Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 5, 960-978
2025
Publisher: Learning Gate
DOI: 10.55214/25768484.v9i5.7044

Implementation of agroforestry system for improved performance and sustainability of coffee farming in west Lampung regency, Indonesia

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Abstract: The global coffee industry, including in Indonesia, faces economic and environmental sustainability challenges, with low productivity and negative impacts of climate change. Although agroforestry systems can be a solution to address these challenges, the adoption of agroforestry practices among farmers is still low. This study aims to analyze the performance and sustainability of coffee farming by comparing three farming systems: coffee monoculture system (CMS), simple agroforestry system (SAFS), and complex agroforestry system (CAFS), and formulate strategies to improve the sustainability of coffee farming. A survey approach involving 210 coffee farmers in two sub-districts in West Lampung assessed farm performance based on farm productivity and income. Sustainability was analyzed using the Multi-Aspect Sustainability Analysis (MSA) method. The results showed that CAFS significantly improved coffee farming performance. The sustainability analysis showed that the sustainability value of coffee farming in West Lampung Regency with CAFS (60.20) shows the highest sustainability value compared to SAFS (57.39) and CMS (53.80). These findings confirm that agroforestry implementation elevates coffee farming's sustainability value. Key improvement strategies target multiple factors: enhanced land conservation, road access, increased capital availability, improved market access, higher productivity, strengthened safety and security, microfinance institution development, corporate cooperation, quality seedlings, and advanced harvesting techniques.

Keywords: *Coffee agroforestry, Farm income, Productivity, Strategy, Sustainability index.*

1. Introduction

Coffee is an excisable commodity that is subject to international trade. Over the past 26 years, coffee has experienced a 67.9% surge in demand. It is now considered one of the most economically important traded commodities in the world, with the global coffee industry worth an estimated US$60 billion by 2022 [1]. However, the coffee industry faces serious challenges related to economic and environmental sustainability. Market price fluctuations, climate change, and land degradation are major threats to the sustainability of coffee farming, especially for smallholders, who are the backbone of global coffee production [2].

Indonesia is the fourth largest coffee producer globally, accounting for 9.25% of world coffee production in 2023 [3]. As one of the major producers, Indonesia has great potential to meet domestic demand as well as exports. However, Indonesia's coffee productivity is low, at only 618.59 kg/ha [4], far below Brazil and Vietnam, which reach 1,750 kg/ha and 2,550 kg/ha, respectively [3]. This low productivity is caused by various factors, such as the old age of coffee plants, suboptimal cultivation practices, and the impact of climate change and weather variability [5, 6].

History: Received: 17 February 2025; Revised: 22 April 2025; Accepted: 25 April 2025; Published: 10 May 2025
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One solution to address the impacts of climate change is the implementation of agroforestry systems, namely the integration of shade plants with coffee plants [7]. Agroforestry has significant benefits in increasing farmers' productivity and income by regulating temperature and rainfall extremes. For example, in Tulungrejo, Malang, Indonesia, coffee agroforestry contributed 58.47% to farmers' total income [8]. In addition, the system is more resilient to coffee price fluctuations due to product diversification and sustainable ecosystem benefits [9]. Although often considered less productive than monocultures, research shows that agroforestry has equivalent or even better economic performance due to lower input costs and the ecosystem benefits it provides [9, 10].

West Lampung Regency, as one of the robusta coffee production centres in Indonesia, has favourable geographical and climatic conditions for coffee cultivation [11]. However, farmers in this area face challenges similar to those in other regions, such as low productivity due to climate change [12, 13] conventional cultivation practices without conservation [14] crop age [15], and low technology adoption [16, 17], as well as inappropriate use of shade trees [18, 19].

Coffee farms in West Lampung are mostly located in hilly areas with an altitude of 300-1.170 meters above sea level [20]. The hilly topography with high land slope and lack of ground cover plants will increase the risk of erosion [21-23]. For this reason, it is necessary to manage conservation practices properly, for example, by vegetative conservation, namely planting shade trees that also function as shade between coffee plants or by implementing an agroforestry system in the coffee plantation [24, 25].

The application of agroforestry systems can be a solution with benefits that include improved soil fertility [26, 27] income diversification [28] climate change mitigation, and biodiversity preservation [26, 29]. In addition, agroforestry provides additional income from shade tree products such as fruits or timber while supporting the ecological and social stability of local communities [10, 30].

With these benefits, coffee agroforestry plays an important role in improving farm performance and sustainability through economic, ecological, and social contributions. The system helps farmers increase income through product diversification, reduce input costs such as fertilizers and pesticides [10, 31, 32] maintain biodiversity, and improve soil fertility through nitrogen-fixing tree litter [33, 34]. In addition, agroforestry also supports social welfare by providing fuel, building materials, and medicines to local communities while reducing land conflicts around forests [10, 32, 35].

The implementation of conservation systems through coffee agroforestry is closely related to farmers' behavioural problems. The problem of farmer behaviour stems from farmers' awareness of maintaining the sustainability of their farms. Although the agroforestry system is believed to fulfil economic and ecological functions, not all farmers in West Lampung apply it. For this reason, it is necessary to analyse the performance and sustainability of coffee farming in various farming systems (monoculture, simple, complex), and the research is expected to formulate strategies to improve the sustainability of coffee farming. The novelty of this research lies in the coffee farming system analysed, namely by comparing various systems. Previous studies have analysed the performance and sustainability of farms globally or in aggregate without comparing between systems, and previous studies have not analysed how strategies to improve farm sustainability. In this study, the performance and sustainability of farming in three systems were analysed, namely monoculture coffee farming, simple agroforestry, and agroforestry complexes, and strategies to improve the sustainability of coffee farming.

2. Material and Methods

2.1. Study Location

Data collection activities in this study took place over five months, from January ~~2023~~ to June 2023. In its implementation, researchers applied a survey approach as the main method, where data was obtained through a direct interview process with respondents. The research subjects focused on the coffee farming community residing in the two main sub-districts of West Lampung Regency, namely Way Tenong Sub-district and Batu Brak Sub-district, which have been known as coffee-

Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 5: 960-978, 2025
DOI: 10.55214/25768484.v9i5.7044

producing centres. In the sampling process, researchers selected two villages from each subdistrict. A map of the geographical locations of the two sub-districts can be seen in Figure 1 to provide a more comprehensive understanding of the research area.

