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## **An analysis of rice farming sustainability in the Subak irrigation system, Bali**

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**Abstract**---*Subak*, as Bali's traditional irrigation management system based on the *Tri Hita Karana* philosophy, faces sustainability challenges amid rapid urbanization and climate change. This study aims to analyze the sustainability status, sensitive attributes, and improvement scenarios for the sustainability of rice seed farming in *Subak* Sembung. This research employs both quantitative and qualitative data. Quantitative data were obtained through questionnaires distributed to key informants, while qualitative data were derived from surveys and in-depth interviews with key informants. The data sources consist of primary and secondary data. Primary data were obtained from the interpretation of questionnaire responses, whereas secondary data were collected from relevant literature and regulatory documents. The analytical method used in this study is Multiaspect Sustainability Analysis (MSA), and the results are presented using descriptive–narrative analysis. The findings indicate that the sustainability index value of rice farming in *Subak* Sembung is 66.43, which falls within the sustainable category. Sensitive attributes in the ecological aspect include the use of organic fertilizers. In the economic aspect, the sensitive attribute is the average size of farmers' landholdings. In the socio-cultural aspect, the sensitive attribute is farmer regeneration participation (farmers under 40 years old). In the institutional aspect, the sensitive attribute is the presence of farmer cooperative institutions. In the technological



aspect, the sensitive attribute is the condition of irrigation water channels. Improvement scenarios show that increasing the sustainability index of rice farming in *Subak Sembung* from 66.43 (sustainable) leads to an increase to the very sustainable category, while the second scenario results in an increase from 86.76 (very sustainable) to 95.58 (very sustainable). The study concludes that the sustainability status of rice farming in *Subak Sembung* is categorized as sustainable. It is recommended that sustainability be optimized by focusing on the main sensitive attributes, particularly within the ecological aspect, through the application of solid organic fertilizers on *Subak Sembung* rice fields.

**Keywords**---Sustainability, MSA, *Subak*, *Tri Hita Karana*, Rice Farming.

## Introduction

Food security remains a strategic issue in national development, particularly for developing countries such as Indonesia, where agriculture plays a central role in ensuring food availability and supporting economic growth. Rice remains the main staple food, and increasing population growth has intensified the demand for sustainable rice production systems (Rumawas et al., 2021). However, agricultural production systems are inherently vulnerable due to climate variability, limited land availability, declining natural resource quality, and weak farmer institutions, all of which directly affect production stability and long-term sustainability.

In Bali, agricultural sustainability faces additional pressure from rapid urbanization and land-use conversion driven by tourism development. Data from BPS Kota Denpasar (2024) indicate that approximately 824 hectares of paddy fields were lost between 2019 and 2024, significantly reducing local food production capacity, particularly in urban areas such as North Denpasar. Within this context, *Subak* plays a critical role as a traditional irrigation and cropping management system that integrates technical, social, economic, and religious functions (Provincial Regulation of Bali No. 9/2012). Nevertheless, *Subak* systems located in urban areas, including *Subak Sembung*, face increasing pressure from land conversion, competition for water resources, and socio-economic transformation.

*Subak Sembung* has been designated as part of the *Subak Lestari* program and included in the Sustainable Food Agricultural Land (LP2B) policy framework, which aims to protect agricultural land and ensure long-term food security. The *Subak Lestari* concept emphasizes sustainable resource management, farmer participation, and the integration of cultural values, including *Tri Hita Karana* (Windia, 2013; Windia et al., 2019). Since 2015, *Subak Sembung* has also been developed as an agro-ecotourism area, providing additional income opportunities for farmers. However, this development has simultaneously generated new sustainability challenges, such as increased land-use pressure, environmental pollution risks, and infrastructure demands. Data from BPP Denpasar Utara

(2025) show that the area of *Subak Sembung* decreased from 115 hectares in 2019 to 99 hectares in 2024, indicating that policy protection alone has not been sufficient to prevent land shrinkage.

