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Sustainability and strategic development of biogas generated from tofu manufacturing wastewater

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ABSTRACT

Tofu is a widely consumed soy-based food in Indonesia, and its liquid waste is utilized for biogas in Sambak Village, addressing both renewable energy and waste management issues. However, the system's sustainability faces challenges. This research aimed to assess the current sustainability status of the tofu-wastewater-based biogas system and formulate strategic measures to optimize its long-term continuity. Sustainability was analyzed across five dimensions (ecological, economic, social, technological, and institutional) with multidimensional scaling (MDS) method, while strategies were formulated using SWOT analysis. The results showed an overall moderately sustainable system with an index score of 74.15. The ecological, economic, and social dimensions were rated very sustainable, while the technological dimension was quite sustainable, and the institutional dimension was less sustainable. The top priority strategy identified is the development and innovation of biogas installations. While biogas offers significant environmental and social economic benefits, sustainability is hindered by limited biogas volume and weak institutional management. Therefore, guidance, regular monitoring involving all stakeholders, and future supply-demand forecasting are crucial for its long-term viability.

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1. INTRODUCTION

Energy is a fundamental necessity that underpins almost all aspects of modern human life [1]-[3]. In Indonesia, rapid population growth and the expansion of key sectors such as transportation, industry, residential, and public services continue to drive an increasing demand for energy [4]. Currently, the country's energy consumption remains heavily dependent on fossil fuels, with oil accounting for 40.2 percent (%), coal for 25.3%, and natural gas for 19.8% of the total primary energy use [5]. These resources are finite, with current projections suggesting that Indonesia's oil reserves may be depleted within 9.5 years, natural gas within 19.9 years, and coal within 65 years if no discoveries are made [6]. The Indonesian government has a policy to maximize the use of renewable energy as an effort to address energy problems, namely by issuing Law No. 5/2006 concerning the use of new and renewable energy [2], [7]. The environmental implications of fossil fuel use—particularly greenhouse gas emissions—pose serious threats to global climate stability, human health, and ecosystem integrity [8]. As a response, biogas has emerged as a promising renewable energy source [3], [7]. Produced through the anaerobic digestion of organic matter, biogas not only generates clean energy but also offers a sustainable method for waste treatment [9]. Its adoption supports Indonesia's commitment to reducing greenhouse gas emissions by 26% and aligns with the United Nations' Sustainable Development Goal-7, which advocates for universal access to affordable and sustainable energy by 2030 [10]. Indonesia's tofu industry, which includes approximately 84,000 production units with a combined processing capacity of 2.56 million tons of soybeans per year, is a significant source of organic waste [11]. On average, this sector generates 20 million cubic meters (Mm^3) of liquid waste and 1.024 million tons of solid waste annually [12].

Tofu wastewater, in particular, is characterized by high levels of organic pollutants such as total suspended solid (TSS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD), but it also contains proteins and carbohydrates that are ideal substrates for biogas production [13]. If not properly treated, this waste contributes to environmental pollution and public health issues, while also emitting greenhouse gases. Prior to the implementation of biogas for the treatment of tofu industry wastewater, the Sambak community frequently encountered environmental degradation, including odor, wastewater pollution, and diminished agricultural output, stemming from unregulated tofu industrial waste, which led to conflict and demonstrations. These disagreements hindered the acceptance of the tofu industry and exacerbated social skepticism.

Sambak Village, Magelang Regency, is one of the notable tofu-producing regions which have adopted biogas systems to process tofu wastewater. The communal biogas system in Sambak Village consists of 6 digester units that utilize liquid tofu wastewater as feedstock, sourced from 14 local producers, to supply energy for 68 households. Despite the early success of these initiatives, several operational challenges have emerged over time, including deterioration of biogas infrastructure, inadequate maintenance, limited funding, and insufficient stakeholder involvement. Similar research assessing urban forest eco-tourism in Dumai found that while the system achieved a moderate overall sustainability rating, it was considered less sustainable across the specific dimensions of ecology, economy, social, and institutional [14]. Given these constraints, there is a pressing need to assess the current utilization and management of tofu wastewater biogas systems in Sambak Village. This study aims to evaluate the sustainability status and identify development strategies to ensure the long-term viability of biogas as a renewable energy solution within the framework of community-based energy self-sufficiency.