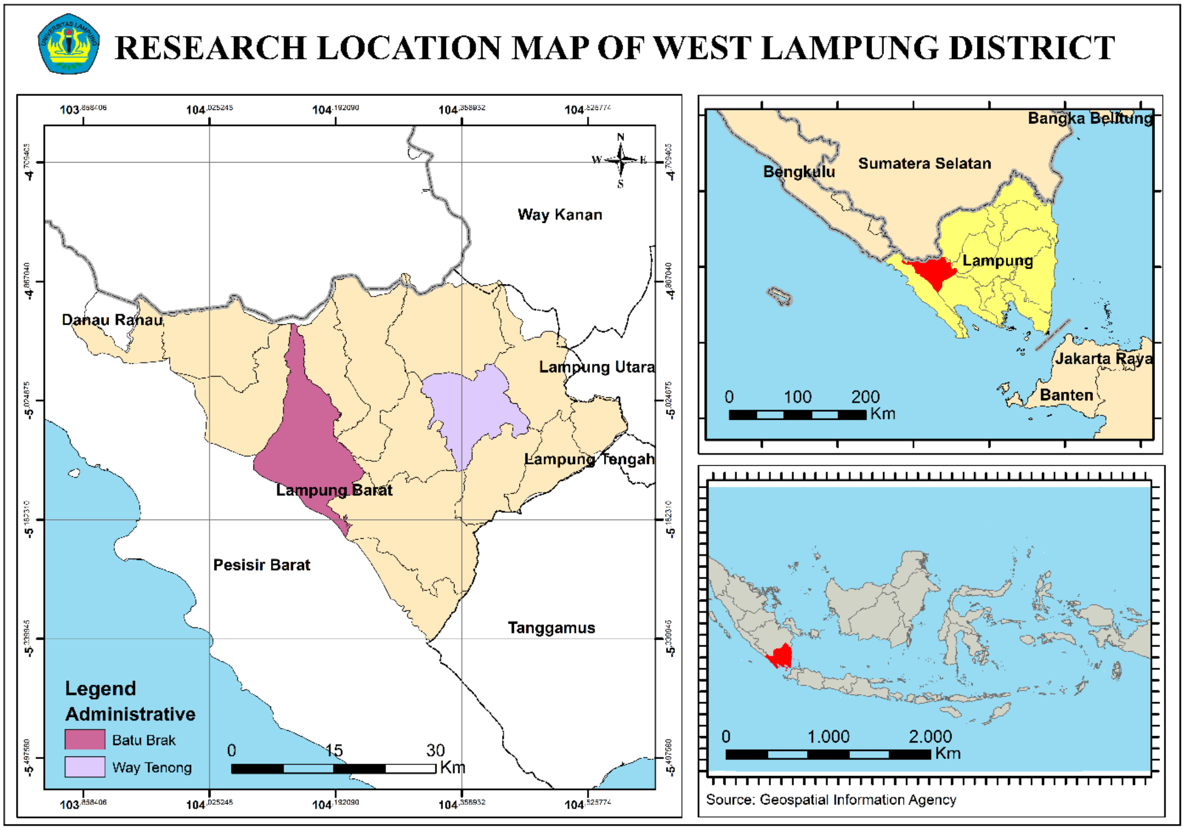

Figure 1.
Research areas in Lampung Province, Indonesia.

In this study, sample categorization was carried out by considering variations in the implementation of agroforestry systems on coffee land, which were then divided into three groups of farmers, namely: CMS (Coffee Monoculture System), SAFS (Simple Agroforestry System) and CAFS (Complex Agroforestry System). CMS refers to coffee farms managed as monocultures without shade trees, while SAFS involves one to two species of shade trees grown alongside coffee plants. CAFS, or complex agroforestry systems, are systems that integrate more than two shade tree species with coffee crops, providing environmental benefits and more sustainable agriculture [36]. For ease of understanding and subsequent discussion, the abbreviations CMS, SAFS, and CAFS will be used in this study. This study involved 210 respondents, consisting of 70 farmers in each system, as well as expert respondents who understand the sustainability of coffee farming, namely from Field Agricultural Extension Workers, the Office of Agriculture, marketing actors, and academics.

2.2. Data Analysis

In assessing the performance of coffee farms, this study adopted an approach that focuses on farm productivity and income. Productivity is divided into coffee productivity and land productivity. Coffee productivity refers to the output produced by coffee plants per unit of land area, reflecting the extent to which the resources and cultivation techniques used are effective. On the other hand, land productivity assesses the extent to which the land used for coffee farming can produce maximum output, be it coffee or by-products from intercropping systems or other cropping patterns. Land productivity is calculated by combining coffee yield per hectare and coffee-equivalent production from intercropping per hectare [37-39]. The calculation of land productivity can be done using equations (1-2).

$$LP = Y_c + Y_{ce} \quad (1)$$

$$Y_{ce} = \frac{Y_i \times P_i}{P_c} \quad (2)$$

LP denotes land productivity (kg/ha), where Y_c is the yield of coffee (kg/ha), Y_{ce} is the yield of coffee equivalent (kg/ha), Y_i is the yield of intercrops (kg/ha), while P_c and P_i refer to the market price of coffee and intercrops [37-39].

Farm income is divided into two, namely (a) coffee income is the receipt of coffee farming minus the costs incurred in one year measured by IDR, and (2) land income is the receipt of all plants on the coffee farm (coffee income and agroforestry crop income) minus the costs incurred in one year measured by IDR. To test whether there are differences in farm performance between patterns, an ANOVA test (F test) is used. Furthermore, to distinguish productivity and income between the two agroforestry systems using the post-hoc test (Duncan's test).

Furthermore, in assessing the sustainability of coffee farming and strategies to improve it, the Multiaspect Sustainability Analysis (MSA) technique was used with the help of Exsimpro software. The MSA analysis framework provides a multidimensional perspective on system sustainability by covering five fundamental aspects, namely environmental, economic, social, institutional, and technological. In this case, MSA is not only used to assess the sustainability index and status but is also able to identify sensitive factors of each aspect through leverage analysis [40]. These factors, which can be found in detail in Table 1, form the basis for developing scenarios to determine strategies for improving the sustainability of coffee farming.

The sustainability analysis process was conducted through eight systematic stages visualized in Figure 2. The stages began with preparing a questionnaire designed based on the identification of research objectives. The next step is to collect preliminary data through field observations and evaluate the data obtained, then develop a scoring method using an ordinal scale with a score of 0 to 4 (0 bad category and 4 good category). The collected data was then processed using MSA (Multidimensional Scaling Analysis) software to produce a sustainability score while identifying sensitive factors that most influence sustainability. These sensitive factors formed the basis for designing scenarios to improve sustainability. The final stage is to implement the results of the analysis in real-life scenarios to achieve the expected sustainability goals [41].

Table 1.
Aspects and factors of coffee farm sustainability.