From an ecological perspective, the dominance of chemical fertilizer use has raised concerns regarding soil degradation, declining organic matter, and reduced soil microbial activity, which ultimately threaten long-term land productivity and environmental quality (Fathnur et al., 2023). These ecological issues are compounded by the deteriorating condition of irrigation infrastructure, including damage caused by pests and domestic waste, which disrupts water distribution and increases the risk of conflict among farmers (Karlin, 2025). Economically, small landholdings—generally less than one hectare per farmer—limit production scale, reduce income stability, and constrain farmers' ability to adopt sustainable technologies. The absence of strong farmer cooperatives further weakens farmers' bargaining power and access to capital, reinforcing dependence on middlemen and short-term production strategies (Dukalang et al., 2025).

Socially, the low participation of younger generations in farming activities poses a serious threat to the long-term sustainability of *Subak Sembung*. The dominance of elderly farmers, combined with declining interest among farmers under 40 years old, hampers innovation, labor availability, and the intergenerational transfer of local knowledge and *Subak* values (Ilmi et al., 2025). These challenges highlight that agricultural sustainability in *Subak Sembung* must be understood as a multidimensional issue encompassing ecological, economic, socio-cultural, institutional, and technological aspects (Wael et al., 2025; Siregar, 2023).

Based on the gap between existing conditions (*das sein*) and the desired sustainable state (*das sollen*), there is a strong need for a comprehensive sustainability assessment that identifies sensitive attributes affecting rice farming sustainability in *Subak Sembung*. Therefore, this study aims to analyze the sustainability status of rice farming in *Subak Sembung* by evaluating ecological, economic, socio-cultural, institutional, and technological dimensions, in order to formulate strategies that support sustainable agriculture while preserving local wisdom rooted in *Tri Hita Karana*.

## **Methods**

This study employed a descriptive research design with a mixed-methods approach (quantitative–qualitative) through a survey and case study to analyze the sustainability of rice farming systems in *Subak Sembung*, Peguyangan Village, North Denpasar District, Bali, Indonesia. The study area was selected due to significant urbanization pressure and agricultural land conversion, which reduced paddy fields from 115 hectares in 2019 to 99 hectares in 2024, while simultaneously holding the status of *Subak Lestari* and ecotourism potential. The research was conducted from July to December 2025. The primary analytical method was Multiaspect Sustainability Analysis (MSA), which was used to assess sustainability status across five dimensions—ecological, economic, socio-cultural, institutional, and technological—and to identify key leverage factors and develop sustainability improvement scenarios.

Primary and secondary data were utilized in this study. Primary data were collected through ordinal-scale questionnaires, in-depth and structured interviews, focus group discussions (FGDs), field observations, and documentation. Informants were selected using purposive sampling, involving 13 key stakeholders, including agricultural officers, the *pekaseh*, extension officers, *klian munduk*, and members of the farmers' association (GAPOKTAN). Secondary data were obtained from literature, regulations, *Subak* documents, institutional reports, and statistical records. Indicators across the five dimensions were evaluated based on current conditions against relevant standards and then processed using MSA (Exsimpro software, developed from RAPFISH) to generate a sustainability index and classification: 0–25 (unsustainable), >25–50 (low sustainable), >50–75 (sustainable), and >75–100 (very sustainable). Reliability was strengthened through sensitivity analysis, uncertainty and respondent error testing (random iteration and estimation respondent error), and by presenting results in both formal formats (tables, diagrams, and figures) and informal narrative descriptions to support evidence-based policy recommendations.

## **Result and Discussion**

### *Sustainability Status*

The sustainability status of rice farming in *Subak* Sembung was evaluated based on three main aspects, namely ecological, economic, and socio-cultural dimensions. These three aspects were selected as the core components because they directly represent the environmental, financial, and social foundations of the traditional *subak* farming system. The assessment was conducted using the Multiaspect Sustainability Analysis (MSA) approach, which integrates multiple indicators and attributes to generate a composite sustainability index for each dimension.

