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ARTICLE

Performance and Strategies to Enhance Sustainability of Cocoa-Based Agroforestry in Lampung Province, Indonesia

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ABSTRACT

The sustainability of cocoa-based agroforestry in Indonesia is challenged by low yield and quality, pests and diseases, and climate change, raising questions about its continued sustainability. The objectives of this research are to examine existing performance, sustainability, and strategies to enhance the sustainability of cocoa-based agroforestry in Indonesia. Research was conducted in Tanggamus Regency, Lampung Province, which applied a survey method, located in 3 sub-districts chosen purposively among the main producers of cocoa, and interviewed 116 farmers of cocoa agroforestry, who were randomly sampled from cocoa farmer groups. This research performed descriptive statistics, Revenue/Cost (R/C), and Multi-Aspect Sustainability Analysis (MSA). Results indicate that cocoa agroforestry is economically viable, with cocoa yield reaching 740 kg per hectare and income of IDR 40.4 million with R/C 5.86, while non-cocoa production (mainly coffee, banana, and black pepper) generates an additional equivalent of 231.8 kg of dry cocoa bean, bringing total income to IDR 50.1 million and R/C 7.69. Sustainability analysis reveals a “moderately sustainable” status with an MSA index of 62.87. The findings conclude that enhancing the performance and sustainability of cocoa agroforestry requires integrated strategies, including improved financial access, adoption of farm accounting systems, market development, optimization of post-harvest processing (drying

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and fermentation), enhanced marketing systems, guaranteed availability of production inputs, and increased cocoa productivity.

Keywords: Cocoa Agroforestry; Economic Performance; MSA; Sustainability Strategy; Sustainability Index

1. Introduction

Cocoa plants grow and produce well in tropical areas known as the cocoa belt, including Indonesia, which is the third largest cocoa producer after the Ivory Coast and Ghana [1]. From 2002 to 2022, Indonesia's average national productivity remained low at 0.5 tons per hectare. However, a more critical trend has emerged since 2013, with both plantation area and productivity declining at average rates of 1.79% and 1.04% per year, respectively. This dual decline triggers an economic sustainability crisis, generating insufficient returns for farmers. Consequently, they lack the capital to address root causes such as aging trees, poor crop management, and land degradation due to the expansion and improper intensification of cocoa plantations [2]. This leads to a downward spiral of productivity and profitability.

Cocoa is cultivated in various regions in Indonesia, especially in Sulawesi and Sumatra, including in Lampung Province, which is the centre of cocoa production on Sumatra Island [3]. In Lampung, cocoa is planted in lowland areas up to the foothills of the mountains at altitudes of 50–800 m a.s.l. In these areas, various industrial crops such as cassava, banana, coffee, black pepper, and rubber are cultivated. Land use is dynamic as a result of land conversion for the cultivation of these commodities in monoculture, polyculture and agroforestry. In 2023, Lampung Province produced 47.8 thousand tons of dry bean cocoa from the acreage of 76.5 thousand hectares, with productivity only 0.62 ton ha^{-1} [4], a figure that remains far below its agronomic potential. This low productivity directly undermines farmer livelihoods and the economic viability of smallholder systems. The challenges confronting cocoa farmers in Lampung are multifaceted and deeply interlinked across sustainability dimensions [5]. These are not merely agronomic issues but stem from underlying technological gaps (e.g., cocoa genotype, pruning, hand pollination) [6–8], institutional failures (e.g., inadequate access to fertilizer supply chains and formal credit) [9], environmental, and socio-cultural limitations [10]. Meanwhile, Muhardi et al. [11] reported some problem of cocoa sustainability in Indonesia, including improper aged cocoa trees, applying organic matter, pruning, pests and diseases controlling. This synergy of constraints creates a detrimental cycle where the lack of technological adoption, driven by institutional weaknesses and social barriers, leads to poor farm economic performance.

Agroforestry plays an important role in mitigation [12] and adaptation to climate change [13]. Trees in agroforestry systems play a critical role in carbon sequestration, enhancing both environmental sustainability and crop productivity. Their deep root systems facilitate efficient exploration of soil water and nutrients, while their canopy provides shade, maintaining a favourable microclimate for cocoa cultivation. Additionally, tree litter contributes to soil cover, improving water infiltration and retention within the soil regime [14]. Agroforestry also has potential for adaptation to climate change through improving soil fertility [15], conserving biodiversity [16] and diversifying farmers' income. Tree-based production systems in agroforestry often produce crops of higher value [14], higher yield and income, and reduce farmers' household vulnerability to climate change [17]. Farmers adopt and manage crop varieties, tree species, and livestock that are adaptive to climate change [18]. Important source of income in agroforestry includes associate trees and non-trees such as bananas and food crops [19].

Recently, agroforestry is gaining recognition as a sustainable and climate-smart approach, particularly in perennial crop systems such as cocoa farming with shade more than 50 trees per hectare [19]. Climate-smart practices involve adapting to long-term climate shifts and unpredictable weather, mitigating climate impacts by lowering greenhouse gas emissions and potentially capturing carbon from the atmosphere, while also sustainably boosting agricultural productivity [20]. Management practices of shade trees in agroforestry functions in promoting biodiversity conservation [21] and ecosystem service such as provisioning, regulating, supporting services [22]. Moreover, implementing agroforestry might improve the performance and sustainability of farming through enhancing ecological, economic, social, institutional, and technological aspects [23].

Despite the recognized potential of agroforestry, prior research on cocoa sustainability has often been siloed. The concept of sustainability initially has three main pillars: economic, social, and environmental. These concepts were then combined into four pillars by adding institutional aspects. Several recent studies add a technological aspect [24]. Several studies on cocoa agroforestry are still focused on only one aspect, rather than a multi-faceted approach. An example of a study that discusses the ecological aspect [15, 16] or only economic aspects like yield and income [25]. A critical synthesis of the literature reveals a significant gap: a lack of integrated analysis that simultaneously assesses the ecological, economic, social, institutional, and technological (EEIST) dimensions of cocoa agroforestry sustainability [10, 11].