Factor	Operational Definition
Ecological	
1. Land and agro-climatic suitability	Land suitability and agro climate for coffee plants
2. Land area	Cropland area managed coffee
3. Grafting	Percentage of coffee plants that have been grafting
4. Plant age	Age coffee plants
5. Pest and disease attacks	Attack rate pest disease (%)
6. Coffee waste utilization	Utilization of waste for organic fertilizer
7. Land distance	Coffee farm distance with home where to live
8. Conservation land	Conservation measures land
9. Coffee shade	Amount of shade (trees/ha)
10. Use of chemical fertilizers	Use of chemical fertilizers
11. Road access	Farm road access
12. Drought	Frequency of drought in the last 10 years
Economic	
1. Advantages of coffee	Advantages of coffee farming (R/C)
2. Advantages of intercroppings	Advantages of intercropping coffee (share to coffee)
3. Capital availability	Farmers' ability to access and use funds for coffee production
4. Location of coffee sales	Locations where coffee farmers sell their products, including local markets and export hubs
5. Market access	Coffee farmers' ability to access and utilize markets
6. Productivity	Coffee productivity
7. Coffee income contribution	Contribution of coffee income to neighbourhood income
8. Income compared to minimum wage	Income compared to minimum wage
9. Pricing	Traders, farmers, or both influence coffee prices
10. Coffee price	Farmer's Coffee Price
Social	
1. Education	Level formal education of farmers
2. Gender roles	Women's involvement
3. Land status	The classification of land as forest land/lease, owned land, or certified owned land
4. Age of farmer	Average age farmers
5. Access to agricultural activities	Community access to agricultural activities
6. Role of public and private institutions	Empowerment communities from the government and private sector in agricultural activities
7. Child engagement	Labor engagement <18 years
8. Time allocation for farming	Time allocation for coffee farming
9. Safety and security	It involves protecting workers, crops, and equipment from risks like accidents and theft
10. Infrastructure	Infrastructure availability in agricultural activities
Institutional	
1. The role of extension workers	Existence and the role of the agricultural extension service
2. Agricultural inputs store	Facility kiosk agricultural production
3. Microfinance institutions	Existence microfinance institutions (MFIs)
4. Participation farmers in groups	Participation farmers in farmer groups
5. Access to technology sources	Farmers' access to technology sources
6. Partnership cooperation with companies	Partnership cooperation with private companies
7. Marketing channel	Marketing channel length
8. Activity and financial reports	Activity and financial reports
Technology	
1. Use of quality seeds	Use of quality and certified seeds
2. Coffee entry clones	The types of coffee clones used are local, mixed, and superior
3. Grafting	Percentage of coffee plants that have been grafted
4. Coffee drying	The method of drying beans using ground floor, tarpaulin, drying floor, or a combination

5. Fertilization measures	Farmers' fertilization following recommendations, or none is done
6. Action crop pruning	Coffee plant pruning practices by farmers
7. Routine shade pruning	Routine shade pruning measures
8. Harvesting technique	The collection of coffee cherries, ranging from pickling to those that are still red.
9. Level mastery and application of technology	Level mastery and application of cultivation technology owned by farmers
10. Plant spacing	The distance between coffee plants is suitable or not suitable

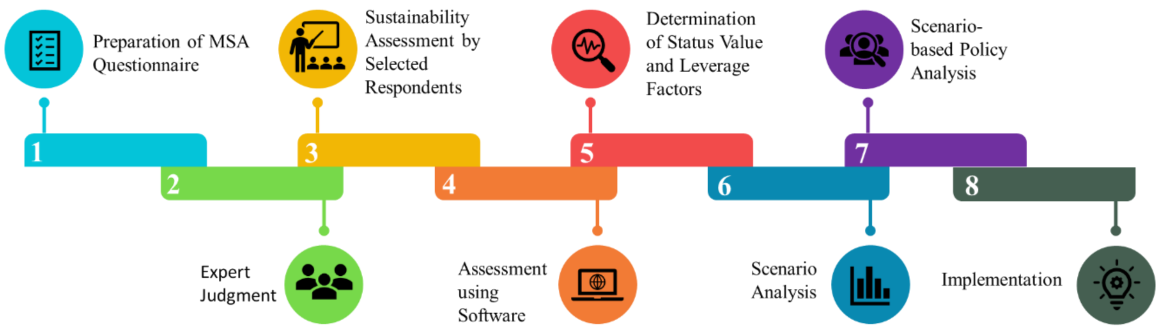

Figure 2.
Sustainability analysis stages.

3. Result and Discussion

3.1. Characteristics of Respondents

The characteristics of coffee farmers collectively affect the productivity and income levels of farmers. Coffee farming in West Lampung Regency is predominantly conducted by male farmers (99.05%). This trend is consistent with previous findings in developing countries, which state that male dominance is consistently high in economic and agricultural enterprises (e.g. coffee production), as women tend to be more involved in reproductive and non-economic activities than men [42].

Table 2 illustrates the characteristics of coffee farmers in West Lampung Regency. The average age of farmers in the CMS, SAFS, and CAFS systems is 44.67 years, 43.99 years, and 46.03 years, respectively. Most farmers have a limited level of formal education, with the majority graduating from primary school, namely 81.43% in the CMS system, 55.71% in the SAFS system, and 42.86% in the CAFS system. This limited level of education affects farmers' ability to adopt new practices and actively participate in marketing activities. In addition, farmers have an average of 18 to 19 years of coffee farming experience for the three agroforestry systems. The average number of family members of farmers ranged from 3 to 4 people, which also affected their level of expenditure and capacity to invest in farming. All farmers who adopted the agroforestry systems, whether CMS, SAFS, or CAFS, also belonged to farmer groups, which supported joint activities and information exchange among farmers.

Table 2.
Demographic aspects of respondents.

Category	CMS		SAFS		CAFS	
	Mean	**Std. dev**	**Mean**	**Std. dev**	**Mean**	**Std. dev**
Education (years)	6.66	1.97	8.26	3.03	8.84	3.04
Age (years)	44.67	12.15	43.99	12.44	46.03	12.43
Number of family members (people)	3.60	1.10	3.49	0.88	3.60	1.12
Farming experience (years)	18.36	10.26	19.06	12.15	19.06	11.05

3.2. *Overview of Coffee Farming*

The complex agroforestry system has the largest area compared to the other systems, with 1.52 ha, as shown in Table 3. Coffee plants in this region have an average age of 21-23 years, which may affects the quality and taste of the coffee beans, in line with the findings of Lucchese and Di Carlo [43]. Land distances to the farmers' homes range from 4 to 8 kilometres, with the complex agroforestry system having the longest land distance at 7.94 kilometres. The average land elevation of the three systems is >800 meters above sea level. This elevation creates optimal environmental conditions to support the growth of coffee plants with superior taste, considering that robusta coffee (Coffea canephora) is cultivated at an optimal elevation between 600-1000 masl [44, 45]. On the other hand, the complex agroforestry system has the lowest number of main plants, with 2,347 trees/ha, but also the highest number of intercropped plants, with 353 trees/ha.