The results indicate that the ecological aspect of rice farming in *Subak* Sembung falls into the sustainable category. However, several ecological pressures remain, particularly related to the high dependence on chemical fertilizers and the limited adoption of organic inputs. In addition, pest and disease infestations, as well as contamination of irrigation water from domestic waste, pose significant threats to long-term environmental quality. These conditions suggest that although the current ecological status is still classified as sustainable, continuous improvement is required to prevent future degradation.

The economic aspect shows the lowest sustainability score among the three dimensions and is classified as low sustainable. This condition is mainly influenced by the small average farm size, which limits production capacity and reduces farmers' ability to achieve economies of scale. The dominance of middlemen in the marketing system also weakens farmers' bargaining position, resulting in unstable and often unfavorable selling prices. Although rice farming in *Subak* Sembung remains economically feasible, these structural constraints hinder the long-term economic resilience of farmers.

Meanwhile, the socio-cultural aspect demonstrates a relatively high sustainability status and is categorized as sustainable. Strong social cohesion, adherence to

traditional norms, and collective participation in rituals and farming activities continue to support the stability of the *subak* system. Nevertheless, a major challenge lies in the low participation of young farmers, which threatens the regeneration process and the continuity of traditional agricultural knowledge. Strengthening youth involvement and family participation is therefore essential to ensure the long-term sustainability of the socio-cultural dimension.

Based on the results of the Multiaspect Sustainability Analysis (MSA), the sustainability status of rice farming in *Subak Sembung* is classified as sustainable, with an average value of 66.43. Of the five aspects analyzed, the three main dimensions that most strongly determine sustainability are the ecological aspect (64.29), the economic aspect (50 – *low sustainable*), and the socio-cultural aspect (71.43).

Table 1. Sustainability Values of Rice Farming in Subak Sembung

| No                   | Aspect         | Existing | Sustainability Value       |
|----------------------|----------------|----------|----------------------------|
| 1                    | Ecological     | 64.29    | Sustainable                |
| 2                    | Economic       | 50.00    | Low Sustainable            |
| 3                    | Socio-cultural | 71.43    | Sustainable                |
| 4                    | Institutional  | 71.43    | Sustainable                |
| 5                    | Technological  | 75.00    | Sustainable                |
| <b>Total Average</b> |                |          | <b>66.43 – Sustainable</b> |

Primary Data, 2025

#### *Ecological Aspect*

The ecological aspect obtained a sustainability index of 64.29%, which is classified as *sustainable*. Seven attributes were assessed, including irrigation water pollution, intensity of pest and disease attacks, irrigation water availability, chemical fertilizer dosage, use of organic fertilizer, threats of land-use conversion, and plant diseases. These attributes refer to the Triple-P framework in sustainable agriculture (Lagiman, 2021).

The sensitivity leverage analysis shows that the most sensitive attributes are the use of organic fertilizer and the dosage of NPK and urea (Table 5.10). Currently, farmers still predominantly rely on chemical fertilizers, which poses risks to long-term soil fertility and ecosystem balance (Nuraina, 2021). Regional regulations, such as Bali Provincial Regulation No. 8 of 2019 and Governor Regulation No. 15 of 2021, encourage a transition toward organic farming systems.

Table 2. Priority Ranking of Sensitive Factors in the Ecological Aspect

| No | Sensitive Factor              | Priority |
|----|-------------------------------|----------|
| 1  | Use of organic fertilizer     | 1        |
| 2  | NPK and urea dosage           | 2        |
| 3  | Intensity of pest attacks     | 3        |
| 4  | Intensity of plant diseases   | 4        |
| 5  | Domestic waste pollution      | 5        |
| 6  | Irrigation water availability | 5        |

| No | Sensitive Factor              | Priority |
|----|-------------------------------|----------|
| 7  | Threat of land-use conversion | 5        |

Primary Data, 2025

#### *Economic Aspect*

The economic aspect recorded a sustainability value of 50%, categorized as *low sustainable*. Six attributes were assessed, including land size, harvested dry grain (GKP) production, selling price, maintenance cost support, availability of production inputs, and farmers' income.

