion concentration in the soil (pH), although most soils had a slightly acidic to neutral pH (5.2–6.67). This pH range is still within the optimal range for robusta coffee growth, which generally grows optimally at a pH of 5.0–6.5. This indicates that soil acidity in Nawangan has not yet become a major limitation for robusta coffee development. Furthermore, all locations had relatively low organic carbon values, ranging from 0.16–

1.12%. The availability of macronutrients such as nitrogen (N), phosphorus (PO_2), and potassium (K_2O_5) was also still low to moderate. Some locations, such as Pakisbaru and Penggung, had slightly better levels, but overall, phosphorus deficiency remained the main limiting factor. It should be noted that phosphorus is crucial for flower formation and fruit filling in coffee plants. This situation underscores the importance of balanced fertilization based on soil test results, so that each location receives the appropriate fertilizer dosage for its specific needs.

Morphologically, soil depth in most locations is still generally adequate (50–100 cm); however, locations with shallower depths require caution, as they can limit lateral root growth, reduce the plant's ability to access water, and affect nutrient uptake during the dry season. Nevertheless, slopes of 8–15% in most areas are considered relatively safe, posing only a mild to moderate risk of erosion if proper management is applied. Implementing conservation practices, such as planting cover crops, applying organic mulch, and maintaining vegetation buffers, can significantly help preserve soil stability, enhance water retention, and reduce nutrient loss caused by rainwater runoff (Irawan & Antriyandarti, 2021; Maja et al., 2017; Ngangom et al., 2020). These measures are essential to ensure sustainable soil productivity and support healthy crop growth in the long term.

Table 7. Potential land classes and improvement efforts

Location	Actual class	Limiting factors	Improvement efforts	Potential class
Gondang	S3- na	P_2O_5, K_2O	b,d,e,f	S3
Jetis Lor	S3- rc, nr, na	Soil depth, C-org, P_2O_5, K_2O	b,d,e,f, g	S3-rc
Mujing	S3-rc, na	Drainage, C-org, P_2O_5, K_2O	b,d,e,f, g	S3-rc
Nawangan	S3- oa, nr, na	Drainage, C-org, P_2O_5, K_2O	b,d,e,f, g	S3
Ngromo	S3- oa, nr, na	Drainage, soil depth, P_2O_5, K_2O	b,d,e,f, g	S3
Pakisbaru	S3- oa, nr, na	Drainage, soil depth, P_2O_5, K_2O	b,d,e,f, g	S3
Penggung	S3-nr, na	C-org, P_2O_5, K_2O	b,d,e,f	S3
Sempu	S3-nr, na	C-org, P_2O_5, K_2O	b,d,e,f, g	S3
Tokawi	S3-na	P_2O_5, K_2O	d,e,f, g	S3

Notes: a = irrigation; b = organic fertilization; c = liming; d = NPK; e = SP36; f = KCl; g = mechanical intervention (Darsowiyono et al., 2023).

Based on the land suitability evaluation, all observation locations in Nawangan District fall into the S3 (marginally suitable) class for robusta coffee. This indicates that the land can still be used for coffee cultivation with appropriate interventions. Overall, Nawangan District has significant potential for sustainable coffee development if efforts are made to improve organic matter, increase phosphorus and potassium availability, and manage drainage and water conservation. With adaptive land management and modern conservation techniques, even marginal land can be optimized into a productive ecosystem supporting both economic and environmental sustainability. The land suitability class evaluation results are presented in the table above.

Based on table 7, the dominant limiting factors at the research site were drainage, low organic matter (C-organic) content, and relatively low availability of phosphorus (P) and potassium (K) nutrients. These conditions affect the efficiency of plant nutrient absorption and coffee root development. In several locations, such as Jetis Lor, Ngromo, and Pakisbaru, an additional limitation was also found in the form of relatively shallow soil depth. The results of research by Darsowiyono et al., (2023) showed that improvement efforts such as irrigation, drainage, addition of organic matter, liming, nitrogen fertilization, phosphate rock fertilization, potassium fertilization, and the creation of ridges/terraces made the actual conditions at the research site quite suitable (S2). Gondang, Tokawi, and Penggung villages are classified as having lighter constraints (S3–na and S3–nr,na) so that effective and efficient fertilization efforts can increase, which is mainly due to low levels of P and K nutrients. Meanwhile, Nawangan, Mujing, and Pakisbaru villages face double constraints in the form of drainage, soil depth, and nutrient retention, making them more vulnerable to decreased productivity. Thus, land improvement efforts through the addition of organic matter, micro-drainage improvement, and balanced fertilization (N, P, K) are very necessary to increase the potential suitability class to S2 (moderately suitable). Overall, the characteristics of the land in Nawangan District still have the potential to be developed as a robusta coffee center, especially if integrated soil fertility management and land conservation are carried out to support sustainable production.