2. METHOD

2.1. Data collection

This study was intentionally carried out at Sambak Village, Magelang Regency, Central Java, Indonesia (Figure 1) from November 2024 to February 2025. This study utilizes a mixed-methods approach, integrating quantitative and descriptive qualitative data, which are then transformed into quantifiable metrics. Primary data were collected through observation, comprehensive sample questionnaires administered to 68 biogas users, encompassing the entire population (saturated samples), and in-depth interviews with 10 key informants, including representatives from government, academia, environmental advocacy, and the tofu industry. The sample size aligns with the requirements of the multidimensional scaling (MDS) Rapfish system, which has a data input limitation of a maximum of 100 entries [15]. According to [16], as cited in research methods for business, an appropriate sample size for research ranges from 30 to 500 respondents. A sample of more than 6 key informants can be considered sufficient to reach data saturation [17]. Secondary data included literature such as journals, documents, or related reports.

2.2. MDS Rapfish sustainability analysis

Sustainability analysis was conducted using the MDS method with a modified Rapfish program, reviewed through five dimensions: ecological, economic, social, technological, and institutional, with a total of 32 attributes. According to [18], the selection of attributes can be adjusted based on field conditions, as assessment criteria may vary from one case to another. Ideally, each dimension should consist of 6 to 8 attribute items. MDS Rapfish has been extensively applied in evaluating the sustainability of various environmental management efforts, including biogas-related initiatives [14]. The steps for sustainability analysis using the MDS method can be seen in Figure 2.

The scores classified based on the sustainability index values (Table 1). The final outputs of the rap-biogas analysis include the sustainability status, the coefficient of determination (R^2), and the stress value (S). A good model is indicated by a stress value of less than 0.25 and an R^2 value approaching one [14], [19]. An attribute is considered sensitive and selected as a key leverage factor if its RMS value is above the median or is the highest among other attributes within each sustainability dimension [14]. Monte Carlo analysis is employed to test the validity or estimate the random error with a minimum confidence level of 95%, and iterations adjusted as needed to approach the most accurate value [20].

Table 1. Index categories and sustainability status

Index	Category	Sustainability status
0.00-25.00	Bad	Unsustainable
25.01-50.00	Less	Less sustainable
50.01-75.00	Enough	Quite sustainable
75.01-100.00	Good	Very sustainable