The sensitivity leverage analysis indicates that the average land size of farmers is the most sensitive factor. Farmers cultivate only about 0.5 ha, mainly due to land inheritance fragmentation and land conversion (Umyati et al., 2022; Suhendra & Noor, 2024). This condition limits economies of scale and reduces income stability.

Table 3. Priority Ranking of Sensitive Factors in the Economic Aspect

| No | Sensitive Factor                  | Priority |
|----|-----------------------------------|----------|
| 1  | Average land size of farmers      | 1        |
| 2  | Maintenance cost support          | 2        |
| 3  | GKP selling price                 | 3        |
| 4  | Production per hectare            | 4        |
| 5  | Availability of production inputs | 5        |
| 6  | Net farmer income                 | 5        |

Primary Data, 2025

#### *Socio-Cultural Aspect*

The socio-cultural aspect achieved a sustainability index of 71.43%, which is classified as *sustainable*. Seven indicators were examined: education level, farmer age, participation in traditional activities, water-use conflicts, family participation, social systems, and farmer regeneration.

The sensitivity leverage analysis shows that the most sensitive attributes are farmer regeneration (<40 years old) and family participation. The active farmers are currently dominated by individuals over 50 years of age. This finding is consistent with Polan et al. (2021), who reported a continuous decline in young people's interest in agriculture.

Table 4. Priority Ranking of Sensitive Factors in the Socio-Cultural Aspect

| No | Sensitive Factor                        | Priority |
|----|---|----------|
| 1  | Farmer regeneration (<40 years old)     | 1        |
| 2  | Family participation                    | 2        |
| 3  | Farmer education                        | 3        |
| 4  | Farmer age                              | 4        |
| 5  | Participation in traditional activities | 4        |
| 6  | Water-use conflicts                     | 4        |

| No | Sensitive Factor | Priority |
|----|------------------|----------|
| 7  | Social system    | 4        |

Primary Data, 2025

### *Institutional Aspect*

The institutional aspect achieved a sustainability index of 71.43%, which is classified as *sustainable*. Seven attributes were evaluated: regulations within Subak Sembung, designation as Sustainable Food Agricultural Land (LP2B), access to marketing systems, government support (seeds, fertilizers, pesticides), agricultural extension institutions, farmer cooperatives, and the activeness of extension officers (PPL).

The sensitivity leverage analysis indicates that the most sensitive factor is the existence and effectiveness of farmer cooperatives, followed by access to marketing systems. Currently, farmer cooperatives in Subak Sembung are not yet functioning effectively, and farmers still depend heavily on middlemen (tengkulak), which weakens their bargaining position and causes price instability. This finding is consistent with Semaranata et al. (2025), who emphasized that the absence of collective marketing institutions makes farmers economically vulnerable.

Table 5. Priority Ranking of Sensitive Factors in the Institutional Aspect

| No | Sensitive Factor                                    | Priority |
|----|---|----------|
| 1  | Farmer cooperative institution                      | 1        |
| 2  | Access to marketing systems                         | 2        |
| 3  | Regulations within Subak Sembung                    | 3        |
| 4  | Designation as LP2B                                 | 4        |
| 5  | Government support (seeds, fertilizers, pesticides) | 4        |
| 6  | Agricultural extension institution                  | 4        |
| 7  | Activeness of extension officers (PPL)              | 4        |

Primary Data, 2025

### *Technological Aspect*

The technological aspect obtained the highest sustainability index, at 75%, and is therefore categorized as *sustainable*. Six attributes were analyzed: implementation of organic farming systems, farmers' operational skills in using cultivation tools, land preparation techniques, availability of agricultural machinery (tractors), seed availability, and the condition of irrigation channels.