To bridge this multidimensional gap, this study employs a conceptual framework that posits the sustainability of cocoa agroforestry as an outcome of dynamic interlinkages between all five EEIST dimensions. The novelty of this research lies in its integrated diagnostic approach, which provides a holistic assessment of cocoa agroforestry systems in Lampung, Indonesia, by simultaneously evaluating ecological, economic, social, institutional, and technological aspects. Consequently, this study aims to examine the economic performance of these systems, conduct a comprehensive sustainability assessment across all five dimensions, and formulate prioritized enhancement strategies. The findings are expected to provide stakeholders with an evidence-based roadmap for developing cocoa plantations that are not only productive but also resilient, inclusive, and sustainable.

2. Materials and Methods

The research is located in Tanggamus Regency, Lampung Province, Indonesia, within the Southern Bukit Barisan mountain range, characterised predominantly by sloping and steep terrain. It has elevation of 0–2115 m above sea level, average of air temperature 19.2–32.5 °C, humidity 85%, and annual rainfall 2614 mm with drought in June–September. It is dominated by dryland agriculture including coffee, cocoa, black pepper, clove, coconut, rubber, nutmeg, durian, and banana [4]. The research applied a survey method, with 3 sub-districts, including Pugung, Pulau Panggung, and Air Naningan. The selection of these specific locations was based on their status as the primary cocoa production center in the region, hosting the largest concentration of cocoa farmers. This approach ensured that the collected data was representative of the predominant cocoa farming systems and conditions in Tanggamus. It is between 5.22–5.50 South Latitude and 104.62–104.90 East Longitude (**Figure 1**). The soil types were Andic Dystrudepts (Inceptisols), Typic Hapludands (Andisols), Typic Hapludox (Oxisols) [26].

Data collection was conducted between March and June 2024. The study employed a multi-stage random sampling method to select respondents. First, two villages were randomly selected from each of the three chosen sub-districts. Subsequently, two cocoa farmer groups were randomly chosen from each selected village. From each of these farmer groups, farmers who implemented cocoa agroforestry systems were randomly selected, resulting in a total sample of 116 farmers who were interviewed using a structured questionnaire. Additionally, focused group discussions (FGDs) were held with key stakeholders who understand the sustainability of cocoa agroforestry. The stakeholders involved included two representatives each from the Lampung Provincial Plantation Service, the Tanggamus Animal Husbandry and Plantation Service, academia (experts), market players, and Field Agricultural Extension Workers.

The performance of cocoa agroforestry was analysed using the productivity, revenue, R/C ratio and income approach. The productivity of multiple cropping consists of the main crop and land productivity [27]. Cocoa productivity is the cocoa beans produced per unit of land area. On the other hand, land productivity measures the extent to which land used for cocoa farming can produce output, both cocoa and yield from intercropping other agroforestry plants. The study computed land productivity as the sum of direct cocoa harvest and the cocoa-yield equivalent of intercropped plants per hectare. The equivalence is based on the price ratio. Furthermore, the R/C ratio was calculated to assess economic performance using the formula (1)[28]:

$$\text{R/C Ratio} = \frac{\text{TR}}{\text{TC}} \quad (1)$$

where TR represents Total Revenue and TC represents Total Cost. The assessment criteria are as follows: R/C < 1 indicates the cocoa farming is operating at a loss, R/C > 1 signifies a profitable cocoa farming, and R/C = 1 represents the break-even point for the cocoa farming.

This research uses Multi-Aspect Sustainability Analysis (MSA) and is processed using Exsimpro software (https://msa.exsimpro.com/). The use of MSA was first developed by Firmansyah[29] and was used in some research of sustainability assessment including Juhandi et al.[24] and Prasmatiwi et al.[23]. We use MSA to calculate sustainability status scores and performance indices, then derive required future strategies. MSA analysis can provide good, fast, effective, and efficient decisions, with multi-aspect considerations[29]. The MSA approach allows for a holistic assessment by considering five main aspects: ecology, economy, social (community), institutions, and technological innovation. In addition to measuring the sustainability index, this method can also reveal sensitive factors that influence each aspect through leverage analysis. These factors then become a reference in formulating strategies to improve sustainability.