3.3 Socio-Economic Index

The Socio-Economic Index (SEI) is used to assess the level of social and economic preparedness of the community to support robusta coffee development in Nawangan District. This index is constructed from several indicators relevant to farmer conditions, including population, farmer groups, health facilities, agricultural shops, distance to markets, number of markets, financial institutions, productivity, and coffee area (Taghizadeh-Mehrjardi et al., 2020). Each indicator is categorized based on its direction of influence, namely positive (the larger the better) or negative (the smaller the better, such as distance to markets). All data are normalized to a 0–1 scale using the min–max normalization method to equalize units between variables. The results of the normalization and analysis of socioeconomic aspects are presented in table 8 below.

Table 8. Results of socio-economic indicator analysis

Location	Market Distance (km)	Wide (ha)	Production (ton)	Resident	Farmer groups	Farm shop	Market	Financial institutions	Health facilities	ISE
Gondang	0.03	0.01	0.01	0.01	0.00	0.00	0.08	0.07	0.00	0.20
Jetis Lor	0.08	0.10	0.15	0.10	0.15	0.00	0.00	0.00	0.05	0.63
Mujing	0.08	0.01	0.00	0.06	0.00	0.00	0.10	0.10	0.00	0.35
Nawangan	0.09	0.00	0.02	0.06	0.00	0.10	0.10	0.03	0.10	0.50
Ngromo	0.01	0.06	0.13	0.05	0.05	0.00	0.03	0.00	0.00	0.33
Pakisbaru	0.02	0.07	0.12	0.00	0.10	0.00	0.08	0.03	0.00	0.42
Penggung	0.01	0.05	0.10	0.08	0.10	0.00	0.05	0.07	0.00	0.45
Sempu	0.07	0.00	0.02	0.03	0.00	0.00	0.03	0.00	0.00	0.15
Tokawi	-0.01	0.10	0.14	0.00	0.10	0.00	0.10	0.00	0.00	0.43

The results of the Socio-Economic Index (ISE) analysis indicate disparities in social and economic readiness among villages in Nawangan District in supporting sustainable robusta coffee development. ISE values range from 0.15 to 0.63, indicating fundamental differences in social capacity, farmer institutions, and access to economic infrastructure and health services. Villages with high ISE values generally have strong social networks, active farmer groups, and good access to markets, production facilities, and health facilities. These readiness aspects certainly play a crucial role in driving local economic activity centers. Jetis Lor Village (0.63) and Nawangan (0.50) occupy the highest positions in the ISE category. These two villages demonstrate mature social and economic readiness, reflected in high coffee productivity, geographical factors of distance to trade centers, and strong institutional support. For example, Jetis Lor, with four active farmer groups and an annual coffee production of 21.7 tons, and Nawangan, with better access to agricultural inputs, markets, and facilities, have the potential to become centers for the development and dissemination of robusta coffee agricultural innovations. This aligns with the findings of Heron et al. (2018), who emphasized that the success of smallholder coffee development is strongly influenced by the functioning of local institutions and effective market connectivity.

Meanwhile, Mujing Village (0.35), Pakisbaru (0.42), Penggung (0.45), and Tokawi (0.43) fall into the medium category. These four villages have promising economic potential based on their relatively high land area and coffee production volume, but still face structural limitations in terms of institutional and social infrastructure. Some have established local markets and village financial institutions, but agricultural inputs and the number of farmer groups are still minimal, limiting the diffusion of innovation and access to the coffee value chain. These villages have the potential to advance to the high category with targeted interventions, such as strengthening farmer institutional capacity, providing agricultural input facilities, and access to microfinance. According to Parmawati et al. (2023), institutional factors play a strategic role in increasing production efficiency, farmer participation, and the economic resilience of coffee communities at the local level.

