

SUSTAINABILITY ANALYSIS OF TILAPIA CULTIVATION IN FLOATING NET CAGES (FNC) IN KEDISAN VILLAGE, BALI PROVINCE

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ABSTRACT

Floating net cage (FNC) are an aquaculture system that utilises natural water circulation through netted enclosures installed to float on the water's surface. The village of Kedisan, Bangli, Bali located on the shores of Lake Batur has developed tilapia (*Oreochromis mossambicus*) aquaculture using the FNP system as one of its key economic sectors. However, this practice faces pressures in the form of upwelling phenomena and declining water quality due to the intensification of aquaculture. This study aims to analyse the level of sustainability of tilapia aquaculture in FNS from economic, social, and environmental perspectives, identify sensitive attributes that influence sustainability, and develop scenarios for improving sustainability. The approach used was a descriptive qualitative method employing Multiaspect Sustainability Analysis (MSA) using the Eximpro software based on Rapid Appraisal for Fisheries (RAPFISH). Primary data were obtained through surveys, in-depth interviews, and questionnaires administered to 13 key informants. Secondary data were sourced from official statistics and previous studies. The results of the study indicate that the sustainability score of 72.01 falls within the sustainable category. The economic aspect scored 81.44, and the social aspect scored 89.29; both aspects are classified as highly sustainable. Meanwhile, the environmental aspect scored 45.29, falling into the less sustainable category. Leverage analysis identified the key sensitive attributes for each aspect. Sensitive attributes for the economic aspect include the impact of upwelling and the savings rate; for the social aspect, they encompass knowledge utilization and educational level; while for the environmental aspect, they consist of FNC density and aquaculture waste management. A scenario simulation of improvements through moderate interventions on these sensitive attributes increased the sustainability score to 85.83. Meanwhile, an optimistic intervention increased the score to 96.05, placing it in the highly sustainable category. These findings confirm that strengthening the socioeconomic capacity of aquaculturists and improving environmental management are key to ensuring the long-term sustainability of tilapia aquaculture in floating nets in Kedisan Village.

Keywords: Sustainability; Floating Net Cages (FNC); Multiaspect Sustainability Analysis (MSA)

INTRODUCTION

Freshwater aquaculture has become a strategic sector in supporting food security, providing a source of protein, and improving community well-being. The high pressure on marine resources due to overfishing has driven the development of freshwater aquaculture as a more sustainable alternative food source. Aquaculture activities not only ensure the availability of fish supplies and price stability but also serve as a pillar of economic growth for rural and coastal communities (Cojocar *et al.*, 2022; Nawik *et al.*, 2025). This is in line with Presidential Regulation No. 59 of 2017 on the implementation of the Sustainable Development Goals (SDGs), which emphasizes the importance of the conservation and sustainable use of marine and fisheries resources.

The province of Bali has great potential for freshwater aquaculture, such as tilapia, Nile tilapia, and catfish, particularly in the Lake Batur area, Kintamani Subdistrict, Bangli Regency (Yustiati & Lusia, 2025). Based on 2022 aquaculture (fish farming) production data published by the Central Statistics Agency (BPS), Bangli Regency ranked second in Bali Province as an aquaculture producer, with total production reaching 4,379 metric tons that year (BPS, 2023). Freshwater fish grow-out aquaculture activities in Lake Batur, Bangli Regency, are dominated by tilapia (*Oreochromis mossambicus*) using the floating net cage (FNC) system. Tilapia was chosen as the

flagship species because it is highly adaptable to water conditions, grows relatively quickly, and enjoys stable market demand, thereby offering good economic prospects for aquaculturists (Affandi *et al.*, 2025).

Data from the Bali Provincial Ministry of Marine Affairs and Fisheries shows that the number of fish farmers in Bangli Regency fluctuated between 2019 and 2023. In 2019, there were 2,036 fish farmers, and this number increased to 2,434 in 2020. However, in 2021, the number dropped to 1,979 and did not increase through 2023. The lack of growth over the past three years indicates that fish farming activities in Bangli Regency have slowed down, both in terms of the growth of new farmers and the sustainability of existing ones. This situation points to a decline in aquaculture activities in the region, including among tilapia farmers in Kedisan Village, Kintamani Subdistrict, Bangli Regency, Bali Province.

Over time, the sustainability of tilapia farming in floating nets in Kedisan Village has faced challenges spanning economic, social, and environmental aspects. The economic challenges faced by farmers stem from climatic factors, specifically the phenomenon of sulphur upwelling from the bottom of Lake Batur. This phenomenon causes tilapia mortality to increase significantly, thereby directly impacting farmers' production and income. According to information from the farmers, when upwelling occurs, tilapia mortality rates rise significantly to 50%–100%, whereas under normal conditions,

mortality rates range from 20% to 40%. The main social challenge in this aquaculture sector relates to the educational level of the farmers, the majority of whom have completed high school. Educational level is one of the sociodemographic factors influencing the adoption of aquaculture technologies; the higher the education level, the greater the tendency for farmers to adopt technological innovations and implement more efficient and sustainable business management (Kumar *et al.*, 2018). Another challenge in the social aspect is the potential for conflict over the use of lake waters due to the increasing number of floating net units, which is not always accompanied by optimal zoning regulations.

In terms of the environment, the main challenge stems from the intensive use of floating net aquaculture (FNC) in the Kedisan Village area. The high density of FNC further exacerbates water quality conditions through the accumulation of organic waste from uneaten feed and fish excrement, thereby increasing the pollution load and accelerating the degradation of aquatic environmental quality. The increase in the number of floating nets in Lake Batur has led to a rise in nutrient loads in the water, where decomposing organic waste from uneaten feed and fish metabolism produces nitrogen and phosphorus, thereby degrading water quality (Sani *et al.*, 2024). Furthermore, according to Garno *et al.*, 2024, the impact of cage aquaculture intensification in Lake Batur has led to a decline in water quality due to organic waste from feed, with an excess production of 5,947 metric tons per year. Under certain conditions, the upwelling phenomenon triggers increased tilapia mortality rates. Upwelling is the process by which water masses rise from the lake bottom to the surface, carrying toxic compounds and reducing dissolved oxygen levels, thereby causing mass fish deaths (Fukushima *et al.*, 2017). The interaction between anthropogenic pressures from tilapia farming activities in the floating nets in Kedisan Village and natural factors such as upwelling has made the aquatic ecosystem in the Kedisan Village area increasingly vulnerable to environmental degradation.