Table 3.
Overview of coffee farming.

Category	CMS		SAFS		CAFS	
	Mean	**Std. dev**	**Mean**	**Std. dev**	**Mean**	**Std. dev**
Land area own per farmer (ha)	1.21	0.69	1.13	0.54	1.52	1.05
Distance from house to coffee farm (km)	4.06	5.70	4.66	6.70	7.94	10.63
Elevation of coffee farm (above sea level)	866.67	142.23	829.55	198.00	845.45	101.08
Plant age (years)	21.14	7.62	22.10	11.56	23.27	10.82
Number of coffee plants (trees/ha)	2,427	451	2,405	447.50	2,347	353.52
Number of intercropped plants (trees/ha)	00.00	00.00	231.38	129.60	353	112.50

Intercropping plants in coffee plantations have been demonstrated to form coffee-based agroforestry systems, thereby functioning as coffee shade, which plays a pivotal role in the development of sustainable coffee agroecosystems. Conversely, in coffee monoculture system, farmers do not typically engage in intercropping practices. In West Lampung, intercropping plants are predominantly fruit and plantation crops, including avocado, durian, banana, duku, dog fruit, stink bean, candlenut, cloves, cinnamon, and black pepper that climbs on gliricidea (*Gliricidea sepium*) or coral tree (*Erythrina lithosperma*) plants. Additionally, wood-producing trees such as umbrella tree (*Maesopsis eminii*), champaca wood (*Michelia champaca* L), medang (*Litsea* spp.), rosewood (*Dalbergia latifolia* Roxb), silk tree (*Albizia chinensis*), and cotton wood (*Ceiba pentandra*) are utilized. The number of intercropping plants in the SAFS pattern is 231 trees/hectare, and in the CAFS pattern, 353 trees/hectare. The intercropping of plants in coffee plantations has been shown to generate substantial income, with the SAFS pattern yielding IDR 3,733,237.02/ha/year and the CAFS pattern generating IDR 5,448,173.71/ha/year. The predominant crop in both patterns is black pepper, accounting for 84.95% in the SAFS pattern and 52.62% in the CAFS pattern. A noteworthy finding is that the complex agroforestry system exhibited a higher intercropping income of 44.94% compared to the simple agroforestry system, thereby underscoring the notion that diversification of crops within agroforestry complex systems leads to enhanced economic benefits for farmers.

3.3. *Coffee Farm Performance*

The coffee farm performance analysed in this study was coffee productivity, land productivity, coffee price, coffee income, and land income. Coffee productivity calculates only coffee production (in the form of dried ground coffee). In contrast, land productivity is obtained by calculating the total output of all crops on the coffee farm and equating it to coffee production. Thus, land productivity is the total revenue from all crops divided by the price of coffee.

Coffee farm income is the difference between total revenue and farm costs. Total coffee farm income is the product of production (kg) with the price per unit of production (IDR/kg) received by farmers. Coffee income is when the income earned by farmers that calculated only from coffee production. At the same time, land income is when the income earned by farmers also takes into account the income from intercropping crops. The performance of coffee farming in West Lampung is shown in Table 4.

Table 4.
Performance of coffee farming in West Lampung.

Decription	CMS	SAFS	CAFS	F	Sig.
Coffee productivity (IDR/ha)	815.18[a]	888.75[b]	965.21[c]	5.812	0.0035
Land productivity (IDR/ha)	815.18[a]	994.50[b]	1,119.73[c]	22.549	0.0000
Coffee price (IDR/kg)	35,748.57[a]	35,301.43[a]	35,260.00[a]	1.058	0.3489
Coffee income (IDR/ha)	21,756,344.14[a]	24,523,309.72[b]	26,854,753.39[b]	6.070	0.0027
Land income (IDR/ha)	21,756,344.14[a]	27,832,685.69[b]	31,829,620.50[c]	17.402	0.0000

Note: Means in the same row followed by the same letter are not significantly different according to Duncan's test 0.05.

CAFS coffee productivity was the highest of the three patterns at 965.21 kg/ha, and the lowest was CMS at 815.18 kg/ha (Table 4). Similarly, for land productivity, CAFS was the highest (1119.74 kg/ha), followed by SAFS (994.50 kg/ha), and the lowest was the CMS (815.18 kg/ha). Anova test results showed there were differences in coffee and land productivity between the three systems. The results of further tests with Duncan's post-hoc test (Table 4) reinforced that coffee and land productivity were respectively the highest in CAFS, SAFS, and CMS. Shade crops can serve as an important source of organic matter that is cheap and easy to obtain, thus increasing productivity. In terms of farm-gate coffee prices, there is statistically no difference in the selling prices of the three agroforestry patterns, which range from Rp35,260.00/kg - Rp35,748.57. The quality of coffee beans produced by farmers is almost the same, and farmers usually sell coffee to collectors in the village.

High coffee and land productivity in CAFS and SAFS resulted in high farm income (Table 4). Coffee farm income was IDR 21,756,344.14/ha for CMS, IDR 24,523,309.72/ha for SAFS, and IDR 26,854,753.39/ha for CAFS, and land income was IDR 21,756,344.14/ha for CMS, IDR 27,832,685.69/ha for SAFS, and IDR 31,829,620.50/ha for CAFS, respectively. Farmers who implement agroforestry will get additional income from shade trees and intercropping crops. Further test results from Duncan's test showed that land income in CAFS was higher than in SAFS, and SAFS was higher than in coffee monoculture system (CMS). Almost all farmers use gliricidea as coffee shade trees. Besides being used for coffee shade, gliricidea are also used as climbing trees for black pepper plants. At the time of the research, the price of pepper was IDR 88,628.00/kg. The number and type of plants chosen influence the increase in income in the agroforestry system.

Agroforestry applied by farmers can increase coffee productivity, land productivity, coffee income, and land income. Agroforestry systems are beneficial for increasing soil moisture, nutrient content, and soil chemical status [46, 47]. Agroforestry systems can provide additional ecosystem services, including carbon sequestration, pest control, and income diversification through the integration of other crops, such as bananas or avocados [3, 48].

The above analysis suggests that coffee-based agroforestry crops increase farmers' incomes and can reduce losses if coffee prices fall. The main challenge in agroforestry systems is competition between coffee plants and shade trees, which can sometimes reduce coffee yields. Therefore, it is necessary to select shade species with high economic value and pay attention to shade density.