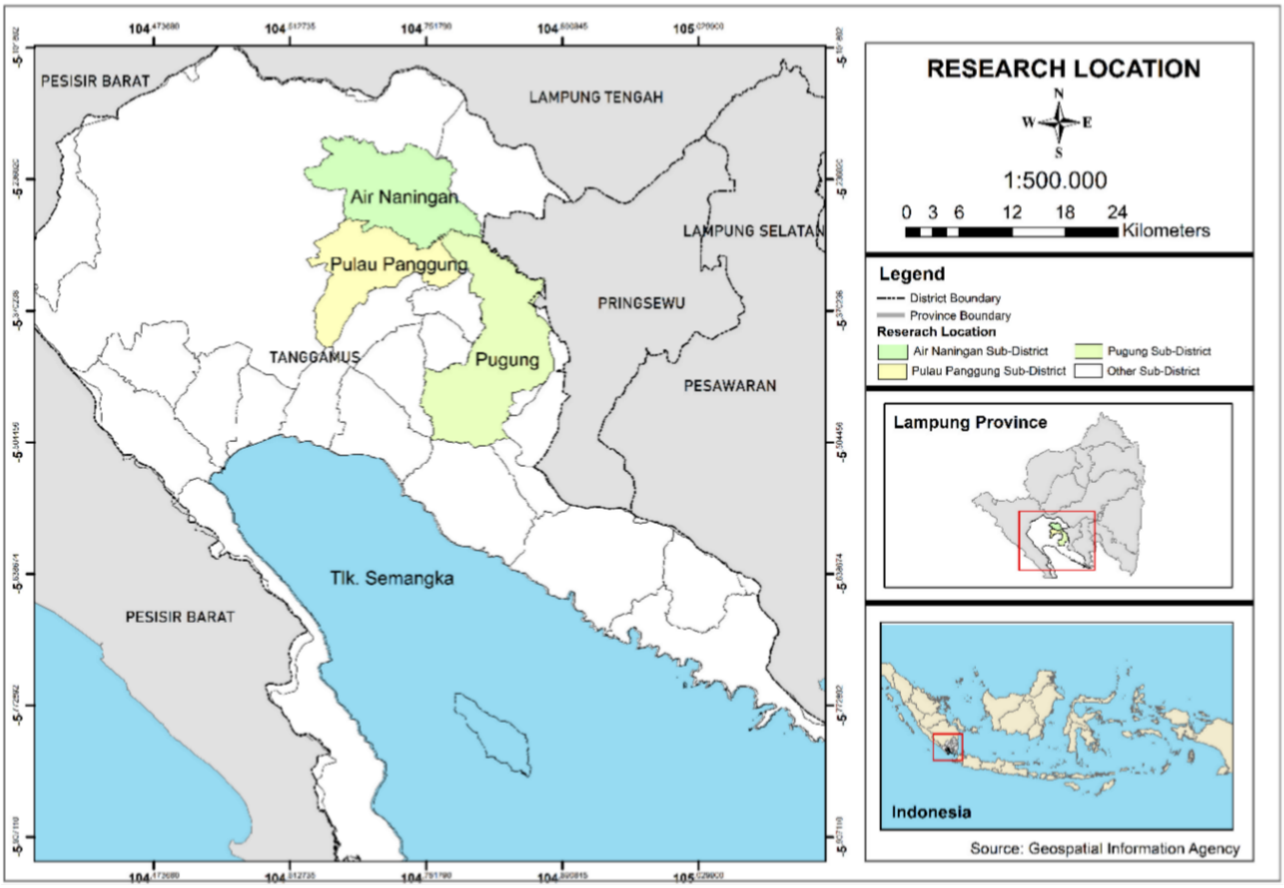


Figure 1. Research location in Tanggamus Regency, Lampung Province.

The analysis procedure consists of several sequential steps. The initial stage begins with determining the aspects and factors used and assessing each factor on an ordinal scale, with ordinal scoring ranging from 0 (bad) to 3 or 4 (good). The variation in scoring ranges (0–4, 0–2, 0–3) was not arbitrary but was deliberately designed based on the results of Focus Group Discussions (FGDs) with stakeholders. Factors and scores are determined based on literature studies, discussions with experts and stakeholders, and field observations. Five aspects were determined to measure the sustainability of cocoa farming, namely ecological, economic, social, institutional, and technological aspects. The factors for each aspect are determined alongside the scores, as presented in **Table 1**. The next step is the sustainability assessment by selected respondents. The collected data is then processed using Exsimpro software to assess the index and sustainability status in each aspect, and to determine sensitive leverage factors in each aspect through leverage analysis. The last stage is scenario analysis for the formulation of the Sustainability Strategy. The analysis results then form the basis for the design of improvement scenarios.

Table 1. Aspect and factors scoring.

No	Aspect & Factor	Score	No	Aspect & Factor	Score
	1. Ecology			**2. Economy**	
1.1	Climate suitability	0–3	2.1	Advantages of intercropping	0–4
1.2	Land suitability	0–3	2.2	Advantages of cocoa	0–4
1.3	Elevation	0–2	2.3	Harvest sales	0–3
1.4	Land area	0–4	2.4	Cocoa productivity	0–3
1.5	Land slope	0–3	2.5	Market access and price information	0–3
1.6	Cocoa plant age	0–2	2.6	Income status of cocoa farming for the household	0–3
1.7	Pests and diseases	0–3	2.7	Availability of production facilities	0–4
1.8	Utilization of waste for organic fertilizer	0–3	2.8	Pricing	0–3
1.9	Extreme weather	0–4	2.9	Cocoa price	0–3
1.10	Shade density	0–4	2.10	Cocoa farming costs	0–3
1.11	Road access	0–3			
	3. Social			**4. Institution**	
3.1	Land ownership status	0–3	4.1	Existence of Microfinance Institutions (MFIs)	0–3
3.2	Education	0–4	4.2	Agricultural store	0–3
3.3	Age of farmer	0–3	4.3	Farmer participation in farmer groups	0–3
3.4	Community access to agricultural activities	0–3	4.4	Existence of the role of the Agricultural Extension Service	0–3
3.5	Community perspective on cocoa farming	0–3	4.5	Existence of farmer groups	0–3
3.6	Family participation in cocoa farming	0–3	4.6	Accessibility of farmer groups to banking and technology sources	0–3
3.7	Community empowerment from government and private sector	0–4	4.7	Partnership cooperation with private companies	0–3
3.8	Frequency of conflict	0–4	4.8	Length of marketing channel	0–4
3.9	Labor criteria	0–3	4.9	Farm financial reporting	0–3
3.10	Cocoa pod theft	0–4	4.10	Benefits of agricultural institutions	0–3
	5. Technology				
5.1	Grafting	0–3	5.6	Cocoa drying	0–3
5.2	Use of quality and certified seedlings	0–3	5.7	Harvesting technique	0–3

Table 1. *Cont.*

No	Aspect & Factor	Score	No	Aspect & Factor	Score
	5. Technology				
5.3	Cocoa entres clones	0–3	5.8	Cocoa bean fermentation	0–3
5.4	Sun drying time	0–4	5.9	Plant pruning and shading measures	0–3
5.5	Fertilization	0–3	5.10	Level of mastery and application of cultivation technology	0–3