These conditions pose a serious challenge to the sustainability of tilapia aquaculture in floating nets in Kedisan Village, necessitating a comprehensive study that integrates economic, social, and environmental aspects. Several previous studies have evaluated the sustainability of aquaculture using various approaches. (Akbarurrahyid *et al.*, 2020) used the AHP-SWOT method to analyze sustainability strategies based on five key factors. At the same time (Putri *et al.*, 2019) applied the Multidimensional Scaling (MDS) approach to assess the sustainability of fish farming in floating nets at Jatiluhur Reservoir. However, sustainability studies using the Multiaspect Sustainability Analysis (MSA) method in floating net aquaculture systems in volcanic lakes such as Lake Batur remain limited. Research on Lake Batur to date has primarily focused on water quality and biological conditions. At the same time, studies integrating economic, social, and environmental aspects into a single sustainability analysis framework are still rare. MSA is a multidimensional approach capable of simultaneously identifying sensitive attributes that influence sustainability status, thereby providing a more comprehensive picture compared to analyses conducted in isolation (Paulus *et al.*, 2023). Therefore, this study aims to analyze the sustainability

level of tilapia aquaculture in floating nets in Kedisan Village, identify sensitive attributes that influence sustainability, and develop scenarios for improving sustainability.

This study uses the MSA to measure sustainability in an integrated manner across economic, social, and environmental aspects. The objectives of this study are: 1) to analyze the level of sustainability of tilapia farming in floating nets in Kedisan Village from economic, social, and environmental perspectives; 2) to identify sensitive attributes that influence the sustainability of tilapia farming in floating nets in Kedisan Village; and 3) to formulate priority scenarios to improve the sustainability of tilapia farming in floating nets in Kedisan Village.

RESEARCH METHODS

Time and Location of the Study

The research was conducted from September 2025 to January 2026. The research location was in Kedisan Village, Kintamani Subdistrict, Bangli Regency, Bali Province. Kedisan Village is located at coordinates 8°16'47.93" S and 115°22'53.71" E (−8.279981; 115.381587), with an area of approximately 11.75 km². The study site was selected purposively because Kedisan Village is geographically situated on the shores of Lake Batur, and the local community engages in tilapia farming using floating nets as a source of income. The study site map in Kedisan Village is marked with blue and red dots, as shown in the Google Satellite imagery in Figure 1.

Type of Research

This study employs a descriptive qualitative approach to analyze the sustainability of tilapia farming in floating nets in Kedisan Village based on current conditions. This approach was chosen because it provides a comprehensive understanding of the sustainability of the farming system from economic, social, and environmental perspectives through the interpretation of empirical data obtained directly from research informants.

Types and Sources of Data

The types of data in this study consist of primary and secondary data. Primary data is data obtained directly from key informants through surveys, in-depth interviews, and questionnaires. The primary data collected includes information on the state of tilapia farming in Kedisan Village, fish production levels and mortality rates, the upwelling phenomenon, environmental management practices, and assessments of sustainability attributes in economic, social, and environmental aspects.

Secondary data was obtained from literature reviews and various relevant official sources. The secondary data collected includes fisheries production data for Bangli Regency from 2019 to 2023, the number of fish farmers in Bangli Regency from 2019 to 2023, policies and regulations related to aquaculture, general conditions of the study area, and previous research findings related to the sustainability of aquaculture. Sources of secondary data included the Ministry of Marine Affairs and Fisheries, the Central Statistics Agency of Bali Province, and other scientific publications.