3.4. Sustainability of Coffee Farming

3.4.1. Determination of Validation Status

Validation in MSA is done by comparing the random and mode values of each factor assessed. According to the validation principle in this method, the accepted error value should not exceed 0.5 in absolute terms from the mode value [40]. The average validation score for all aspects reached 1.89% (Table 5), below the 5% threshold. It indicates that the data generated is valid and can be used in the sustainability analysis. This value also indicates that the variation in scoring due to differences in respondents' opinions is small, the analysis process is stable over multiple iterations, and errors in data

Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 5: 960-978, 2025
DOI: 10.55214/25768484.v9i5.7044

processing are minimized. This validity ensures that iterative analysis results in consistency and avoids the risk of error or bias in data input.

Table 5.
Validation status of sustainability aspects in coffee farming.

Aspect	Status Validation (%)
Ecological	2.42
Economic	0.00
Social	1.40
Institutional	3.00
Technology	2.64
Average	1.89

3.4.2. Sustainability Status

The grouping of sustainability status is divided into five categories: value 0-20 for unsustainable category, value >20-40 for low sustainability category, value >40-60 for medium sustainability category, value >60-80 for sustainable category, and value >80-100 for very sustainable category [40]. Figure 3 shows the sustainability value of coffee farming in each agroforestry system.

The analysis revealed that coffee farming with an agroforestry complex system (CAFS) has the highest sustainability value. This system shows economic and ecological advantages compared to simple agroforestry and coffee monoculture system. It shows that the agroforestry complex system can maximize environmental benefits while increasing economic benefits. The coffee industry, prone to price fluctuations, requires strategies combining ecological practices with economic resilience to ensure long-term sustainability [49].

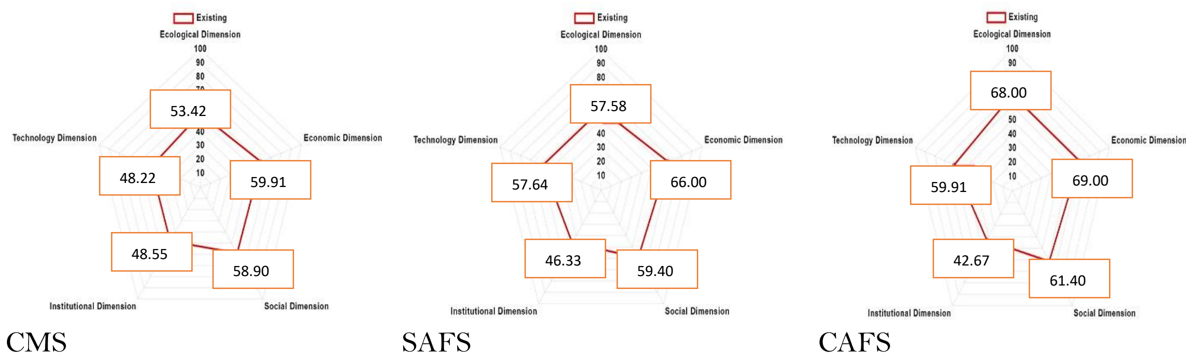

Figure 3.
Status values between aspects in coffee farming.

The sustainability status of coffee farming in West Lampung is categorized as moderately sustainable for all three types of agroforestry systems: coffee monoculture system (CMS), simple agroforestry system, (SAFS) and complex agroforestry system (Table 6). Improving sustainability status needs to focus on factors that support the sustainability of coffee farming. Ecological, institutional, and technological aspects require comprehensive and continuous improvement. Neel [50] reported that improvements in ecological and institutional aspects are needed to improve the sustainability of coffee farming. Improving environmental practices and considering biodiversity from an ecological perspective is important. Meanwhile, on the institutional side, stronger support and better governance structures are needed to support the sustainability of coffee farming.

DOI: 10.55214/25768484.v9i5.7044

Table 6.
Comparison of sustainability status between agroforestry systems.

No.	Aspect	CMS	SAFS	CAFS
1	Ecological	53.42	57.58	68.00
2	Economic	59.91	66.00	69.00
3	Social	58.90	59.40	61.40
4	Institutional	48.22	46.33	42.67
5	Technology	48.55	57.64	59.91
Total Average		53.80	57.39	60.20
Sustainability Status		Moderate Sustainable	Moderate Sustainable	Moderate Sustainable

3.4.3. Leverage Factors in Each Aspect

Identifying the driving or leveraging factors is important in providing information regarding which factors can be improved to improve the overall sustainability status. In the visualization of the analysis results, there are two important indicators; the green color represents the sensitivity max value, which reflects how much the factor can be moved. The larger this value, the higher the sensitivity of the factor and the yellow color represents the sensitivity value, which is the actual value of the factor. In general, the combination of sensitivity max and sensitivity value results in the sensitivity leverage value, which indicates the priority of the factor in improvement. The factor with the highest leverage is the top priority for improvement because it has the greatest influence on improving the sustainability index.

3.4.3.1. Ecological Aspect

In simple and complex agroforestry systems, the factors that have the highest sensitivity to sustainability are drought and coffee waste utilization (Figure 4). Drought proved to be very significant in threatening sustainability as it can cause a decrease in plant vigor, inhibit flowering and seed formation, and negatively impact productivity and yield, as described by Ning, et al. [51]. In addition, coffee farming produces a high volume of waste. However, the lack of understanding of farmers regarding the potential benefits of waste causes the majority of farmers to be reluctant to process it, as stated by Parsa and Sarraf [52].

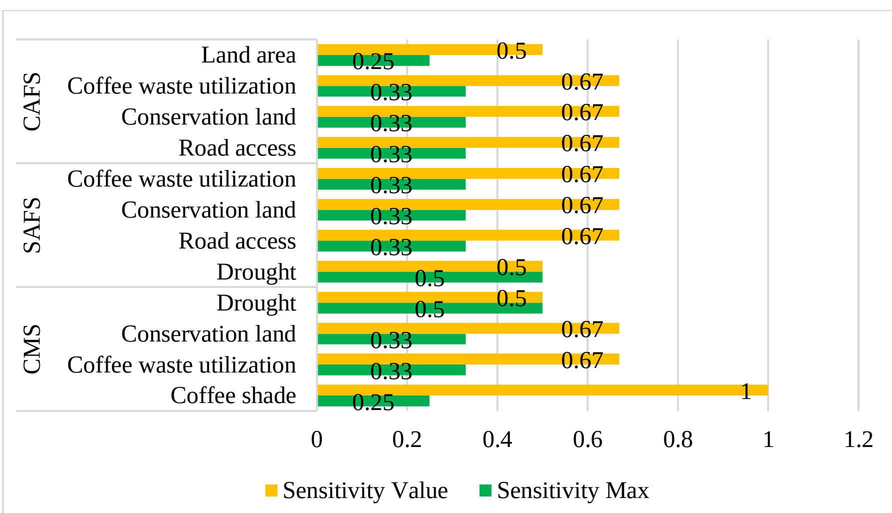

Figure 4.
Sensitivity leverage factors for ecological aspects.