On the other hand, Gondang Village (0.20), Ngromo (0.33), and Sempu (0.15) exhibit low ISE values. This reflects social and economic vulnerability due to the lack of active farmer organizations, relatively long distances to markets (more than 6 km), and limited access to social facilities such as financial institutions and health services. This phenomenon indicates that spatial accessibility is a determining factor in the socio-economic preparedness of coffee farmers. Villages closer to the sub-district center, such as Jetis Lor, Mujing, and Nawangan, generally have higher ISE values, indicating a positive relationship between geographic access to markets and public facilities and the adaptive capacity of farming communities. Thus, the spatial pattern of ISE in Nawangan District indicates that socio-economic inequality stems not only from institutional factors but also from limited regional infrastructure and spatial accessibility. Therefore, coffee development policy interventions must be implemented differentially across regions, focusing on strengthening farmer institutions in marginalized areas, developing village market networks, and improving the quality of social infrastructure such as agricultural shops, financial institutions, and health services. Such a region-based approach can increase the socio-economic resilience of smallholder farmers while strengthening the foundations of a sustainable robusta coffee production system in Nawangan District.

3.4 Integration of socio-economic indices with land suitability classes

The integration of the Socio-Economic Index (SEI) analysis results with the Land Suitability Evaluation (LACE) was conducted to obtain a more comprehensive picture of the potential for robusta coffee development in Nawangan District. This approach is crucial because the success of agricultural commodity development is determined not only by the biophysical suitability of the land but also by the community's socio-economic readiness to manage existing resources. Through this integrative approach, the analysis results not only indicate areas physically suitable for coffee cultivation but also identify villages most socially and economically prepared to be developed as coffee production centers. The results of the analysis are presented in table 9 below.

Within this analytical framework, a weight of 0.65 is assigned to biophysical aspects (MPA) and 0.35 to socio-economic aspects (ISE). This proportion is based on the justification that soil, climate, and physical land conditions remain the primary determinants in determining crop suitability. Meanwhile, socio-economic aspects act as supporting or enabling factors, strengthening the sustainability of production systems through access mechanisms, institutions, and local economies.

Table 9. Results of integration of land suitability classes with socio-economic indexes

Location	Land suitability			Socio-economic			SESI	Class
	KKL	Weighting	Result	ISE	Weighting	Result		
Gondang	0.55	0.65	0.36	0.20	0.35	0.07	0.43	Low
Jetis Lor	0.45	0.65	0.29	0.63	0.35	0.22	0.51	Currently
Mujing	0.45	0.65	0.29	0.35	0.35	0.12	0.42	Low
Nawangan	0.45	0.65	0.29	0.50	0.35	0.18	0.47	Low
Ngromo	0.45	0.65	0.29	0.33	0.35	0.11	0.41	Low
Pakisbaru	0.45	0.65	0.29	0.42	0.35	0.15	0.44	Low
Penggung	0.50	0.65	0.33	0.45	0.35	0.16	0.48	Low
Sempu	0.50	0.65	0.33	0.15	0.35	0.05	0.38	Low
Tokawi	0.55	0.65	0.36	0.43	0.35	0.15	0.51	Low

The integration results indicate that the Socio-Environmental Suitability Index (SESI) ranges from 0.38 to 0.51, representing low to moderate conditions for robusta coffee development in Nawangan. Jetis Lor (0.51) and Tokawi (0.51) villages are categorized as moderate, reflecting a relative balance between biophysical potential and socio-economic readiness. More specifically, Jetis Lor serves as an interesting illustration of how the social dimension can compensate for biophysical limitations, as Ren (2025) argues that social capital and local institutional support play a vital role in increasing farmers' adaptive capacity to environmental constraints. Jetis Lor has a high ISE score (0.63), supported by a coffee productivity of 21.7 tons, active farmer groups, and good market access, which in turn strengthens the socio-economic resilience of its communities.