The assessor's score for each aspect is rated on a scale from 0% (bad) to 100% (good), categorized into five sustainability levels: 0–20% (unsustainable), $>$20–40% (low sustainability), $>$40–60% (moderate sustainability), $>$60–80% (sustainable), and $>$80–100% (highly sustainable) [30]. A sustainability scale of 0–100% was then calculated using the Exsimpro methodology, which aggregates the normalized and weighted raw scores into a single composite index. The final score for each aspect was calculated using the following formula (2) [29]:

$$\mathbf{Y} = \frac{y_1 + y_2 + y_3 + y_4 + .. + y_3}{n} = \frac{\sum y_{\mathrm{n}}}{n} \qquad (2)$$

where Y represents the sustainability score, calculated from y (the individual indicator scores) and n (the total number of indicators within the aspect). A scenario analysis approach was applied to the most sensitive leverage factors to enhance cocoa farming sustainability. This study developed two improvement scenarios targeting key leverage factors across sustainability aspects. Policy validation involved comparing scenarios 1 and 2 to evaluate their effectiveness and impacts. Scenario 1 increases the score by one level for a sensitive aspect that is feasible for farmers to address. Scenario 2 yields more optimal outcomes by elevating scores one level higher than scenario 1.

3. Results

3.1. Characteristic of Farming

The study results obtained a comprehensive picture of the profile of cocoa farmers that shows interrelated characteristics. Regarding farming experience, most farmers have had cocoa farming experience for more than two decades. This mature experience is also supported by the participation of farmers in farmer institutions, namely, all respondents are actively involved in local farmer groups. In terms of demographics, most cocoa farmers are aged 40 years and over, indicating that cocoa farming is generally run by farmers already in their productive age. Regarding education level, most respondents have a formal educational background equivalent to Junior High School. The characteristics of the respondents also show that male farmers dominate cocoa farming. Regarding family structure, the average cocoa farmer household consists of 3–4 family members, reflecting the form of a nuclear family commonly found in rural areas (**Table 2**).

Farmers in Tanggamus Regency cultivate cocoa plants with an average density of 675 trees per hectare (**Table 3**). Each family generally manages a relatively small cocoa land, with an average area of only 0.71 hectares. On the same land, farmers practice an agroforestry system by planting various types of tress such as stink bean, durian, dog fruit, papaya, avocado, coffee, black pepper, banana, nutmeg, rubber, coconut, vanilla, cloves, jackfruit, areca nut, and various of wood trees including rain wood (*Gliricidia*), coral tree, lead tree, champaca wood, teak, African wood, silk-cotton tree, as many as 380 trees per hectare. Cocoa plants in this area are included in the mature category because they have reached an average age of 10.67 years. According to Andres et al. [31], cocoa plants at the age of 10–15 years enter the adult phase, where their growth slows down and fruit production is stable, but they become more vulnerable to environmental pressures. This condition is exacerbated by the location of the plantations, which are on average 1.3 km from residential areas, thus hindering farmers from carrying out intensive cocoa care.

3.2. Performance of Cocoa Farming

This study analysed indicators of cocoa farming performance in Tanggamus Regency, including cocoa productivity, land productivity, revenue, farming cost, income, and R/C ratio. **Table 4** presents the harvestable intercrops (those with products that can be sold) based on the average data across all surveyed farmers. Intercrops revenue reached IDR 15,262,883 with the largest share coming from coffee, bananas, and black pepper. This revenue is equivalent to 231.8 kg of cocoa (**Table 4**). The location of this research is a coffee-based agroforestry area [32] with mixed crops, especially coffee, bananas, and black pepper, which contribute important income to farming families.

Cocoa farmers in Tanggamus Regency currently produce an average of 740.59 kg per hectare (**Table 5**). This result is consistent with the findings of Nunoo and Owusu [33] that a cocoa agroforestry system with moderate shade can produce 735 $kg.ha^{-1}$. However, this finding requires a broader interpretation of productivity. While Niether [12] observed that cocoa yields in agroforestry systems might be 25 percent lower than monocultures, the same study highlighted that total system productivity incorporating both cocoa and intercrops can increase approximately tenfold. Supporting this perspective, research by Tinoco-Jaramillo [34] revealed superior productivity in agroforestry systems (532.0 kg per hectare) compared to monoculture plantations (435.4 kg per hectare). Collectively, these findings indicate that the principal advantage of cocoa agroforestry in Tanggamus lies not in maximizing cocoa yields alone, but in enhancing farmer resilience and livelihood security through diversified production.

Table 2. Socio-demographic Characteristics of Respondents.

Variable	Min	Max	Mean
Cocoa farming experience (year)	3.00	52.00	20.77
Education (year)	0.00	16.00	9.39
Farmers' age (year)	23.00	74.00	47.89
Family member (people)	1.00	5.00	3.88

Table 3. Overview of Cocoa Farming.

Description	Min	Max	Mean	SD
Number of cocoa tree (tree/ha)	200.00	1600.00	675.18	284.20
Land tenure (ha)	0.25	2.50	0.71	0.46
Cocoa plant age (year)	1	27	10.67	6.21
Number of companion tree (tree/ha)	50	1445.00	380.09	258.17
Farm distance from home (km)	0.10	7.00	1.30	1.21

Table 4. Revenue from intercrops.