Meanwhile, in the coffee monoculture system (CMS), the highest sensitivity factor was the number of coffee shade plants (1.00), followed by coffee waste utilization (0.67) and drought (0.50). This difference occurs because, in the CMS, shade crops play an important role in improving sustainability by supporting biodiversity, maintaining soil health, and strengthening resilience to climate change, as described by Pisano and Landriani [53]. Therefore, although coffee waste utilization and drought are major factors in agroforestry systems, the integration of shade crops in CMS contributes greatly to sustainability and environmental resilience.

3.4.3.2. Economic Aspect

In simple and complex agroforestry systems, capital availability and market access are the most sensitive factors to sustainability (Figure 5). Capital availability and market access are the main factors affecting sustainability in both simple and complex agroforestry systems. Limited capital is the main obstacle for farmers to rehabilitate coffee farms, which leads to many old coffee plants and decreased productivity, thus negatively affecting farmers' income and the sustainability of the coffee farm itself [54]. In addition, good market access allows farmers to sell their crops at more favorable prices, especially in coffee supply chains that often experience price asymmetry. Many smallholders in the coffee supply chain struggle due to limited direct access to the market, so they rely on intermediaries that reduce the profit margins they receive [55, 56].

In the monoculture system, farmers only rely on income from coffee plants, so the most sensitive factor is the profit from intercropping (0.67), in addition to the availability of capital and market access. In contrast to this system, in simple and complex agroforestry systems, farmers have two sources of income, namely from coffee plants and intercropping plants. Implementing agroforestry systems provides opportunities for farmers to grow companion crops alongside coffee, which not only creates additional income streams but also supports economic sustainability through farm diversification [57].

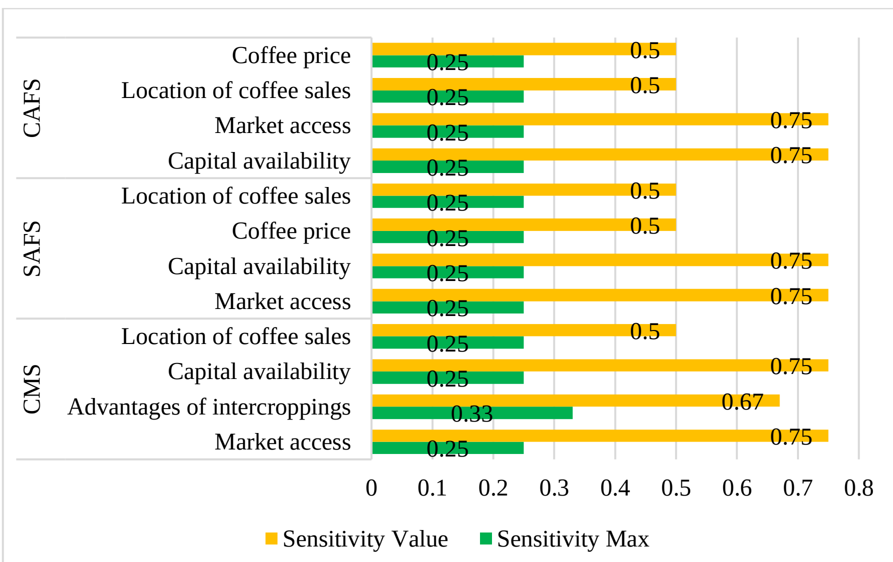

Figure 5.
Sensitivity leverage factors for economic aspects.

3.4.3.3. Social Aspect

In the social aspect, the factors that most influence the sustainability of coffee farming, both in simple and complex agroforestry systems, are occupational safety, security, and infrastructure (Figure 6). Most coffee farmers do not use personal protective equipment (PPE) when farming, even though using PPE, especially in pesticide spraying activities, is very important to reduce potential adverse health impacts [58]. In addition, poor road conditions are often an obstacle for farmers when tending crops, harvesting, and transporting crops and production facilities. Infrastructure improvements, such

DOI: 10.55214/25768484.v9i5.7044

as improved road quality, are expected to facilitate access to markets and increase operational efficiency, ultimately contributing to the sustainability of coffee farming [59].

On the other hand, in the coffee monoculture system, the most sensitive factors are the farmer's education level, job security and safety. This is due to farmers' low level of education in the coffee monoculture system, most of whom only have primary school-level education. Higher education can help farmers understand more efficient and environmentally friendly farming techniques [60] thus improving the sustainability of coffee farming in the future.

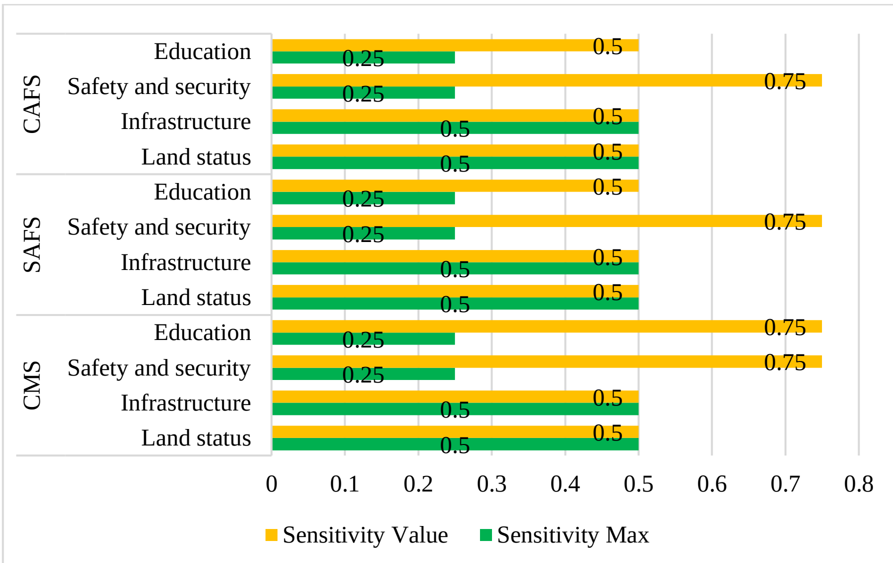

Figure 6.
Sensitivity leverage factors for social aspects.

3.4.3.4. Institutional Aspect

The factors with the highest sensitivity to institutional aspects in agroforestry systems (coffee monoculture, simple agroforestry, and complex agroforestry) that affect the sustainability of coffee farming are activity and financial reports, partnerships with private companies, and the presence of microfinance institutions (Figure 7). Coffee farmers are generally not accustomed to making activity and financial reports, even though good financial management and regular reporting are essential to support accurate information-based decision-making. It will improve operational efficiency and the sustainability of coffee farming in the long term [61]. On the other hand, most coffee farmers in this area have established partnerships with private companies, facilitating their adoption of sustainability certification. This certification significantly increases farmers' income, as described in a study [62].