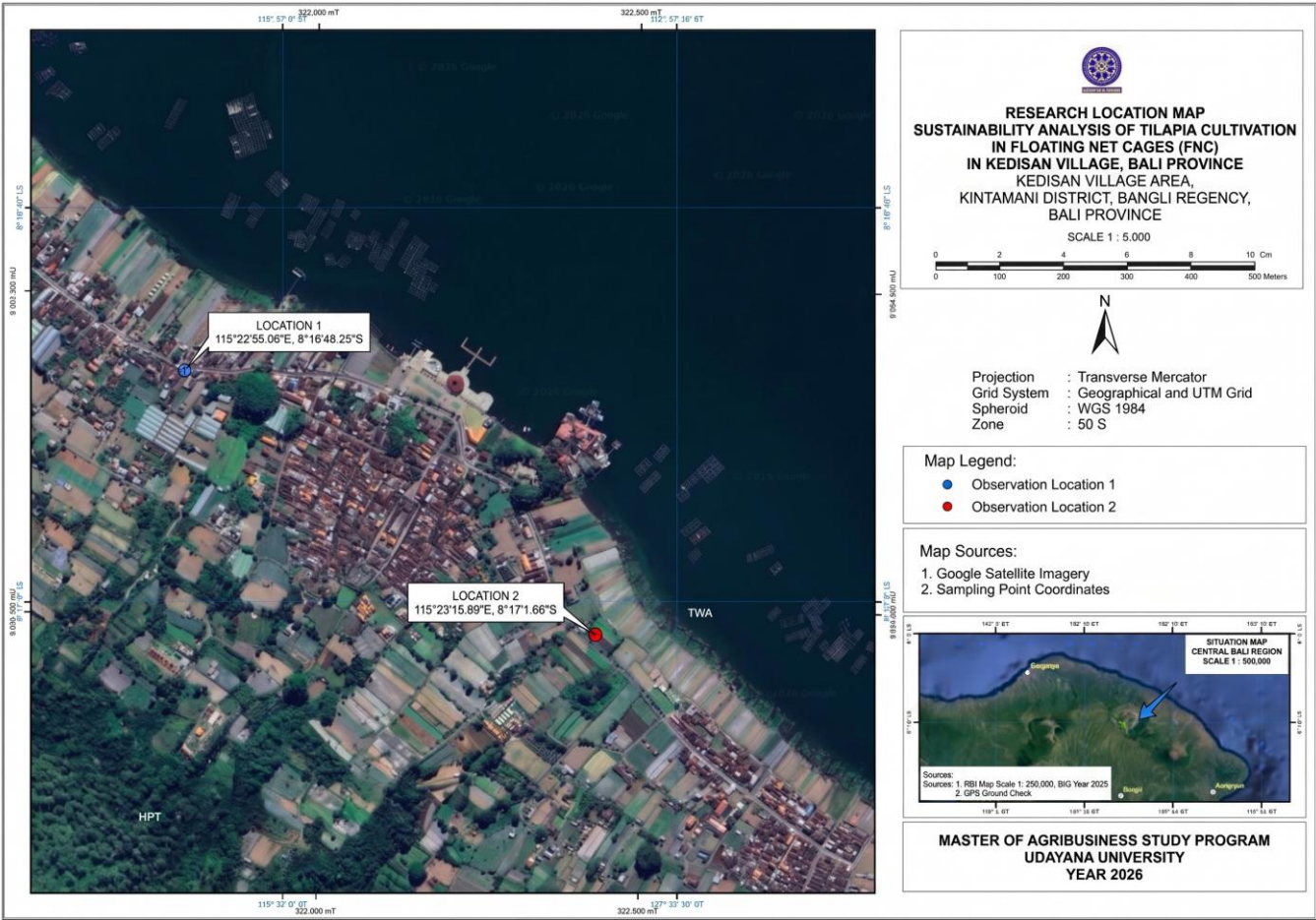


Figure 1. Research Location in Kedisán Village

Selection of Key Informants

There were 13 key informants in this study, consisting of 1 Village Head of Kedisán, 9 tilapia farmers at the floating nets in Kedisán Village, 2 representatives from the Bali Provincial Marine and Fisheries Agency, and 1 representative from the Bali Provincial Forestry and Environment Agency. Key informants were selected using purposive sampling, specifically based on the following criteria: 1) Fish farmers must have been directly involved in tilapia farming in floating nets in Kedisán Village for at least 10 years; 2) They must have a deep understanding of tilapia farming using the floating net system; 3) They must be able to communicate effectively and provide information and data relevant to the research objectives.

Research Instruments and Observation Variables

The research instruments used to assess the sustainability of tilapia farming in floating nets in Kedisán Village consisted of writing materials, questionnaires, a computer for data processing, and documentation tools. Questionnaires were used in this study to collect structured primary data related to the assessment of each aspect of sustainability. The attributes for each aspect of sustainability were determined based on a literature review, the results of previous studies, and adjustments to the actual conditions of tilapia farming at the FNC in Kedisán Village. The aspects and attributes used as observation variables in the MSA analysis regarding the sustainability of tilapia farming at the FNC in Kedisán Village are presented in Table 1.

Table 1. Sustainability Aspects and Attributes

Aspect	Attributes
Economic Aspects	Business viability (Dewi, 2020)
	Fishery household income (RTP) (Tanjov <i>et al.</i> , 2024)
	Savings rate (Hidayah <i>et al.</i> , 2020)
	Stability of fish production prices (Nugroho <i>et al.</i> , 2013)
	Feed price stability (Paulus <i>et al.</i> , 2023)
	Access to capital and credit (Nugroho <i>et al.</i> , 2013)
	Sources of additional business capital (Rachman <i>et al.</i> , 2022)
Social Aspects	Types of marketing channels (Paulus <i>et al.</i> , 2023)
	Impact of the upwelling phenomenon on aquaculture farmers' income (Key Informants)
	Educational level (Hidayah <i>et al.</i> , 2020)
	Frequency of meetings among aquaculture farmers (Nandita <i>et al.</i> , 2021)
	Extension and training (Nandita <i>et al.</i> , 2021)
	Involvement of aquaculture farmers in extension programs (Yuliana <i>et al.</i> , 2017)
	The Use of Knowledge in Aquaculture (Tanjov <i>et al.</i> , 2024)
	Cleanliness of the FNC area (Key Informant)

Aspect	Attributes
Environmental Aspects	Level of conflict among aquaculture farmers (Nandita <i>et al.</i> , 2021)
	Density of floating net cages (Key Informant)
	Aquaculture waste management (Bangli Regency Government, 2013)
	Water quality monitoring (Indonesian Law No. 32 of 2009)
	Use of chemical drugs (Paulus <i>et al.</i> , 2023)
	Frequency of fish mortality due to sulphur emissions (Key Informants)
	Fish catch size (Hidayah <i>et al.</i> , 2020)
	Biotic disturbances/predator attacks (Key Informant)

Stages of Data Analysis (MSA)

In this study, sustainability analysis employs the Multiaspect Sustainability Analysis (MSA) approach, which was developed based on the principles of Multidimensional Scaling (MDS) through an adaptation of the RAPFISH method (MDS–RAPFISH) to assess sustainability indices across multiple dimensions simultaneously (Firmansyah, 2022). The principle applied is a rapid assessment process; respondents are not a sample but rather stakeholders or key informants who can be interviewed in depth or through observation or focus group discussions (Paulus *et al.*, 2023). MSA is used to measure sustainability status and performance indices to plan future strategies, thereby facilitating effective and efficient decision-making (Ardianto *et al.*, 2024; Bancin *et al.*, 2024).

The MSA approach in this study was conducted using Eximpro software, which was developed based on the Rapid Appraisal for Fisheries (RAPFISH) method. All attributes in this study were treated equally, without any specific weighting assigned to individual attributes. This approach follows the basic principles of MDS-based MSA, in which each attribute is analyzed based on an assessment score to form a multidimensional sustainability index. The Eximpro software was used to carry out the MSA analysis process, which consists of several stages, including the calculation of aggregate status values, aspect status values, future condition values, aspect leverage factors, uncertainty errors, validation through random iteration, and policy priority scenarios (Paulus *et al.*, 2023).

The first stage in MSA analysis is the calculation of the aggregate status value to determine the sustainability level. This stage aims to identify the current position of aquaculture on the sustainability scale while also identifying which aspects are already strong and which still need improvement. According to Firmansyah (2022), the stages of MSA analysis using the Exsimpro software begin with the calculation of the aggregate status value using the following formula:

$$Y = \frac{y_1 + y_2 + y_3 + y_4 + \dots + y_n}{n} = \frac{\sum y_n}{n} \dots\dots\dots(1)$$

Where: *Y* = status value (sustainability/performance); *y* = aspect status value; *n* = number of aspects

The aggregate status value can also be calculated based on the weight of each aspect using a scoring method with the following formula:

$$Y_c = \frac{ay_1 + by_2 + cy_3 + dy_4 + \dots + my_n}{n} = \frac{\sum my_n}{n} \dots\dots\dots (2)$$

Where: *Y_c* = sustainability status score with a comparison value/weight value; *y* = aspect status score; *m* = weight value for the aspect; *n* = number of aspects

The aspect status score is derived from the mode of each indicator, which is then compared to the maximum value (the “good/highly sustainable” category) to produce a comparative value. The formula for calculating the aspect status score is as follows:

$$y = \frac{y_{f1} + y_{f2} + y_{f3} + y_{f4} + \dots + y_{fn}}{fn} \times 100\% = \frac{\sum y_{fn}}{fn} \dots\dots(3)$$

$$y_{fn} = \frac{Mo \cdot fn}{G_{fn}}$$

Where: *y* = aspect status value; *y_f* = aspect factor; *Mo* = mode value for the factor; *G* = highest/good score for the factor from the indicator analysis; *f* = factor value