Intercrops	Yield ($kg.ha^{-1}$)	Price ($IDR.kg^{-1}$)	Revenue (IDR)
Coffee	99.76	59,705.88	5,956,258.59
Banana	4006.19	1179.17	4,723,979.06
Black pepper	39.67	82,346.15	3,266,671.77
Stink bean	9.85	30,000.00	295,500.00
Papaya	47.48	2500.00	118,700.00
Coconut	19.78	3714.29	73,468.66
Dog fruit	38.08	8937.5	340,340.00
Avocado	12.82	23,250.00	298,065.00
Rubber	18.99	10,000.00	189,900.00
Sum			15,262,883.08
Cocoa equivalent	231.80	65,846.15	15,262,883.08

Table 5. Performance of cocoa farming.

Description	Mean	SD
Cocoa productivity ($kg.ha^{-1}$)	740.59	398.08

Table 5. *Cont.*

Description	Mean	SD
Land productivity (kg.ha^{-1})	972.39	467.03
Cost of cocoa farming (IDR ha^{-1})	8,327,871.94	4,165,299.91
Cocoa price (IDR kg^{-1})	65,846.15	3219.57
Income from cocoa (IDR ha^{-1})	40,437,128.29	22,715,982.35
Land income (IDR ha^{-1})	55,150,265.86	26,213,746.73
R/C from cocoa production	5.86	
R/C from land production	7.69	

Note: 1 USD = 16,233 IDR.

From the cash flow aspect, cocoa production costs of IDR 8,327,871.94 per hectare for fertilization, pest control, cocoa maintenance wages, land taxes, input, and output transportation costs, incurred collectively, resulted in a good income of IDR 40,437,128 per hectare from the sale of dry cocoa for IDR 65,846.15 per kg and performing R/C 5.86. After adding intercrop income, land income can reach IDR 55,150,265 per hectare with R/C 7.69. According to Murniati et al.[35], cocoa agroforestry contributes a high household income, exceeding the national poverty line and serving as the backbone of the local economy. The findings of Nunoo and Owusu[33] reported that proper shade systems provide the highest returns and ecological benefits, suggesting the superiority of cocoa agroforestry systems.

3.3. Index of Cocoa Farming Sustainability

The results of the Multiaspect Sustainability Analysis in **Figure 2** indicate that cocoa farming in Tanggamus Regency falls into the moderate performance category of sustainable status. This moderate sustainability status also found in other centre cocoa production in Indonesia as reported by Muhardi et al.[11]. A more detailed result reveals variations in performance across aspects, with the ecological aspect recording the highest index (70.45 %), followed by the economic aspect (69.30%) and the social aspect (63.40%). Meanwhile, the main weaknesses are technological (56.00%) and institutional aspects (55.20%). This finding aligns with research by Hidayanto & Fiana[36], which also identified institutional and technological aspects as the most vulnerable aspects in the sustainability of cocoa farming.

This sustainability profile gains greater significance when contrasted with monoculture systems. For instance, Muhardi et al.[11] reported that monoculture cocoa farming was characterized by a weak ecological aspect, scoring only 46.07%. The present study demonstrates that the agroforestry system excels precisely in this ecological dimension. A similar advantage is evident in the economic aspect, where monoculture systems were found to have a much lower sustainability index of 40.15, according to findings by Fairuzia[37]. While technological and institutional aspects remain a challenge, this comparative assessment confirms that the agroforestry model offers a decisive corrective to the critical ecological and economic limitations inherent to monoculture systems, establishing a more robust foundation for sustainable cocoa production.

The validity of this Multiaspect Sustainability Analysis was confirmed through a random iteration test. The results showed a validation value of 1.38, which falls well below the maximum threshold of 5.00, as established by Firmansyah[29]. This low value indicates that the model is stable and reliable, meaning that the sustainability indices obtained for each aspect, namely Ecology (4.00), Economy (2.30), Social (0.40), Institutional (0.20), and Technology (0.00) are robust and not the result of random chance, thereby lending strong credibility to the overall findings.

3.4. Leverage Factors in Each Aspect

Identifying critical factors that have the potential to become key leverages is crucial in prioritizing sustainability improvements. The leverage factors were generated quantitatively through the Exsimpro software algorithm, which performs a sensitivity analysis by calculating the rate of change in the sustainability index when each key factor is perturbed. The visual analysis (**Figure**

3) reveals two key indicators: (1) the maximum sensitivity value (shown in green), which represents the maximum potential for change in a factor, and (2) the actual sensitivity value (shown in yellow), which reflects the actual condition of the factor. The combination of these two values produces a sensitivity leverage index, which serves as the basis for prioritizing interventions. The factor with the highest leverage demonstrates the most significant influence on improving the sustainability index and should therefore be the primary focus of the improvement program.

From an ecological aspect, the three driving factors that most influence the sustainability of cocoa farming in Tanggamus Regency are: (1) plant pests and diseases, (2) the impact of extreme weather, and (3) the use of organic waste. These three factors are interrelated and collectively create complex challenges for cocoa farmers. From an economic aspect, the factors with high sensitivity in influencing the sustainability of cocoa farming are the harvest marketing system, the availability of production facilities, and cocoa productivity.

In the social aspect, **Figure 3** shows that community perceptions of cocoa farming, farm security, education levels, and community empowerment by stakeholders are the main leverages of the social sustainability of cocoa farming. However, multidimensional ecological and economic challenges, ranging from fluctuating commodity prices to the threat of climate change, significantly impact cocoa farmers' perceptions and resilience. Security concerns further exacerbate this situation, particularly when cocoa prices soar. Under these conditions, farmers face the threat of cocoa pod theft from their plantations, reducing their interest in maintaining this farming business. Amid these challenges, education is a critical factor interconnected with the previous issues. For institutional aspects, cocoa sustainability is strongly influenced by three main factors: access to microfinance institutions (MFIs), sound financial reporting, and efficient marketing channels. Limited access to MFIs or cocoa farmer cooperatives makes it difficult to obtain capital. Based on technological aspect, the three main factors driving are drying methods, drying time, and fermentation of cocoa beans. Drying is a major problem because most farmer dry cocoa beans naturally under the sun for several days. This condition results in uneven drying of the cocoa beans and produces many defective bean. Farmers generally only dry cocoa beans for 1–2 days, resulting in a moisture content of 26.44%, far above the standard 6.5%–7.8% to produce high-quality beans and a good market price. Furthermore, farmers in this region rarely practise cocoa bean fermentation.