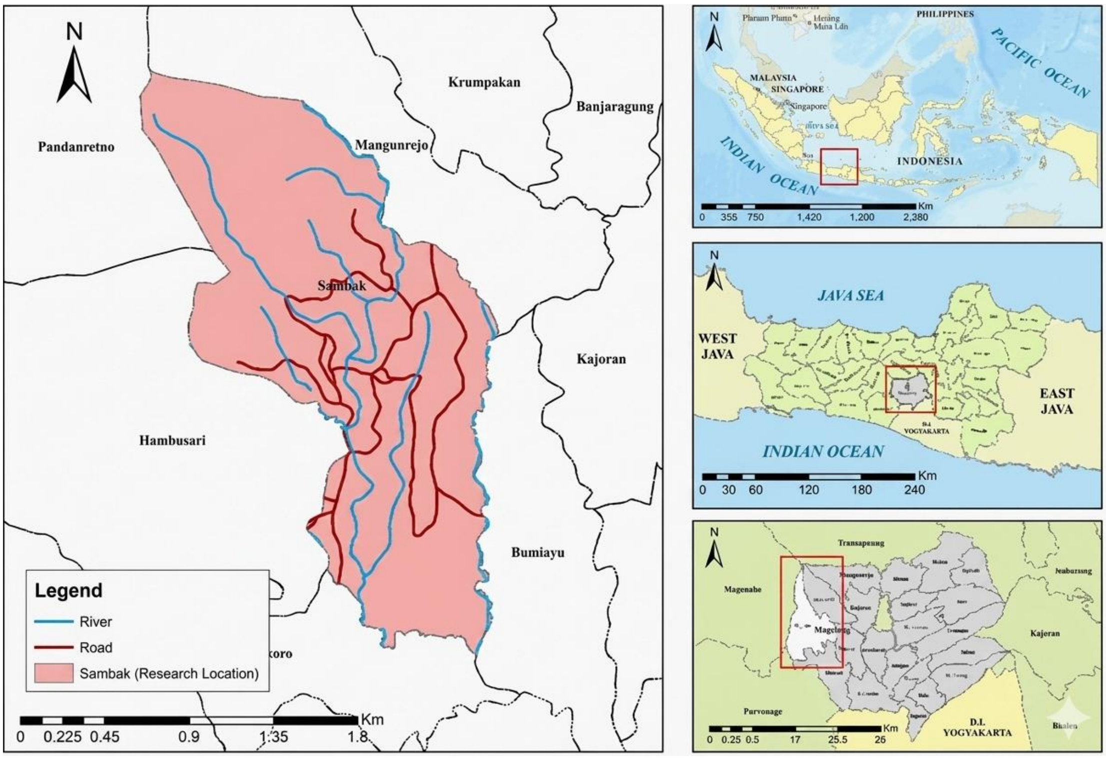

Figure 1. Research location in Sambak Village, Magelang Regency, Central Java, Indonesia

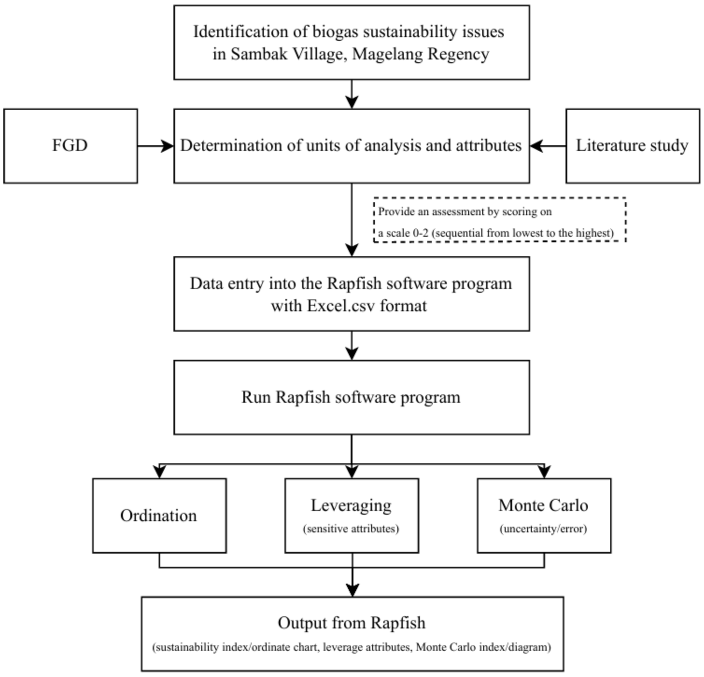

Figure 2. Stages of MDS Rapfish biogas sustainability analysis in Sambak Village, Central Java

2.3. SWOT strategy analysis

The development strategy for tofu wastewater-based biogas in Sambak Village was formulated using strength, weakness, opportunity, and threat (SWOT) analysis to identify current conditions prior to decision-making [21]. The internal factor evaluation (IFE) and external factor evaluation (EFE) matrices were constructed with each factor ideally consisting of 5 to 10 items. The weighting of internal and external factors ranges from not important (0.0) to very important (1.0), with the total weight for each factor not exceeding [22]. The rating is determined based on the level of influence, ranging from 1 (less important), 2 (moderately important), 3 (important), to 4 (very important) [23]. The steps for processing SWOT analysis data are depicted in Figure 3.