The next step is to determine the future condition value. This value represents the trend of change in factors in the future, whether toward an increase or a decrease. The greater the variation in the assessment, the higher the level of uncertainty; therefore, it is necessary to consider the error value to reinforce the analysis results. The calculation formula is presented as follows:

$$F_c = \frac{MoC_1 + MoC_2 + MoC_3 + MoC_4 + \dots + MoC_n}{n} \times 25 \dots\dots\dots(4)$$

Where: *Mo* = the mode value for the factor; *C* = the future condition value for the factor

The leverage analysis phase—or leverage factor analysis—is conducted to identify the attributes that most significantly influence changes in value, thereby enabling the establishment of more targeted improvement priorities. The formula used to calculate the leverage analysis is as follows:

$$L = S_M \times S_V \dots\dots\dots(5)$$

$$S_M = \frac{1}{G_{fn}} \dots\dots\dots(6)$$

$$S_V = (G_{fn} - Mo_{fn}) \times S_M \dots\dots\dots (7)$$

Where: *L* = leverage factor value; *S_M* = maximum sensitivity; *S_V* = sensitivity value; *Mo* = mode value for the factor; *G* = highest (best) score for the factor based on the indicator analysis; *f* = factor value

In leverage analysis, there is a step to calculate the uncertainty error in order to strengthen estimates of future conditions. The error value for this uncertainty should be limited to a maximum of 10%. The validation stage using random iterations in MSA is conducted by considering random values generated from the mode of each factor. The random iteration

values are derived from the distribution of indicator ratings by informants based on the frequency of occurrence of each value, which is then converted into probabilities. The probabilities are aggregated cumulatively until they total 1 and are used as the basis for grouping indicator levels (Firmansyah, 2022).

The final stage involves developing priority policy scenarios based on the most influential attributes and the results of improvement simulations. Scenarios in MSA analysis can be developed in tiers—such as moderate, optimistic, and progressive scenarios—by determining the number of scenarios and driving factors based on the results of previous analyses. The resulting scenario recommendations not only describe current conditions but also provide effective policy guidance to improve the overall sustainability of aquaculture. The priority values for scenarios in MSA analysis are calculated as follows:

$$\Delta y_n = y_{sn} - y_0 \dots\dots\dots(8)$$

$$\Delta y = \bar{y}_{sn} - \bar{y}_n \dots\dots\dots(9)$$

$$P_{sn} = \frac{y_n}{y_1} \dots\dots\dots(10)$$

$$\frac{y_n}{y_1} > 1 \dots\dots\dots(11)$$

Where: y = status value; y_s = scenario status value; n = number of aspects; Δy_n = difference between the scenario status value and the actual condition status value; Δy = difference between the scenario value and the aggregate status value; P_s = scenario priority; Y_n = difference between scenario n and scenario 1; Y_1 = existing value = 1

Sustainability Status Criteria

The sustainability status value in the MSA analysis is derived from the assessment results of attributes in each aspect. Based on the sustainability assessment criteria according to (Firmansyah, 2022), sustainability status values in the range of 0–100 are classified into four categories. Values of 0–25 fall into the “unsustainable” category; the 26–50 range is categorized as “less sustainable”; values of 51–75 fall into the “sustainable” category; and the 76–100 range is classified as “highly sustainable.” The sustainability status index value for each aspect is determined based on the sustainability scale in Table 2 below.

Table 2. Sustainability Status Scores

No.	Criterion Value	Sustainability Status
1.	0–25	Not Sustainable
2.	>25–50	Less Sustainable
3.	>50–75	Sustainable
4.	>75–100	Highly Sustainable

Source: (Firmansyah, 2022)

RESULTS AND DISCUSSION

Sustainability Status

The sustainability status of tilapia (*Oreochromis mossambicus*) aquaculture in floating nets in Kedisan Village was determined through a Multiaspect Sustainability Analysis (MSA) covering economic, social, and environmental aspects. The sustainability analysis was conducted to assess the overall level of sustainability as well as sustainability by aspect. The results of the analysis of the aggregate sustainability status of tilapia farming in the floating net cages in Kedisan Village are presented in Table 3.

Table 3. Sustainability Index Values

No	Aspect	Sustainability Value
1.	Economy	81.44
2.	Social	89.29
3.	Environment	45.29
Average Score		72.01
Sustainability Status		Sustainable

Overall, the MSA results indicate that the sustainability status of tilapia aquaculture in floating nets in Kedisan Village, received an average score of 72.01, placing it in the “sustainable” category. Aggregately, the aquaculture operation has met most of the sustainability indicators in the assessed aspects and demonstrated relatively good performance in supporting the business’s sustainability in the medium term. This achievement is higher than the results of the sustainability assessment of floating net pens (FNC) at Jatiluhur Reservoir, which obtained an index of 51.33% with a “moderately sustainable” status (Putri *et al.*, 2019).

The sustainability score for the economic aspect, at 81.44, falls into the “highly sustainable” category. Aquaculture practices contribute to the income of aquaculture households and have become a leading sector in the Kedisan Village area. This is supported by data from the Bali Provincial Statistics Agency (BPS), which recorded that the volume of aquaculture production in Bangli Regency reached 4,379 metric tons in 2022, making it one of the largest fish farming centres in Bali Province (BPS 2022).

The social aspect received the highest sustainability score of 89.29, placing it in the “highly sustainable” category. This high score reflects the strong social capital built among the aquaculture communities in Kedisan Village. This finding aligns with the results of a study (Syarif *et al.*, 2024), which showed that trust among aquaculture communities coupled with communication and openness plays a very significant role in supporting the sustainability of aquaculture businesses. Furthermore, (Manlosa *et al.*, 2023) state that social capital in the form of bonding, bridging, and linking accessed through small-scale fish farmers’ associations has been proven to contribute significantly to strengthening farmers’ capacity and sustainability.

The environmental aspect scored the lowest compared to the other aspects, thus acting as a limiting factor in overall sustainability. The sustainability score for the environmental aspect is 45.29. This result indicates that the environmental aspect falls into the “less sustainable” category. The impacts resulting from aquaculture practices indicate the presence of ecological pressure. If this condition is not controlled, it has the potential to lower the sustainability status of aquaculture in the long term. Prioritizing interventions in the environmental aspect is necessary to achieve a balance among the various aspects and to comprehensively improve sustainability.

The level of environmental sustainability is influenced by the implementation of environmentally friendly practices and efficiency in resource management (Garlock *et al.*, 2024). Through an integrated approach and collaboration among stakeholders, environmental aspects categorized as less sustainable can be gradually improved. Meanwhile, the economic and social aspects demonstrate highly sustainable achievements that need to be maintained and optimized. Thus, a balance across all aspects of sustainability can be achieved to

strengthen the overall sustainability of tilapia farming in accordance with Presidential Regulation No. 111 of 2022. Figure 2 below is a sustainability diagram of tilapia farming in floating nets in Kedisan Village under real-world conditions.