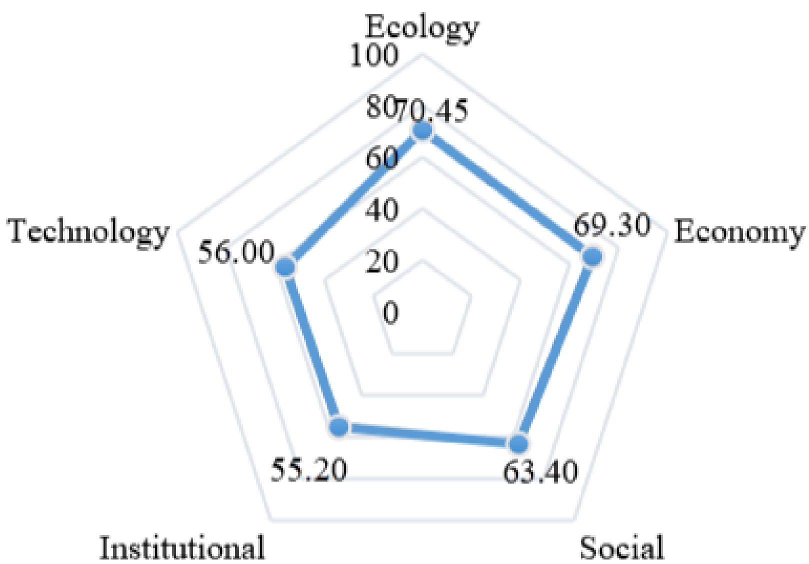
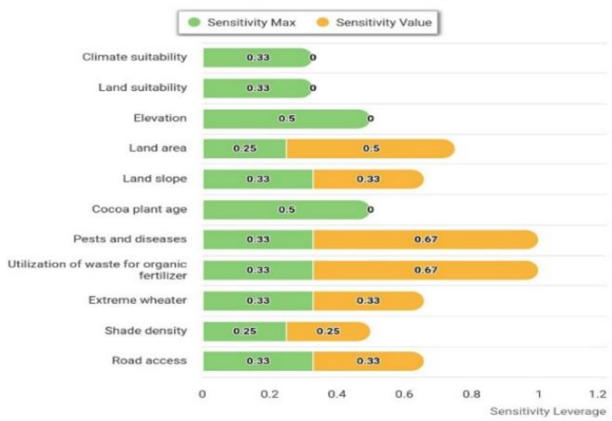
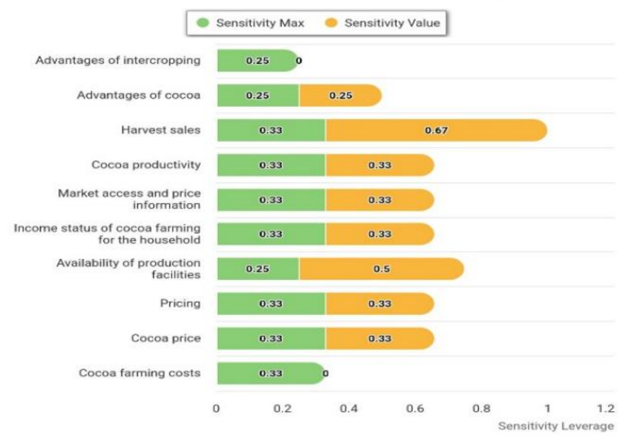


Figure 2. Sustainability index in each aspect.



(a)



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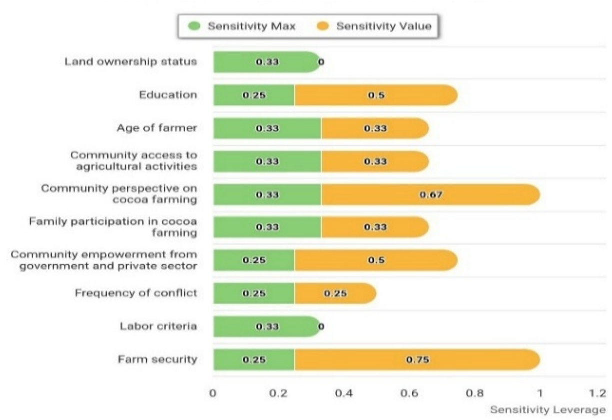
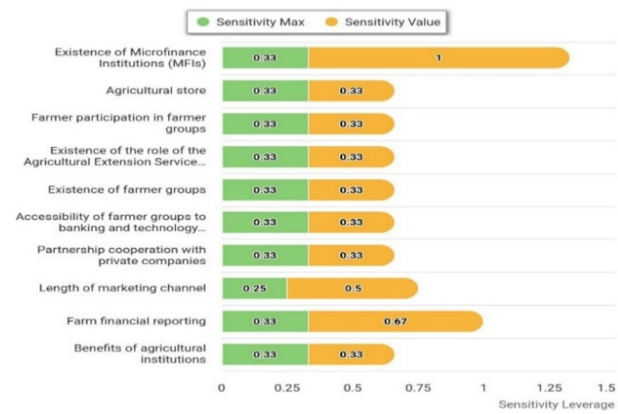


(c)



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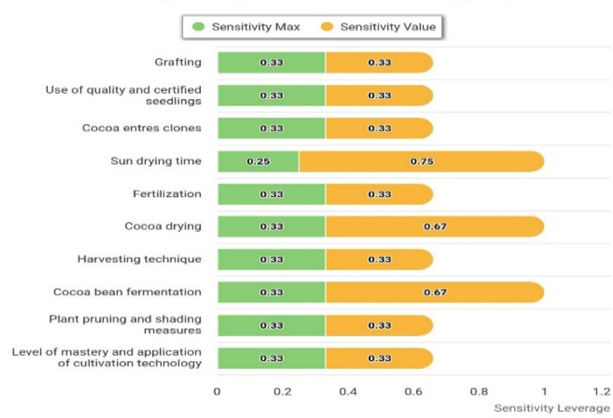

(e)

Figure 3. Sensitivity of leverage factors in aspect of: (**a**) ecological; (**b**) economic; (**c**) social; (**d**) institutional; (**e**) technological.