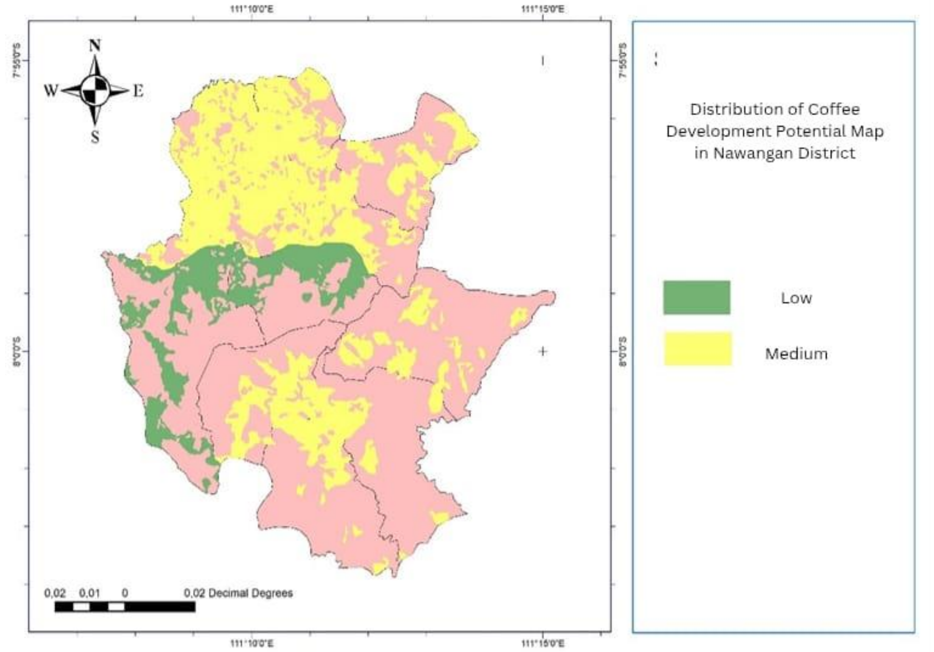

Fig 3. Distribution of potential for robusta coffee development in Nawangan District

Conversely, villages such as Sempu (0.38), Ngromo (0.41), and Gondang (0.43) are categorized as non-priority due to combined physical and social limitations. The lack of farmer institutions, limited access to financial services, and insufficient agricultural facilities are the main constraints hindering improvements in productivity and land-use efficiency. This finding supports the view of Fotakis et al. (2024) that integrating social dimensions into land suitability evaluation is essential to ensure that land-use planning considers not only biophysical characteristics but also the relationship between land and communities in rural development. Consequently, biophysically suitable land may not reach its optimal potential without adequate socio-economic structural support at the community level. The distribution of potential maps is presented in figure 3 above.

4. Conclusions

The results of this study indicate that robusta coffee development in Nawangan District has significant potential if carried out through an integrated approach between biophysical and socio-economic aspects. Based on the results of the land suitability class (KKL) analysis, most areas are classified as S3 (marginally suitable) with the main limiting factors being shallow soil depth, low organic carbon content, and limited availability of macronutrients. However, these conditions still have the opportunity to improve to class S2 (moderately suitable) through soil management interventions, such as the addition of organic matter, improving micro-drainage, and balanced fertilization (N, P, K). The integration of the KKL (weighted 0.65) and the Socio-Economic Index (ISE, weighted 0.35) produce a Social-

Environmental Suitability Index (SESI) that represents low to moderate conditions (0.38–0.51) for robusta coffee development. Jetis Lor Village (0.51) and Tokawi Village (0.51) have the highest values, reflecting a relative balance between biophysical suitability and socio-economic readiness. Active farmer institutions, good market access, and high productivity make these two villages suitable for development as coffee agribusiness growth centers and models for sustainable agricultural innovation. Conversely, villages such as Sempu, Gondang, and Ngromo show low SESI scores due to the lack of farmer groups, limited financial access, and long distance from markets, highlighting the importance of social and institutional interventions in enhancing local capacity. Therefore, robusta coffee development in Nawangan District should be guided through a region-based approach that emphasizes synchronization between land resource management and local socio-economic empowerment.

Acknowledgement

The authors would like to thank all parties who contributed to the completion of this research, particularly those who provided valuable support, feedback, and assistance during the research and manuscript preparation process.

Author Contribution

The authors were solely responsible for the conceptualization, methodology, data collection, data analysis, interpretation of results, drafting of the manuscript, critical revision of the content, and approval of the final version of the manuscript.

Funding

This research received no external funding.

Ethical Review Board Statement

Not available.

Informed Consent Statement

Not available.

Data Availability Statement

Not available.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the authors used Grammarly to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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Biographies of Author

Suko Irawan, Department of Soil Science, Faculty of Agriculture, Universitas Sebelas Maret, Surakarta, Central Java 57126, Indonesia.

- Email: sukoirawan9@gmail.com
- ORCID: 0000-0003-3472-0500
- Web of Science ResearcherID: N/A
- Scopus Author ID: 57213238848
- Homepage: N/A