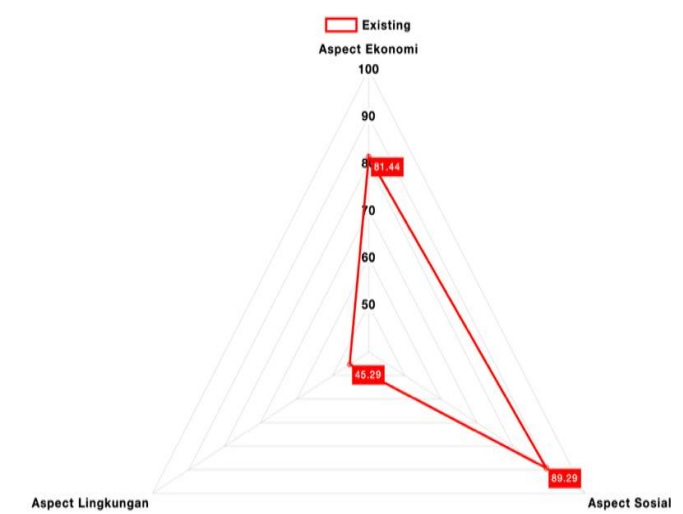


Figure 2. Layang Diagram

Sensitive Attributes of the Economic Aspect

The sustainability status of the economic aspect in tilapia farming at the FNC in Kedisan Village falls into the “highly sustainable” category. This indicates that tilapia farming has served as a leading sector supported by the involvement of the local community. This aligns with the findings of Nova *et al.* (2025), who state that economic sustainability will increase if supported by community participation and the strengthening of key commodities as drivers of the regional economy.

Sensitive attributes in the sustainability of tilapia farming in floating nets in Kedisan Village were identified through a leverage analysis to determine which attributes had the greatest influence on changes in the sustainability index value. The economic aspect measures the level of sustainability of tilapia farming based on the economic resilience of farming households against various business risks. This aspect consists of nine attributes, including business viability, farmer household income, savings rate, stability of production and feed prices, access to and sources of capital, marketing channels, and the impact of upwelling phenomena on farmers’ income. The results of the leverage analysis in Figure 3 show that “ ” is the most sensitive attribute with the highest sensitivity value within the economic aspect.

An analysis of leverage in the economic aspect identified the most sensitive attribute—with a sensitivity value of 1 as the impact of upwelling on aquaculturists’ income. This value is the highest compared to other attributes in the economic aspect. This finding indicates that the upwelling phenomenon has a very significant impact on the economic aspects of aquaculture practices. When this phenomenon occurs, the risk of mass fish mortality increases, production declines, and aquaculturists suffer direct financial losses. Consistent with the study by Silvia & Resdati (2025), fish mortality increases due to the upwelling phenomenon, reducing harvest yields and weakening aquaculturists’ financial capacity to manage business capital, thereby creating significant economic pressure at the household level.

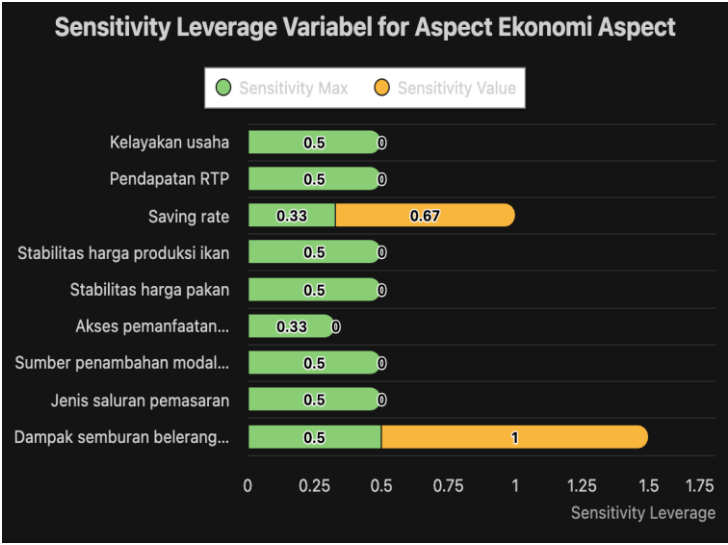


Figure 3. Results of the Economic Leverage Analysis

The saving rate is the second most sensitive attribute in the economic aspect, with a sensitivity value of 0.67. This attribute indicates that the farmers’ ability to save influences changes in the sustainability value of the economic aspect. Thus, the lower the ability to save, the more likely the economic sustainability value is to decline. The saving rate decreases when upwelling occurs because farmers use their savings to cover losses resulting from fish mortality. A decline in production reduces household financial reserves and weakens economic resilience. This situation highlights the importance of fish farmers’ ability to maintain financial reserves as a means of preparing for business risks. This aligns with the findings of Vatria (2020), who stated that improved economic sustainability can be achieved by strengthening fish farmers’ ability to save. Increasing the savings rate is a key strategy for strengthening the economic sustainability of tilapia aquaculture in floating nets in Kedisan Village, particularly in the face of external risks such as upwelling phenomena.

The attributes of business viability, RTP revenue, production price stability, feed price stability, access to capital, sources of additional capital, and types of marketing channels all show a sensitivity value of 0. The contribution of these seven attributes to changes in the sustainability value for the economic aspect is not as significant as that of the upwelling impact or the savings rate. Thus, the economic structure of tilapia farming in floating nets in Kedisan Village remains highly vulnerable to external ecological disturbances.

Sensitive Attributes in the Social Aspect

The sustainability index for the social aspect falls into the “highly sustainable” category. This indicates that the social structure, participation, and interactions among tilapia farmers at the floating net aquaculture site in Kedisan Village are functioning adaptively and effectively, thereby supporting the sustainability of the business. This is consistent with the findings of Saragih *et al.* (2020), who state that social sustainability can be maintained through periodic evaluations and the strengthening of synergies among stakeholders. The results of the social aspect leverage analysis are shown in Figure 4.