3.5. Strategy for Sustainable Cocoa Farming

Based on the evaluation results presented in **Figure 4**, both tested scenarios (scenario 1 and 2) have achieved the sustainable category. In scenario 1, the value of ecological aspect is improved from 70.45 to 78.18 while in scenario 2 the value is improved to 81.18. For aspect of economy, the value is improved from 69.3 to 78.5 using scenario 1, to 90.9 using scenario 2. For social aspect, the value is improved from 63.4 to 69.3 using scenario 1, to 78.4 using scenario 2. For institutional aspect, the value is improved from 55.2 to 61.1 using scenario 1, to 80.1 using scenario 2. For aspect of technology, the value is improved from 56.0 to 65.3 using scenario 1, to 81.0 using scenario 2.

This finding indicates that implementing integrated strategies across various aspects can improve the sustainability performance of cocoa farming from moderate to very good performance. Although both are in the sustainable category, scenario 2 shows a more significant improvement compared to scenario 1, with a significantly higher average value. Scenario 2 is indicated as having greater potential to promote holistic cocoa agribusiness sustainability. Meanwhile, scenario 1 has excelled in several aspects, but still has weaknesses in the institutional, technological, and social aspects.

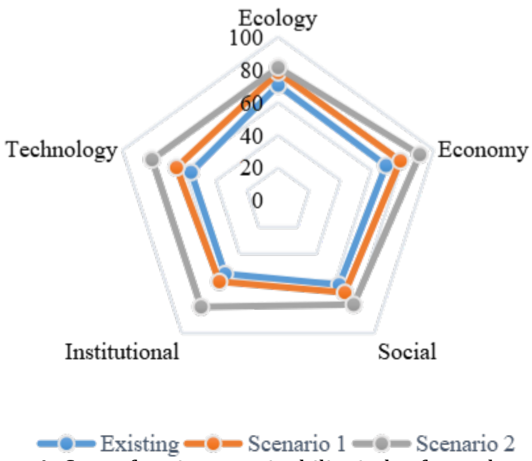

Figure 4. Cocoa farming sustainability index for each scenario.

Scenario 2 is also better based on the priority scenario test by analysing the ΔS1S and ΔS2S values, which indicate improvements or changes in aspects in scenario 1 (S1) and scenario 2 (S2). The ΔS2S/ΔS1S ratios, all above 1, indicate the effectiveness of scenario 2 in strengthening institutional systems, technology adoption, and farmer social empowerment. The institutional aspect recorded the highest ratio (4.22), followed by technology (2.69) and social (2.54). The average scenario priority of 2.64 confirms that scenario 2 is 2.64 times more effective overall than scenario 1. The value of 2.64 represents the ratio of the improvement in the sustainability index (ΔS) achieved by Scenario 2 compared to Scenario 1 (i.e., ΔS2/ΔS1). This finding suggests that scenario 2 is worthy of being a focus for implementation because it encompasses institutional strengthening, technological innovation, economic improvement, and a social approach.

4. Discussion

The moderate sustainability status (62.87%) of cocoa agroforestry in Tanggamus Regency reveals both strengths and challenges in current farming practices. The ecological dimension emerged as the strongest aspect (70.45%), demonstrating agroforestry's advantage in maintaining environmental functions, while the economic dimension (69.30%) reflects reasonable viability given current market conditions. However, the social (63.40%), technological (56.00%), and institutional (55.20%) dimensions indicate significant constraints that require targeted intervention. This pattern aligns with findings from Hidayanto & Fiana [36] in other Indonesian cocoa regions, suggesting common challenges across smallholder systems. The relatively strong ecological performance contrasts with study of Muhardi et al. [11] on monoculture systems, which reported much weaker ecological sustainability (46.07%), highlighting agroforestry's potential for environmental conservation.

The technological constraints identified stem from particularly in post-harvest processing and pest management. Only 22% of farmers practice proper fermentation, and reliance on chemical pesticides remains high despite available alternatives. Institutionally, weak farmer organizations and limited access to formal credit create dependency on traders, reducing farmers' bargaining power. Socially, the aging farmer population (average age 47 years) and lack of youth engagement threaten long-term sustainability. These interconnected constraints create a self-reinforcing cycle where technological limitations reduce economic returns, thereby constraining farmers' capacity to reinvest in technological upgrades.

The actual condition of cocoa farming is still less ideal, with most existing scores hovering around 1. This condition indicates the need for comprehensive improvements in various aspects. Ecologically, pest and disease attacks, particularly Cocoa Fruit Borer (CFB) and Helopeltis, can be sustainably controlled through an integrated approach [38], including the use of botanical insecticides and biological agents, regular pruning, and planting superior clones.

The impact of extreme weather, particularly drought, has been occurred in cacao yields in the last five years. Therefore, system would be even better if combined with drought-resistant varieties, forming a comprehensive adaptation strategy. This approach aligns with the principle of optimizing agricultural plans by accounting for climate variability [1], plant physiology, and resource constraints increases land productivity. Furthermore, cocoa harvest waste remains untapped, with 17.80% of farmers unaware of its potential. Cocoa by-products can be utilized as animal feed and organic fertilizer, as high-value products such as activated carbon and other green technologies [39]. Intensive outreach programs are needed to transform waste from an environmental problem into a source of additional income, while simultaneously closing the nutrient cycle in the cocoa cultivation system.