In addition, the presence of microfinance institutions (MFIs) also greatly supports coffee farmers by providing access to financial services that help improve their economic stability, particularly for underserved groups [63]. Overall, these institutional factors play a very important role in strengthening the sustainability of coffee farming, both in agroforestry and coffee monoculture systems.

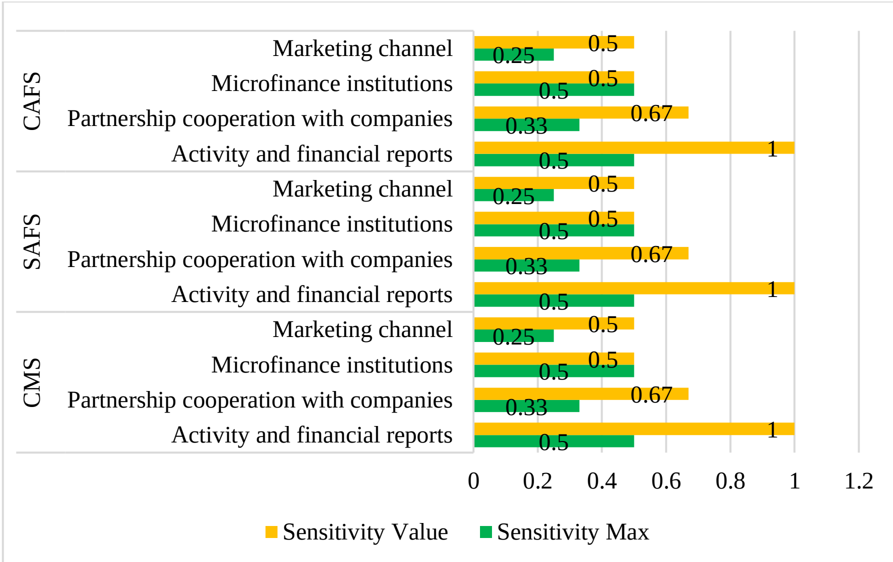

Figure 7.
Sensitivity leverage factors for institutional aspects.

3.4.3.5. Technological Aspect

In various agroforestry systems, whether coffee monoculture, simple agroforestry, or complex, factors such as spacing, seed sorting, and fertilization are very sensitive elements in supporting the sustainability of coffee farming (Figure 8). Currently, most coffee farmers use a planting distance of 1.5 m x 1.5 m, even though Direktorat Jenderal Perkebunan Kementerian Pertanian [64] recommends a more ideal planting distance of 2.5 m x 2.5 m. The selection of the right planting distance can affect the growth of coffee plants. Choosing the right planting distance can affect plant growth, yield, height, and internode length and increase overall productivity [65]. In addition, many coffee farmers in West Lampung Regency do not sort the beans properly after harvest. An effective sorting process can reduce defects in coffee batches, directly affecting the coffee quality [66]. Using more sophisticated sorting technology can also increase farmers' income by increasing the selling value of coffee [67].

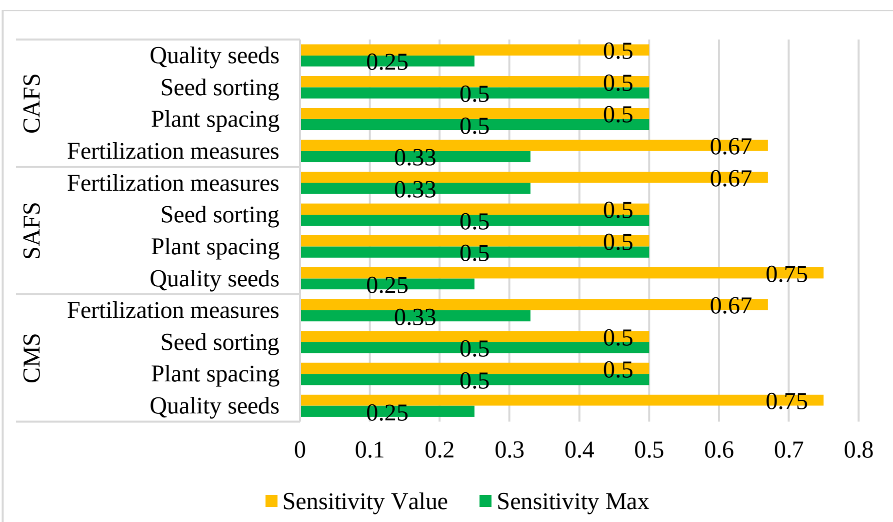

Figure 8.
Sensitivity leverage factors for technology aspects.

Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 5: 960-978, 2025
DOI: 10.55214/25768484.v9i5.7044

On the other hand, most coffee farmers in this area apply inappropriate doses of fertilizer, often due to limited capital to purchase fertilizers. Improper fertilization can lead to problems such as late fruit ripening, flower drop, and increased risk of soil diseases [68]. These factors greatly affect the sustainability of coffee farming, and improvements in spacing management, bean sorting, and fertilization can significantly increase coffee production efficiency and yield.

3.4.4. Strategies for Coffee Farm Sustainability

The sustainability strategy of coffee farming was conducted through scenario analysis of the factors that are most sensitive to its sustainability. Policy scenario validation was conducted by comparing scenario 1 and scenario 2, i.e., which scenario provided the highest scores and most significant changes. Scenario 2 was increased twofold or higher than scenario 1.

On the ecological aspect, 68.67% of farmers face drought. Solutions to reduce the impact of drought on coffee farming include applying shade plants [69]. Improving land conservation can be done by building terraces, mounds, and drainage channels that support increased water infiltration, reduce surface flow, and minimize erosion, thus creating better water retention and healthier soil conditions. Improved road access can be achieved through improving road infrastructure and optimizing the availability of vehicles [70]. Improved road access can be achieved through improving road infrastructure and optimizing the availability of vehicles [71].

From an economic aspect, the availability of capital can be improved through multifaceted approaches such as microfinance, alternative funding sources, and improved financial literacy among farmers [72]. A total of 57.94% of farmers have difficulties in accessing credit. Therefore, adjusting the microfinance payment structure to align with the coffee production cycle will improve capital accessibility. Farmers' market access can be improved through coffee certification, increasing product value and attracting premium markets. 25.24% of farmers in West Lampung have not undergone the certification process. Most farmers sell their harvest to middlemen or intermediary traders, while the remaining 27.61% have direct access to large traders and exporters. Training and access to information on price trends, market demand, and export opportunities can help farmers make better decisions regarding sales.