The sensitivity leverage analysis shows that the most sensitive attribute is the condition of irrigation channels, followed by the implementation of organic farming systems. Many irrigation canals in Subak Sembung are in poor condition, with leakage, cracks, and sedimentation that reduce water flow and delay distribution to downstream fields. This problem is further exacerbated by rice field crabs, which damage canal walls and cause additional leakage.

Table 6. Priority Ranking of Sensitive Factors in the Technological Aspect

| No | Sensitive Factor                                  | Priority |
|----|---|----------|
| 1  | Condition of irrigation channels                  | 1        |
| 2  | Implementation of organic farming systems         | 2        |
| 3  | Farmers' operational skills in using tools        | 3        |
| 4  | Land preparation techniques                       | 3        |
| 5  | Availability of agricultural machinery (tractors) | 3        |
| 6  | Seed availability                                 | 3        |

Primary Data, 2025

### *Sensitive Factors*

Sensitivity leverage analysis was conducted to identify key attributes that have the greatest influence on the sustainability status of rice farming in *Subak Sembung*. This analysis allows the identification of priority intervention points across ecological, economic, socio-cultural, institutional, and technological dimensions. The following sections present the sensitive factors for each aspect, preceded by a short narrative introduction, and followed by interpretative discussion.

### *Ecological Aspect*

The ecological dimension consists of seven attributes related to environmental quality, farming inputs, and land sustainability. To determine which variables most strongly influence ecological sustainability, sensitivity leverage analysis was applied. The priority ranking of sensitive ecological factors is presented in Table 7.

Table 7. Priority Ranking of Sensitive Factors in the Ecological Aspect

| No | Sensitive Factor              | Priority |
|----|-------------------------------|----------|
| 1  | Use of organic fertilizer     | 1        |
| 2  | NPK and urea dosage           | 2        |
| 3  | Pest infestation intensity    | 3        |
| 4  | Plant disease intensity       | 4        |
| 5  | Domestic waste pollution      | 5        |
| 6  | Irrigation water availability | 5        |
| 7  | Land conversion threat        | 5        |

Primary Data, 2025

The most sensitive ecological factor is the use of organic fertilizer, followed by NPK and urea dosage. This indicates that fertilizer management is the key leverage point for improving ecological sustainability. Farmers in *Subak Sembung* still rely heavily on chemical fertilizers, which may degrade soil structure and disrupt microbial activity if used continuously (Nuraina, 2021). Local regulations, such as Bali Provincial Regulation No. 8 of 2019 and Governor Regulation No. 15 of 2021, promote a gradual transition toward organic agriculture to mitigate these impacts.

### *Economic Aspect*

Six economic attributes were evaluated to identify the most influential variables affecting farm viability and income stability. The results of sensitivity leverage analysis are summarized in Table 8.

Table 8. Priority Ranking of Sensitive Factors in the Economic Aspect

| No | Sensitive Factor               | Priority |
|----|--------------------------------|----------|
| 1  | Average land size of farmers   | 1        |
| 2  | Maintenance cost support       | 2        |
| 3  | GKP selling price              | 3        |
| 4  | Production per hectare         | 4        |
| 5  | Production inputs availability | 5        |
| 6  | Net farm income                | 5        |

Primary Data, 2025

The most sensitive economic variable is average land size, which reflects the severe land fragmentation in the study area. Most farmers operate on approximately 0.5 ha, which limits production volume and weakens income stability (Umyati et al., 2022; Suhendra & Noor, 2024). Small landholdings constrain economies of scale and discourage investment in sustainable technologies.

### *Socio-Cultural Aspect*

The socio-cultural dimension includes seven attributes associated with human capital, social cohesion, and generational continuity. Sensitivity leverage results are presented in Table 9.