3. RESULTS AND DISCUSSION

3.1. Sustainability analysis

Sustainability refers to development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs, thereby allowing the implemented system to endure indefinitely [24]. The concept of sustainable development began to gain international attention in 1987 with the release of the Brundtland Report by the World Commission on Environment and Development [25]. Sustainability analysis can serve as a basis for determining sustainability status and as a reference in the formulation of resource management policies [26]. Currently, the sustainable development goals (SDGs) have been adopted as an evolved and more comprehensive framework of the sustainability concept, designed to be implemented by all countries through adaptation to their respective national contexts [27]. Biogas technology derived from organic waste can contribute to the achievement of the SDGs, particularly in ensuring access to affordable and clean energy (SDG 7) and combating climate change (SDG 13). In comparison to solar or micro-hydro systems, biogas derived from tofu waste provides more accessibility for small companies and rural populations, owing to the availability of local feedstock and minimal initial investment. Its deficiencies encompass dependence on a steady garbage supply and the necessity for routine maintenance. Although solar energy is more scalable and necessitates less maintenance, it entails a larger initial investment and is contingent upon weather conditions [2], [7].

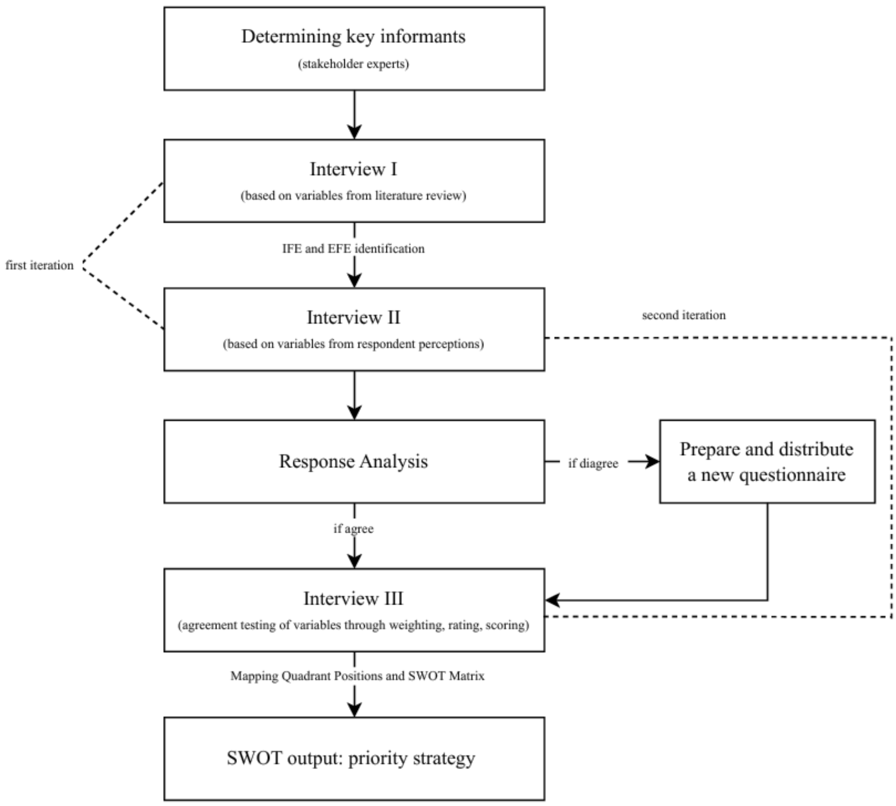

Figure 3. Stages of SWOT biogas strategy analysis in Sambak Village, Central Java

The graphical representation in Figure 4 depicts the positioning of the five dimensions. First, the results of the MDS Rap-Biogas analysis for the ecological dimension indicated a sustainability index score of 82.70, suggesting that the ecological dimension in Sambak Village is classified as very sustainable (75.01-100.00). Second, the sustainability index for the economic dimension yielded an ordination score of 77.01, indicating that the economic aspect is also within the very sustainable category. Third, the social sustainability index of biogas in Sambak Village reached 88.99, representing not only a very sustainable status but also the highest sustainability score among all dimensions assessed. Fourth, the technological dimension recorded an index score of 74.41, which is categorized as quite sustainable (50.01-75.00). Fifth, the institutional dimension showed a sustainability index of 47.63, reflecting a less sustainable status (25.01-50.00) in this area. The average sustainability index of biogas across all dimensions in Sambak Village is 74.15, which falls within the classification of quite sustainable, as presented in Table 2.