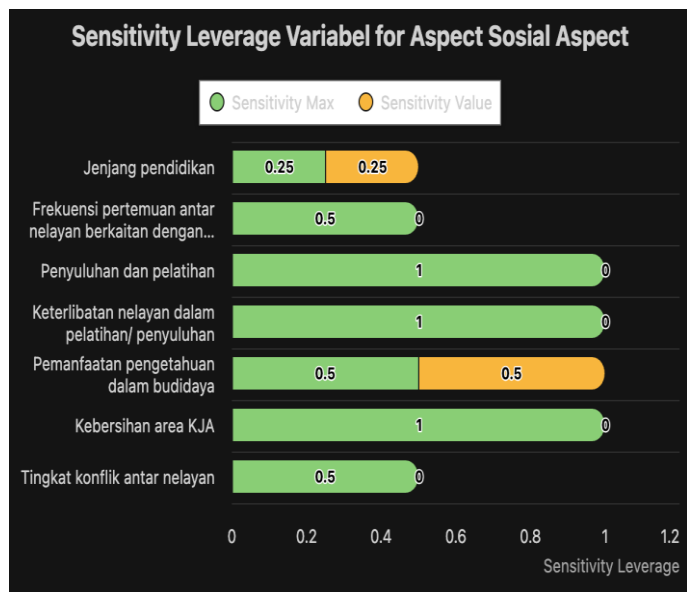


Figure 4. Results of the Social Aspect Leverage Analysis

The results of the social aspect leverage analysis identified two sensitive attributes with the highest sensitivity values: the utilization of knowledge in aquaculture and educational level. The attribute “utilization of knowledge in aquaculture” has a sensitivity value of 0.5, indicating that changes in this attribute have a relatively large impact on changes in the social aspect sustainability index. The social aspect is highly dependent on the extent to which aquaculturists are able to utilize technical knowledge in their farming practices. This is consistent with the findings of Nzaligo *et al.* (2025), who stated that educational level and access to technical knowledge significantly influence the productivity and sustainability of fish farming in FNC.

The attribute with the second-highest sensitivity in the social aspect is educational level, with a sensitivity value of 0.25. The results of the questionnaire completed by key informants indicate that the educational level of tilapia farmers at the FNC in Kedisan Village is generally at the high school level. Limited formal education has the potential to hinder the application of digital aquaculture technologies, which require technical skills in data operation and interpretation. Education serves as a supporting factor in enhancing farmers’ adaptive capacity, particularly in adopting innovations and understanding aquaculture business management. An adequate level of education contributes to improving individuals’ understanding of the importance of sustainable resource management and encourages the development of conservation-oriented behavior (Mongan *et al.*, 2026).

The five other attributes—the frequency of meetings among aquaculture farmers, extension services and training, participation in training, the level of conflict, and the cleanliness of the floating net aquaculture (FNC) area—all showed a sensitivity value of 0. This indicates that the social structure of the aquaculture farmer group in Kedisan Village is fairly stable. Improvements in the social aspect, as noted at , focus on the attributes of knowledge utilization in aquaculture and educational attainment. This finding is consistent with the results of a study (Ibrahim *et al.*, 2024), which indicates that the aquaculture profession does not fundamentally require a high level of formal education; however, education still plays a role

in shaping individuals’ mindsets, perspectives, and abilities to formulate and take strategic steps in running their business activities.

Sensitive Attributes Related to Environmental Aspects

The sustainability index results for the environmental aspect related to tilapia aquaculture activities in floating nets in Kedisan Village fall into the “less sustainable” category. The environmental aspect has not yet reached a stable condition and remains vulnerable to disturbances, whether from aquaculture activities or upwelling phenomena. In line with the study by Purnomo *et al.* (2024), the RAPFISH ordination results for capture fisheries activities in Lake Batur indicate that the sustainability status falls into the “poor” category; therefore, improvement strategies are needed through capacity building, skills development, and the provision of alternative livelihoods for fish farmers. Figure 5 shows the results of the leverage analysis for the environmental aspect.

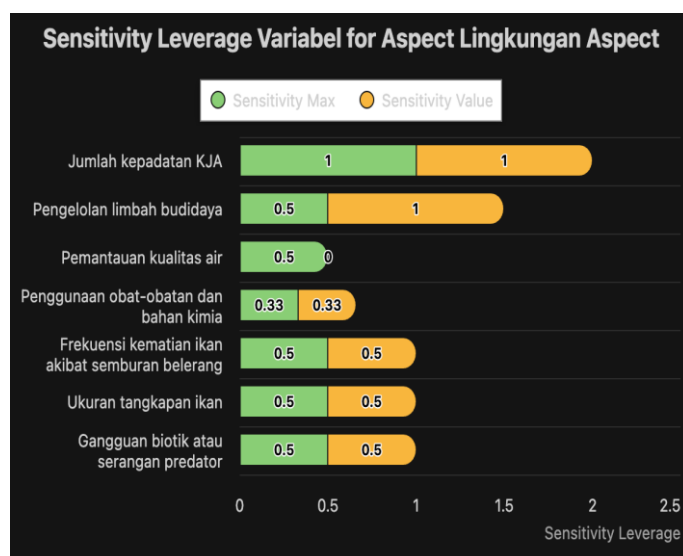


Figure 5. Results of the Environmental Aspect Leverage Analysis

There are two attributes that are the most sensitive, with the highest sensitivity values, making them top priorities for improvement in the environmental aspect. Based on Figure 5, these attributes are the density of floating nets and aquaculture waste management, each with a sensitivity value of 1. This indicates that changes in these two attributes have the greatest impact on changes in the environmental sustainability index.

The attribute of floating net aquaculture (FNC) density is one of the most dominant and sensitive leverage attributes. This indicates that an increase or decrease in the number of FNC units directly increases or decreases the sustainability index in the environmental aspect. This finding is a critical indicator because various previous studies have shown that FNC density in Lake Batur has exceeded the lake’s environmental carrying capacity since around 2018, when the number of FNC units surpassed the maximum recommendation calculated based on the lake’s surface area and water quality. This condition of exceeding carrying capacity correlates with a decline in water quality and has been identified as the primary factor in the ecological degradation of Lake Batur (Garno *et al.*, 2024). As reported by Lusia *et al.*, 2023), the number of floating net aquaculture units in Lake Batur has reached approximately

12,200 units, while the lake’s ecological carrying capacity is estimated at only about 10,047 units; thus, floating net aquaculture activities in Lake Batur are deemed to have exceeded the water body’s carrying capacity.

The second sensitive attribute aquaculture waste management has a sensitivity value of 1. Currently, aquaculturists have not implemented optimal waste management practices. Uneaten feed and fish excreta produced during aquaculture activities accumulate at the bottom of the lake, thereby accelerating the decline in water quality. In line with a study (Garno *et al.*, 2024), Lake Batur has exceeded its carrying capacity since 2018 due to uncontrolled expansion of floating net aquaculture (FNC), where 75–80% of nitrogen and 60–75% of phosphorus from fish feed are released into the aquatic environment as excreta and metabolites, thereby accelerating the lake’s rate of eutrophication.