Table 9. Priority Ranking of Sensitive Factors in the Socio-Cultural Aspect

| No | Sensitive Factor                     | Priority |
|----|--------------------------------------|----------|
| 1  | Farmer regeneration (<40 years)      | 1        |
| 2  | Family participation                 | 2        |
| 3  | Farmer education level               | 3        |
| 4  | Farmer age                           | 4        |
| 5  | Participation in traditional rituals | 4        |
| 6  | Water conflict                       | 4        |
| 7  | Social farming system                | 4        |

Primary Data, 2025

The most sensitive socio-cultural attribute is farmer regeneration, indicating a critical lack of young farmers. The farming population is dominated by individuals over 50 years old, which threatens long-term sustainability. This supports Polan et al. (2021), who found declining youth interest in agriculture due to economic and social factors.

### *Institutional Aspect*

Institutional sustainability is shaped by governance, market access, and collective organizations. The sensitivity ranking for this aspect is shown in Table 10.

Table 10. Priority Ranking of Sensitive Factors in the Institutional Aspect

| No | Sensitive Factor              | Priority |
|----|-------------------------------|----------|
| 1  | Farmer cooperative            | 1        |
| 2  | Market access                 | 2        |
| 3  | Government assistance         | 3        |
| 4  | Agricultural extension system | 4        |
| 5  | Subak regulations             | 5        |
| 6  | LP2B status                   | 5        |
| 7  | Extension officer activeness  | 5        |

Primary Data, 2025

The absence of an active farmer cooperative is the most sensitive institutional issue. Without collective marketing and financing mechanisms, farmers remain dependent on middlemen, weakening their bargaining power (Semaranata et al., 2025).

#### *Technological Aspect*

Technological attributes relate to production systems, tools, and infrastructure. The sensitivity ranking is presented in Table 11.

Table 11. Priority Ranking of Sensitive Factors in the Technological Aspect

| No | Sensitive Factor                | Priority |
|----|---------------------------------|----------|
| 1  | Irrigation channel condition    | 1        |
| 2  | Organic farming system adoption | 2        |
| 3  | Availability of machinery       | 3        |
| 4  | Seed availability               | 4        |
| 5  | Land preparation techniques     | 5        |
| 6  | Tool operation skills           | 5        |

Primary Data, 2025

The most sensitive technological factor is the condition of irrigation channels, followed by the adoption of organic farming systems. Damaged channels disrupt water distribution and reduce productivity, reinforcing the need for infrastructure rehabilitation and technological innovation.

#### *Sustainability Improvement Scenarios*

Based on the sensitivity leverage analysis, several sustainability improvement scenarios were formulated to increase the overall sustainability status of rice farming in *Subak* Sembung. These scenarios were designed by optimizing the most sensitive attributes in each aspect—ecological, economic, socio-cultural, institutional, and technological—through a Multiaspect Sustainability Analysis (MSA) simulation. The scenarios aim to demonstrate how strategic interventions can elevate the sustainability index from the current status toward higher performance levels.

### Scenario 1: Optimization of Sensitive Attributes

This scenario assumes partial improvement of the most sensitive attributes in each sustainability dimension, while other variables remain constant. The simulated sustainability index under Scenario 1 is presented in Table 5.15.

Table 12. Sustainability Index under Scenario 1

| Aspect               | Existing Value | Scenario 1   | Sustainability Status   |
|----------------------|----------------|--------------|-------------------------|
| Ecology              | 64.29          | 78.10        | Very Sustainable        |
| Economy              | 50.00          | 70.25        | Sustainable             |
| Socio-Cultural       | 71.43          | 85.60        | Very Sustainable        |
| Institutional        | 71.43          | 83.40        | Very Sustainable        |
| Technology           | 75.00          | 86.45        | Very Sustainable        |
| <b>Total Average</b> | <b>66.43</b>   | <b>86.76</b> | <b>Very Sustainable</b> |

Primary Data, 2025

Scenario 1 increases the sustainability index from 66.43 (sustainable) to 86.76 (very sustainable). The largest improvements occur in the ecological and socio-cultural aspects, indicating that fertilizer management, farmer regeneration, and infrastructure improvements have the greatest impact.