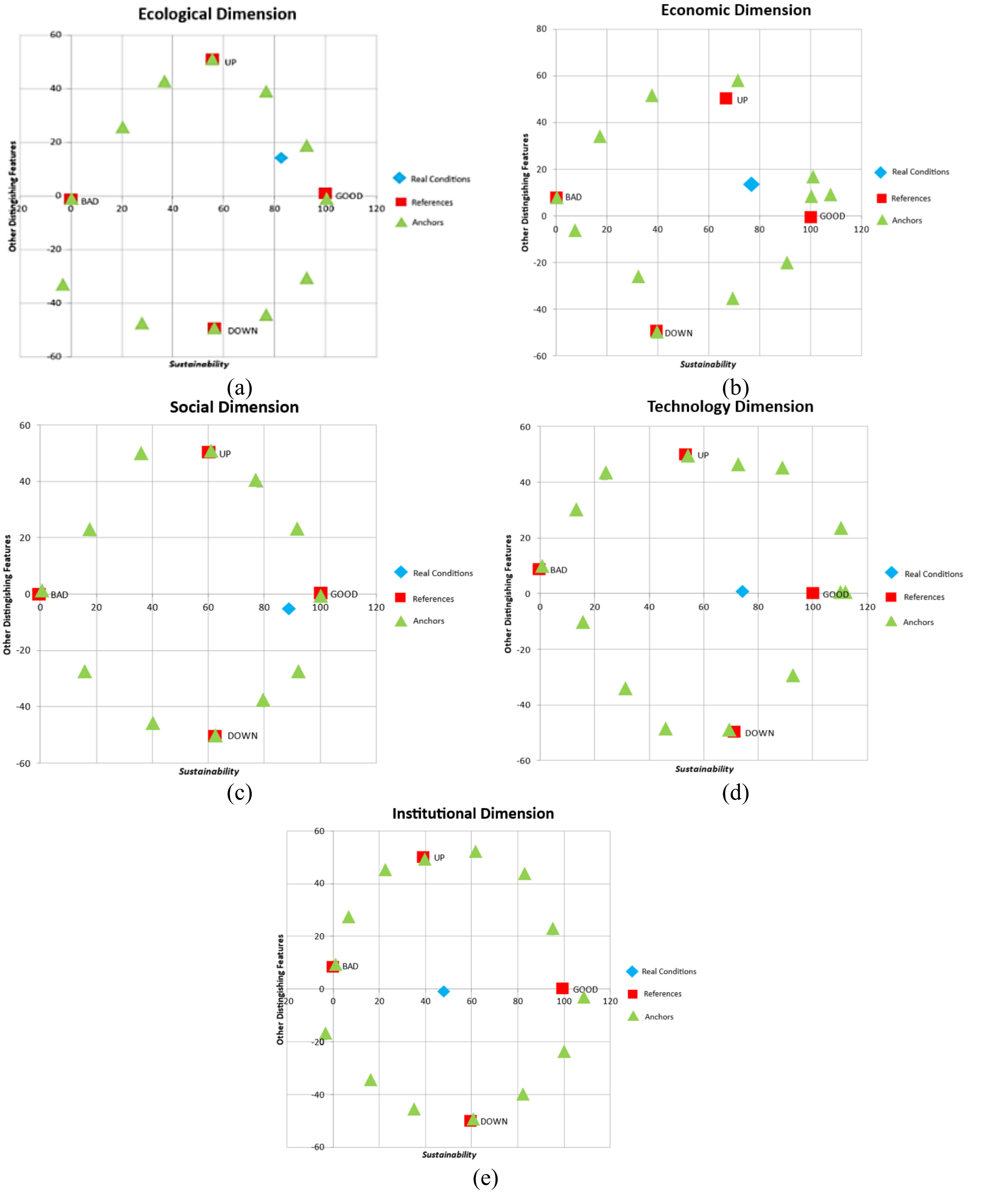

Figure 4. Results of 5-dimensional analysis using MDS: (a) ecological dimension, (b) economic dimension, (c) social dimension, (d) technology dimension, and (e) institutional dimension

The Monte Carlo analysis of biogas sustainability, conducted at a 95% confidence level, resulted in a value difference of 1.8 compared to the MDS analysis, indicating no significant difference. The deviation between the MDS and Monte Carlo analyses is less than 5%, which suggests that the calculations are accurate and meet the necessary reliability criteria. The goodness-of-fit test for model validation includes the stress (S) value, which measures the degree of lack of fit, and R^2, which assesses the proportion of data variability explained by the model or its accuracy [28]. The average S value obtained was 0.17, indicating that the ordination plot represents the modeling analysis fairly well and is close to the actual data. Furthermore, the R^2 yielded a value of 0.95, which is close to 1, suggesting that the model is capable of explaining data variation optimally.

The result of kite diagram (Figure 5) shows that the social component exhibits the highest index score within the very sustainable category. The biogas program transforms waste into a valuable energy resource, mitigates odor and pollution, and provides tangible advantages to homes. This mutual advantage fosters collaboration between tofu industries and local inhabitants, thereby diminishing conflict between the two parties. The institutional dimension was identified as having the lowest level of sustainability (less sustainable category) among all dimensions, followed by the technological dimension, which falls into the quite sustainable category.