There are three other attributes with lower sensitivity values: the frequency of fish mortality due to upwelling, catch size, and biotic disturbances or predator attacks. These three attributes have a sensitivity value of 0.5. The attribute “use of chemicals” has a sensitivity value of 0.33. Meanwhile, the attribute “water quality monitoring” has a sensitivity value of 0. The impact of these attributes is relatively low compared to the two main sensitive attributes. However, they still need to be managed to prevent a decline in the sustainability index for environmental aspects.

Tilapia farmers in floating nets in Kedisan Village have chosen not to use medications in their aquaculture practices, thereby reducing the risk of residue accumulation. Water quality monitoring is routinely conducted in the Kedisan Village area, so this factor does not contribute to a decline in the sustainability index. Continuous water quality monitoring is a key tool in ensuring the sustainability of the aquaculture system, as parameters such as dissolved oxygen, pH, and ammonia significantly affect fish health and aquaculture productivity (Adenaya *et al.*, 2023).

Sustainability Improvement Scenario

The final stage in the MSA method is the development of sustainability improvement scenarios. These scenarios are developed based on the sensitive attributes identified through leverage analysis—that is, the attributes with the highest sensitivity values and the greatest influence on changes in the sustainability index. This is consistent with (Mongan *et al.*, 2026), who state that attributes with the highest Root Mean Square (RMS) values are the primary sensitive attributes that form the basis for developing interventions, while the level of the scenario determines the magnitude of the sustainability improvement applied.

The simulation was conducted by altering the values of sensitive attributes identified as leverage factors in each aspect, in accordance with the interventions in each scenario (Firmansyah, 2022). Scenario 1 represents moderate improvements with limited changes to sensitive attributes, resulting in a gradual increase in the index value. Meanwhile, Scenario 2 reflects a more comprehensive intervention with broader and more intensive changes, resulting in a more significant increase in the index value. The sustainability improvement scenario values were obtained through an ordination process in MSA and represent projections of

sustainability levels based on each scenario, as presented in Table 4.

Table 4. Scenarios for Improving Sustainability

Aspect	Sustainability Status		
	Current	Scenario 1	Scenario 2
Economy	81.44	90.78	100
Social	89.29	100	100
Environment	45.29	66.71	88.14
Average	72.01	85.83	96.05

The overall current sustainability status of tilapia farming in floating nets in Kedisan Village has an average score of 72.01, which falls within the “sustainable” category. Scenario 1’s intervention increased the sustainability score across all aspects to 85.83—an increase of 13.82—thereby changing its status to “highly sustainable.” Furthermore, Scenario 2 shows a further improvement with an average score of 96.05—an increase of 10.22—which further reinforces the “highly sustainable” status. Scenario 1 reflects a moderate improvement, while Scenario 2 illustrates a more optimal and balanced condition across all aspects. The values in Table 4 are visualized in Figure 6 as a scatter plot showing a comparison of the increase in sustainability for each scenario.

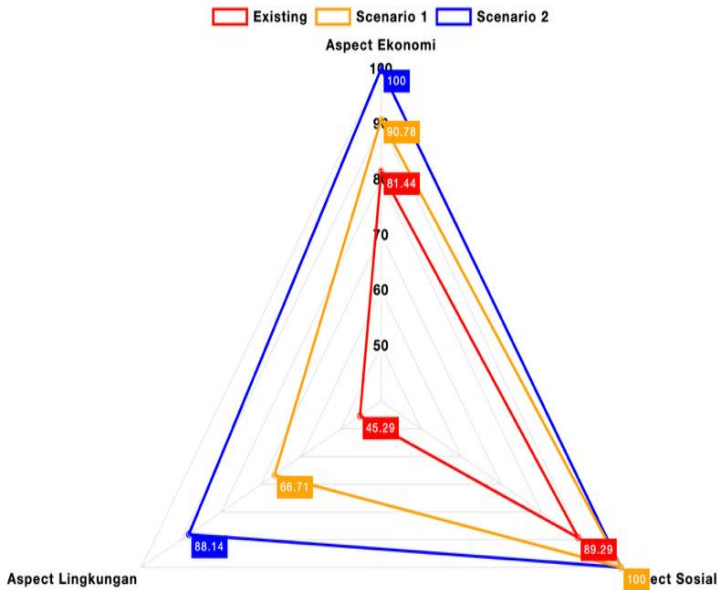


Figure 6. Mind Map of the Sustainability Improvement Scenario

The scenario for improving sustainability in the economic aspect focuses on addressing the first sensitive attribute the impact of upwelling through the implementation of Small-Scale Fish Farmers’ Fisheries Insurance (APPIK). The lack of business protection leaves farmers vulnerable to losses when upwelling occurs. The implementation of APPIK minimizes the risk of losses due to upwelling and supports the sustained improvement of economic aspect. In line with the findings (Octafany *et al.*, 2023), the implementation of insurance administered by the Department of Fisheries, Food Security, and Agriculture (PKPP) provides business protection

and economic benefits for fish farmers and is supported by policies outlined in Law No. 7 of 2016.

The next scenario for improving sustainability in the economic aspect specifically regarding the improvement of the saving rate is achieved through a financial literacy program for aquaculture farmers. This program aims to enhance farmers' understanding of the importance of family financial management, thereby fostering a community that is better informed and well-versed in household financial management (Kalorbobir & Pasamba, 2024). Improving the ability to save through financial literacy is expected to reduce the vulnerability of farmer households in Kedisan Village to income shocks and improve their long-term economic sustainability.

The difference between Scenario 1 and Scenario 2 in economic terms lies in the scope of intervention regarding sensitive attributes. Scenario 1 implements the Small-Scale Fish Farmers' Fisheries Insurance (APPIK) program to address the impacts of the upwelling phenomenon, thereby increasing the sustainability score from 81.44 to 90.78. Meanwhile, Scenario 2 combines APPIK with a Financial Literacy Program to increase the savings rate, resulting in an optimal value of 100 in the "highly sustainable" category. Thus, Scenario 2 is more comprehensive because it addresses both sensitive attributes simultaneously.

The attributes of knowledge utilization in aquaculture and educational level were identified as the most sensitive factors in the social aspect. The recommended scenario for improving these sensitive attributes is a structured and sustainable aquaculture extension and training program. It is hoped that through these programs, aquaculturists will be able to implement more efficient aquaculture practices, understand water quality management, and improve their knowledge-based decision-making abilities. In line with (Saade *et al.*, 2024), intensive aquaculture training and mentoring over a specific period contribute to aquaculturists' ability to apply knowledge and technology.