From an economic perspective, the limited marketing system for cocoa farmers can be addressed by participating in a certification scheme, which can be a strategic solution because it not only improves cocoa quality but also opens access to premium markets by large food companies [40]. Furthermore, limited farm inputs are a major obstacle, particularly access to fertilizer due to its high price and limited availability. Fertilization is a crucial pillar of sustainable cocoa production. An alternative solution is to improve fertilizer management [41], such as utilizing organic fertilizer from farmers' agricultural and livestock waste. Utilizing agricultural waste is an alternative to reduce the need for inorganic fertilizers.

From a social perspective, factors influencing farmers' perspectives include the risk of cocoa plants being attacked by pests and diseases, as well as their vulnerability to climate change, which can reduce their interest in continuing cocoa farming. To address this, stakeholders need to continue providing training and mentoring, especially for youth and establish demonstration plots to stimulate farmers to improve cocoa farming. These are part of a multifaceted approach of cocoa farmer empowerment by stakeholders [42] by providing training, facilities, and accessibility to farming inputs and markets while improving farmer groups, social capital, and community control. Due to high prices, cocoa pod theft has recently become a crucial problem in cocoa farming. Social capital, including trust, norms, networks, collaboration within and among groups, and collective intervention on crop watching and guarding, reduces the risk of cocoa theft [43].

From an institutional perspective, difficulties in accessing bank financing and the absence of microfinance institutions have led farmers to form partnerships with middlemen, often leading to losses and tying them down. To address this, the government has re-established a rural cooperative program as an alternative financing option in rural areas. Another problem is that most farmers are unfamiliar with recording cash flow and financial reports, making it difficult to manage their businesses efficiently. The solution requires training in basic bookkeeping, cash management, preparing financial reports tailored to agricultural needs, and utilizing financial recording applications, which can also facilitate bookkeeping for farmers.

Improving post-harvest coffee bean technology is crucial for improving cocoa quality and the marketing supply chain. Each layer of the supply chain applies specific quality standards. Low-quality cocoa is only acceptable at the middleman level, with a low price paid to farmers, as reported by Beg et al. [44]. Adopting technology and participating in certification programs that are fostered and facilitated by various stakeholders and partnerships [45] are strategic step for cocoa farmer groups. However, strategic efforts for stakeholders include facilitating farmers in procuring superior and disease-resistant cocoa seeds, rehabilitating old cocoa trees, and mastering cocoa cultivation including pruning, fertilizing, and manuring.

This study acknowledges several methodological limitations. The research design did not include a comparative assessment between monoculture and agroforestry systems within the same region, which restricts the ability to directly quantify the specific benefits or trade-offs of the agroforestry approach. Furthermore, the assessment relied heavily on farmer self-reporting, a method that may introduce recall bias, particularly for sensitive topics such as income and input use.

The findings suggest several strategic priorities. First, technological improvements should focus on scalable post-harvest innovations that directly impact income, such as simple fermentation boxes and solar dryers. Second, institutional strengthening through farmer cooperatives could address multiple constraints simultaneously by improving market access, input availability, and knowledge sharing. Third, the ecological advantages of agroforestry should be leveraged through potential payments for ecosystem services, creating additional income streams for farmers. These interventions should be implemented sequentially, beginning with quick-win technologies to build trust before introducing more complex institutional changes.

This study demonstrates that cocoa agroforestry in Lampung maintains better ecological sustainability than monoculture systems but faces significant socio-technical constraints. The moderate overall sustainability score indicates a system in transition, requiring coordinated support across multiple dimensions. Future research should directly compare monoculture and agroforestry systems to quantify trade-offs and synergies. For effective policy implementation, government support should recognize agroforestry's multi-functionality by developing differentiated incentives that reward both production outcomes and environmental services. Such policies could include premium pricing mechanisms for agroforestry-grown cocoa, technical assistance for shade management, and integration of agroforestry into national climate adaptation strategies, ultimately contributing to more resilient and sustainable cocoa livelihoods in Indonesia.

5. Conclusions

The agroforestry cocoa system in Lampung Province has demonstrated profitable farming performance, with a cocoa yield reaching 740 kg per hectare and income of IDR 40.4 million with R/C 5.86. Non-cocoa production (mainly coffee, banana, and black pepper) generates an additional equivalent of 231.8 kg of dry cocoa bean, bringing total income to IDR 50.1 million and R/C 7.69. Agroforestry cocoa farming in Tanggamus Regency has achieved sustainability status in the moderate sustainable category (index 62.87). To advance this status, we recommend the implementation of Scenario 2, which is quantitatively proven to be 2.64 times more effective than the baseline. The implementation pathway is threefold. The short-term focus is on technological innovations by promoting improved fermentation and optimizing drying methods and duration. In the medium term, strengthen institutional capacity by facilitating farmer access to financing, providing training in financial literacy, and expanding collective marketing channels. Finally, for long-term resilience, execute a social empowerment program focused on enhancing farm security and improving farmer perceptions through extension services.

Author Contributions

Conceptualization, R.E. and D.P.; methodology, F.E.P; software, T.N.A.; validation, F.E.P; formal analysis, T.N.A; investigation, R.E., L.M.S.; resources, D.P. and L.M.S.; data curation, R.E., F.E.P., D.P., L.M.S., S., T.N.A.; writing—original draft preparation, R.E. and F.E.P.; writing—review and editing, R.E., F.E.P.; visualization, T.N.A; supervision, F.E.P; project administration, R.E.; funding acquisition, D.P. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable.

Data Availability Statement

The datasets are available from the corresponding author on reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

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