Table 2. Result of MDS and Monte Carlo analysis

Criteria	Sustainability index (MDS)	Monte Carlo	Differences	S value	R^2	Category
Ecology	82.70	80.36	2.34	0.17	0.96	Very sustainable
Economy	77.01	75.36	1.65	0.16	0.93	Very sustainable
Social	88.99	86.82	2.17	0.18	0.97	Very sustainable
Technology	74.41	73.36	1.05	0.17	0.96	Quite sustainable
Institutional	47.63	45.84	1.79	0.16	0.95	Less sustainable
Multidimensional	74.15	72.35	1.80	0.17	0.95	Quite sustainable

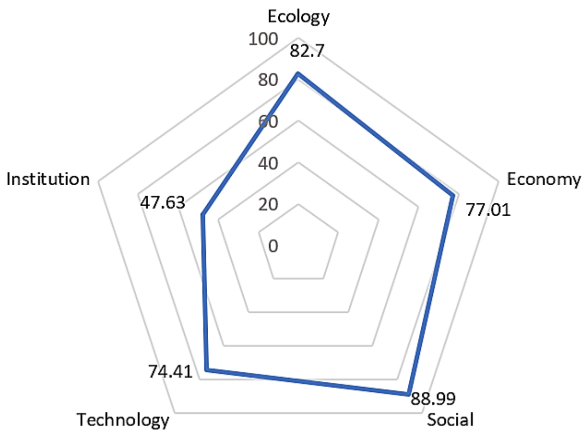

Figure 5. Kite diagram of 5-dimensional MDS analysis results

The institutional factor was assessed as less sustainable because to the lack of defined organizational positions, infrequent group meetings, and an absence of sustainable biogas development initiatives. The reliance on unstructured, volunteer-based management practices leads to inconsistent oversight and significantly impedes long-term strategic planning. These institutional deficiencies substantially impede coordination, technical maintenance, and policy enforcement, thus impacting the system's overall sustainability. Institutional deficiencies immediately affect daily operations, including postponed maintenance, unaddressed user grievances, erratic fee collection, and insufficient troubleshooting procedures. In the absence of organized leadership or clearly delineated tasks, maintenance becomes reactive instead of proactive.