### *Scenario 2: Integrated Sustainability Enhancement*

Scenario 2 simulates full optimization of all sensitive attributes across the five aspects. This scenario represents the ideal condition where ecological practices, economic efficiency, institutional governance, social participation, and technological innovation are implemented simultaneously. The results are presented in Table 13.

Table 13. Sustainability Index under Scenario 2

| Aspect               | Scenario 1   | Scenario 2   | Sustainability Status   |
|----------------------|--------------|--------------|-------------------------|
| Ecology              | 78.10        | 92.35        | Very Sustainable        |
| Economy              | 70.25        | 88.20        | Very Sustainable        |
| Socio-Cultural       | 85.60        | 94.10        | Very Sustainable        |
| Institutional        | 83.40        | 93.25        | Very Sustainable        |
| Technology           | 86.45        | 89.00        | Very Sustainable        |
| <b>Total Average</b> | <b>86.76</b> | <b>95.58</b> | <b>Very Sustainable</b> |

Primary Data, 2025

Scenario 2 further elevates the sustainability index to 95.58, reflecting an optimal balance across all dimensions. This scenario demonstrates that integrated and multi-sectoral strategies provide the greatest potential for long-term sustainability in *Subak Sembung*.

### **Conclusion**

The sustainability status of rice farming in *Subak Sembung* reached a score of 66.43, which falls into the sustainable category. Each sustainability dimension showed varying index values, namely: (1) the ecological aspect scored 64.29

(sustainable); (2) the economic aspect scored 50.00 (sustainable); (3) the socio-cultural aspect scored 71.43 (sustainable); (4) the institutional aspect scored 71.43 (sustainable); and (5) the technological aspect scored 75.00 (sustainable).

The most influential sensitive attributes in each dimension were identified as follows: in the ecological aspect, the intensity of pest attacks; in the economic aspect, the average size of farmers' landholdings; in the socio-cultural aspect, farmer regeneration (<40 years); in the institutional aspect, the existence and effectiveness of farmer cooperatives; and in the technological aspect, the condition of irrigation channels in *Subak* Sembung.

Sustainability improvement was simulated across all aspects using two development scenarios and two driving factors. The first scenario increased the sustainability index from 66.43 (sustainable) to 86.79 (very sustainable). The second scenario further increased the index from 86.76 (very sustainable) to 95.58 (very sustainable), indicating that integrated improvement strategies have a strong potential to enhance the long-term sustainability of rice farming in the study area.

#### *Managerial Implication*

First, agricultural managers and local government authorities should prioritize interventions in the ecological and economic dimensions, as these aspects showed the lowest sustainability scores. The strong sensitivity of organic fertilizer use and pest intensity implies that extension programs must shift from conventional chemical-dependent practices toward integrated and organic-based farming systems. This can be implemented through structured farmer field schools, demonstration plots, and incentive schemes for farmers who adopt environmentally friendly practices. Improving irrigation channel maintenance should also become a routine management agenda to prevent water loss and ensure equitable distribution.

Second, the identification of small landholding size as the most sensitive economic factor highlights the urgency of collective-based farm management. Stakeholders are encouraged to promote cooperative farming models, shared input procurement, joint marketing systems, and access to micro-financing. The establishment and strengthening of farmer cooperatives can improve economies of scale, reduce production costs, and enhance farmers' bargaining positions in the market.

Third, the low participation of young farmers (<40 years) suggests that sustainability is threatened by generational gaps. Therefore, managers should design youth engagement programs, such as agricultural entrepreneurship training, digital farming initiatives, and agrotourism-based employment opportunities, to attract younger generations. This strategy will not only ensure labor continuity but also stimulate innovation within the traditional *Subak* system.

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