The majority of farmers in Kedisan Village are over 35 years old, which limits their ability to pursue formal higher education. The scenario for the sensitive attribute of educational level involves implementing nonformal education programs. These programs aim to enhance knowledge in aquaculture through activities such as courses, skills training, and extension services organized by various institutions (Nawir, 2024).

Scenario 1, in the social aspect, involves structured and sustainable extension services and training in aquaculture, aimed at improving knowledge utilization sensitivity. The intervention in Scenario 1 increased the sustainability score for the social aspect from 89.29 to 100, placing it in the "highly sustainable" category. In Scenario 2, this value remains at 100 even with the addition of a nonformal education program to raise educational attainment levels. This indicates that the interventions in Scenario 1 have reached an optimal value, while Scenario 2 is more oriented toward strengthening long-term sustainability.

The MSA results analyzed the two most sensitive attributes— in the environmental aspect, namely the density of floating net cages and aquaculture waste management. These two attributes are the primary focus of interventions aimed at improving the environmental performance and sustainability of tilapia aquaculture in Kedisan Village. The recommended scenario for the sensitive attribute of floating net cage density is the implementation of a moratorium on the addition of new floating net cage units. Efforts to manage the lake and floating net cages through the implementation of a moratorium on the

addition of new units, accompanied by the provision of alternative livelihoods for affected farmers, are considered an appropriate policy measure (Soejarwo *et al.*, 2022).

Normatively, the moratorium approach aligns with the precautionary principle in fisheries resource management, as reflected in Regulation of the Minister of Marine Affairs and Fisheries (Permen KP) No. 56/PERMEN-KP/2014 on the Temporary Suspension (Moratorium) of Fishing Business Licensing. The implementation of the moratorium in the context of floating net aquaculture in Kedisan Village is expected to strike a balance between economic and environmental interests. The moratorium serves as a preventive policy instrument to curb the expansion of tilapia aquaculture operations in floating nets in Kedisan Village, while simultaneously allowing for a gradual environmental recovery process.

A key aspect of managing sensitive aquaculture waste is the implementation of proper feed management (feeding control), as stipulated in Ministry of Environment Regulation No. 5 of 2014 on Wastewater Quality Standards. Efficiency levels are greatly influenced by adjusting the feeding rate to meet the fish's needs. The implementation of proper feed management plays a crucial role in reducing the amount of uneaten feed and nutrients discharged into Lake Batur. Feeding in the right amounts and at the right frequency not only reduces production costs but also minimizes pollution loads, given that the majority of aquaculture waste stems from unused feed. Research findings (Saputri *et al.*, 2025) indicate that an optimal feeding frequency—such as three times a day—can improve feed utilization efficiency and lower the feed conversion ratio (FCR), a measure of how efficiently feed is converted into fish body weight, which reflects a reduction in the potential for waste released into the aquatic environment.

Key sensitive attributes related to environmental aspects include the density of floating net aquaculture (FNC) units and the management of aquaculture waste. Under current conditions, the sustainability score of 45.29 indicates a "less sustainable" category. Scenario 1, which involves a moratorium on the addition of new FNC units, increases the score to 66.71, shifting it into the "sustainable" category. Furthermore, Scenario 2 combines the moratorium with the implementation of feeding control to improve efficiency and waste management. The intervention in Scenario 2 increased the sustainability score to 88.14, placing it in the "highly sustainable" category. The more significant improvement in this scenario indicates that comprehensive and simultaneous interventions targeting sensitive attributes yield more optimal impacts on environmental sustainability.

Overall, the research findings indicate that tilapia farming in floating nets in Kedisan Village is sustainable, with relatively strong economic and social aspects, but is still constrained by weak environmental aspects. Sensitivity analysis and MSA scenario simulations confirm that managing the risk of sulfur emissions, strengthening the socioeconomic capacity of farmers, and reducing ecological pressure through the regulation of FNC density and waste management are key to improving the sustainability of the aquaculture system. These findings fill a gap in the study of aquaculture sustainability in floating nets in volcanic lake environments and provide an empirical basis for formulating more targeted intervention policies in Kedisan Village and the Lake Batur region.

The policy implications of this study indicate that local governments, fish farmers, academics, and other stakeholders need to strengthen their collaboration. The goal is to ensure that

the recommended improvement scenarios can be effectively implemented. Necessary efforts include the APPIK insurance program, financial literacy programs for fish farmers, controlling the density of floating nets in accordance with the carrying capacity of the waters, strengthening regulations related to aquaculture waste management, increasing periodic environmental monitoring, and developing extension and mentoring programs for fish farmers to improve their adaptive capacity to environmental risks such as upwelling phenomena. Thus, an integrated management policy that balances economic, social, and environmental aspects is essential for ensuring the long-term sustainability of tilapia aquaculture in floating nets in Kedisian Village.

CONCLUSION

Overall, the sustainability of tilapia farming in floating nets in Kedisian Village, Bali Province, falls into the “sustainable” category with a score of 72.01. The economic aspect received a sustainability score of 81.44, while the social aspect scored 89.29. Both aspects demonstrated strong performance and fall into the “highly sustainable” category. Meanwhile, the environmental aspect received a score of 45.29, placing it in the “less sustainable” category and making it the primary limiting factor in improving the overall sustainability status.

The sensitive attributes that have the greatest impact on sustainability in the economic aspect include the effects of upwelling and the savings rate. Furthermore, in the social aspect, sensitive attributes include the application of knowledge in aquaculture and the level of education. Meanwhile, in the environmental aspect, the most sensitive attributes are the density of floating net pens and the management of aquaculture waste.

Based on the results of the leverage analysis, improvement scenarios were developed that focus on interventions targeting key sensitive attributes across all three aspects. Scenario 1, classified as a moderate scenario, is capable of improving the sustainability status from the “sustainable” category to “highly sustainable,” with a score of 85.83. Meanwhile, Scenario 2—the optimistic scenario—raises the sustainability score to 96.05, which also falls within the “highly sustainable” category. These results indicate that interventions focused on sensitive attributes play a significant role in enhancing the sustainability of tilapia farming in floating nets in Kedisian Village, Bali Province.

ACKNOWLEDGMENTS

The author would like to thank Udayana University for its academic support. Appreciation is extended to the Village Head of Kedisian, the tilapia farmers at the floating nets in Kedisian Village, the Bali Provincial Department of Marine Affairs and Fisheries, and the Bali Provincial Department of Forestry and the Environment for providing data and information. The author also extends gratitude to the editor and reviewers for their feedback and constructive suggestions, which have helped improve this manuscript. Thanks also go to my family and colleagues for their prayers, support, and encouragement throughout the process of conducting this research.

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