Operational disruptions may result in diminished user satisfaction and heightened system breakdowns. The results suggest that emphasis on enhancing the institutional and technological aspects is essential for achieving superior overall optimization in sustainable status. Strategy formulation must be informed by a comprehensive analysis of leverage factors or sensitive features to guarantee coherence across all five dimensions. The overall sustainability status is classified as fairly sustainable. However, ongoing monitoring is crucial to preserve and improve this status.

3.2. Leverage analysis

The leverage factor is visually illustrated using a bar chart as shown in Figure 6, where the highest leverage values indicate that intervention in these factors will most significantly influence the sustainability index. Based on leverage analysis of six attributes, the median value of ecological dimension was found to be 5.02. Accordingly, the sensitive attributes influencing the ecological sustainability of tofu wastewater biogas in Sambak Village include: knowledge of waste management benefits (5.51), water quality and ecosystem (5.63), and public awareness of environmental improvement (6.57). These three attributes are the primary factors contributing positive way to the ecological dimension of sustainability. However, the by-product of the biogas process, known as bioslurry, has yet to be utilized. Research conducted by [2], [3], biogas production using rice husk as raw material can produce liquid organic fertilizer as a by-product. Therefore, further research and development are required to explore the potential of tofu wastewater as a fertilizer, particularly for rice cultivation.