There are 19.39% of farmers do not yet have a certificate of ownership, which is very important for maintaining the sustainability of coffee farming. Ownership of certificates protects farmers from land conflicts that could disrupt productivity. The government provides the TORA (Tanah Objek Reforma Agraria) Program, intended for lands managed without clear ownership status. Gara, et al. [73] reported that agricultural sustainability is higher for farmers who own their land than those who only rent land. In addition to land status, infrastructure is important to improve coffee production, distribution, and quality efficiency. Coffee bean drying facilities need to be built, as only 1.42% of farmers have drying floors. Coffee storage warehouses also need to be provided to maintain the quality of the beans before they are sold and reduce the risk of price drops. In addition, farmers' health and safety aspects also need to be considered. A total of 30.97% of farmers experienced health problems due to pesticide exposure. Using personal protective equipment (PPE) during spraying can protect farmers from the dangers of chemicals.

In terms of institutional aspects, the presence of microfinance institutions is an important factor in supporting the sustainability of coffee farming. Although farmers usually borrow from banks, difficult access to credit makes them need other financial institutions, such as cooperatives, which make it easier to borrow capital. As many as 33.09% of farmers feel that cooperatives can reduce financial risks due to capital shortages. Capital shortages can be overcome by cost planning. However, 24.03% of farmers rarely make financial reports on their farms, which hinders efficient cost planning. In addition, partnerships with private companies are also a supporting factor for farm sustainability. In addition to the presence of microfinance institutions, cooperative partnerships with private companies are also a factor driving the sustainability of coffee farming. As many as 68.67% of farmers partnered with private companies found capital, input availability, and marketing easier and more profitable due to shorter supply chains.

Technological aspects also play an important role, including appropriate spacing. As many as 72.53% of farmers do not apply the recommended spacing recommended by Direktorat Jenderal Perkebunan Kementerian Pertanian [64] thus requiring improvement to increase sustainability. Post-harvest seed sorting is also important, but only 18.02% of farmers do it, while 81.79% do not. Manual sorting requires additional labor, and results tend to be inconsistent. Technologies such as Programmable Logic Controllers (PLC) and load cells can help in the accurate measurement and classification of fruits and provide consistent results [72]. These technologies are suitable for smallholder farmers and traders to fulfil the market need for efficient and affordable sorting solutions. On the fertilization factor, 43.78% of farmers did not apply the recommended dosage, with the majority (80.25%) using chemical fertilizers, while the remaining 19.74% used organic fertilizers. Organic fertilizers, such as compost from coffee husk waste, can improve soil fertility, preserve nutrients and water, and increase crop yields [74].

After analysing the two scenarios, the results in Table 7 show that scenarios 1 and 2 are already in the sustainable category. It indicates that implementing various strategies in all aspects can increase the level of sustainability of coffee farming from moderate to very sustainable category. However, Scenario 2 offers a rather high leap for the sustainability value of the coffee farming agribusiness when compared to the average value. Overall, Scenario 2 offers the best potential for sustainability in all dimensions compared to current conditions and Scenario 1. Scenario 1 stands out in some aspects but is weak in institutional, environmental and technological aspects.

Table 7.
Sustainability status across different scenarios by aspect.

No.	Aspect	Existing	Scenario 1	Scenario 2
1	Ecological	57.58	67.42	77.17
2	Economic	66.00	74.36	90.18
3	Social	61.40	73.90	85.50
4	Institutional	48.00	58.50	85.50
5	Technology	57.64	69.82	79.64
Total Average		58.12	68.80	83.60
Status Sustainability		Moderate Sustainable	Sustainable	Very Sustainable

A prioritized scenario test with the values of ΔS1S and ΔS2S shown in Table 8 was performed to evaluate the efficiency of the different sustainability strategies. The values show the improvement or change in each aspect in scenarios 1 and 2. The ratio ΔS2S/ΔS1S measures the extent of change from the initial to the advanced scenario. In ecological aspects, scenario 2 obtained an increase in sustainability of 19.59, almost twice as much as scenario 1, which only reached 9.84. The highest increase occurred in the economic aspect, where scenario 2 showed a ΔS2S of 24.18, almost three times greater than scenario 1. The same can be seen in the social aspect with ΔS2S of 24.10 compared to ΔS1S of 12.50, signalling a significant improvement from the advanced scenario.

Table 8.
Test scenarios prioritize all aspects of sustainability.

Aspect	ΔS1S	ΔS2S	ΔS2S/ΔS1S
Ecological	9.84	19.59	1.99
Economic	8.36	24.18	2.89
Social	12.5	24.10	1.93
Institutional	10.5	37.50	3.57
Technology	12.18	22.00	1.81
Average Scenario Priority			2.44

In addition, the institutional aspect recorded the most striking difference with a ΔS2S/ΔS1S ratio of 3.57, indicating scenario 2's major contribution in strengthening coffee farming institutions. Although the improvement in the technological aspect is not as great as the other aspects, scenario 2 still excels with an ΔS2S of 22.00 compared to 12.18 in scenario 1. The average ΔS2S/ΔS1S ratio of 2.44 confirms that scenario 2 provides more than twice the sustainability impact of scenario 1. Therefore, scenario 2 is selected as the best scenario as it includes significant improvements in all aspects of sustainability. Economic strengthening provides a stable foundation for farmers to adopt sustainable practices, while strong institutions support market access. Combined with technological improvements that promote efficiency and reduce environmental impact, scenario 2 presents a holistic approach to the sustainability of coffee farms.

4. Conclusion

The application of agroforestry systems, especially CAFS (Complex Agroforestry System), has significantly increased coffee and land productivity. In the CAFS system, coffee productivity reached 965.21 kg/ha with land productivity of 1,119.74 kg/ha, higher than the CMS (coffee monoculture system) and SAFS (Simple Agroforestry System) systems. The increase in productivity positively impacted farm income, with income reaching Rp26,854,753.39/ha for CAFS and Rp27,832,685.69/ha for SAFS. Implementing the agroforestry system proved effective in improving coffee farming performance. The sustainability status of coffee farming in West Lampung Regency is in the moderate sustainable category, with the CAFS having the highest sustainability value compared to the CMS and SAFS. The application of agroforestry systems is influential in increasing the sustainability value of coffee farming. An effective and efficient strategy in promoting the sustainability of coffee farming is to implement scenario 2 by improving key factors in five aspects of sustainability: ecological (improved land conservation, road access, drought), economic (increased capital, market access, productivity), social (improved infrastructure, education, safety and security), institutional (microfinance institutions, corporate cooperation, marketing channels), and technological (using superior seeds, adopting efficient harvesting techniques, and conducting routine pruning of shade trees).

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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DOI: 10.55214/25768484.v9i5.7044