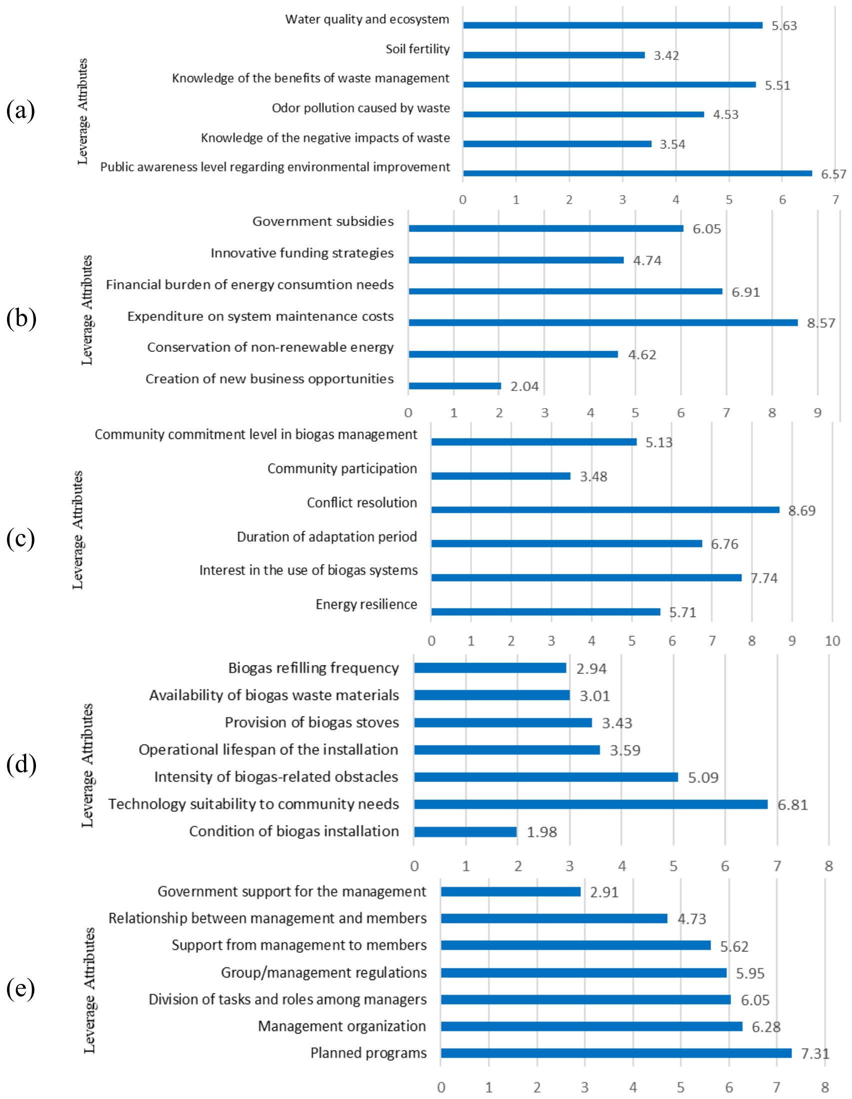

Figure 6. RMS values from leverage analysis of 5-dimensions: (a) ecological dimension, (b) economic dimension, (c) social dimension, (d) technology dimension, and (e) institutional dimension

In the economic dimension, the median leverage value is 5.40. Sensitive attributes include government subsidies (6.05), the burden of energy expenditure (6.91), and the cost of system maintenance (8.57). Biogas users in Sambak Village are subject to a community maintenance fee of IDR 15,000 per month, compared to IDR 18,000–20,000 per 3 kg LPG tank. Biogas often fulfills 70–80% of daily cooking requirements, resulting in considerable savings. Users report being able to save between 0.5 to 2 times their previous expenditure on non-renewable energy sources. The economic benefits' sustainability depends on consistent biogas supply, fair pricing, infrastructure maintenance, and institutional support. Unstable waste input or poor management may reduce benefits over time. To ensure financial sustainability, this can be done by digitalizing payment systems, diversifying revenue through bioslurry and carbon credit schemes, and formalizing funding via village regulations. These models ensure transparency, accountability, and user compliance.

The leverage analysis of the social dimension, derived from the median of six attributes, yields a value of 6.24. Sensitive attributes that support the sustainability of tofu wastewater biogas development in Sambak Village include adaptation time (6.76), interest in biogas system usage (7.74), and conflict resolution (8.69). Prior to the implementation of biogas, residents of Sambak Village suffered losses such as foul odors, decreased soil quality, reduced agricultural productivity, and fish farming failures. The success of biogas as a conflict mediation tool between local residents and tofu producers has increased community interest in biogas systems.

The median value for the leverage attributes in the technological dimension, calculated from seven attributes, is 3.43. Sensitive attributes in this dimension include biogas waste availability (3.59), intensity of biogas system challenges (5.09), and the compatibility of technology with local needs (6.81). In the technological dimension, these sensitive attributes require particular attention and improvement to enhance the sustainability status. The number of biogas users currently exceeds the energy capacity generated, leading to unequal distribution (overcapacity). Based on research conducted by [3], [19], a medium-sized biogas digester with a volume of 6 m^3 connected to a two-burner gas stove can serve the cooking needs of two families. In addition, according to the Merapi Region Energy and Mineral Resources (ESDM), the biogas capacity is 6 families every 20 m^3. However, the expansion of the customer network to date has reached maximum capacity and is still being carried out to reduce conflicts between communities. Furthermore, the tofu wastewater biogas installations in Sambak Village lack purification equipment, resulting in biogas that remains acidic and impure. The presence of hydrogen sulfide (H_2S) in the biogas can cause corrosion in stoves if not routinely purified [29].

Leverage analysis of the institutional dimension indicates dominant influences from task and role distribution among managers (6.05), the managing organization (6.28), and the presence of planned programs (7.31). Structured programs such as regular meetings, consistent evaluations, and biogas development initiatives are currently lacking in Sambak Village. Existing biogas programs are generally incidental, depending on government funding. The biogas group organization tends to be inactive due to its voluntary, non-profit nature, allowing flexibility in management based on individual availability and situational factors.

3.3. Strategy analysis

The strategy formulation for the development of tofu wastewater biogas in Sambak Village was conducted using the SWOT method, based on data obtained through in-depth interviews. The analytical steps included internal factor analysis (strengths and weaknesses), external factor analysis (opportunities and threats), scoring based on weight and rating, mapping strategic quadrant coordinates, formulating SWOT strategies, and determining strategy priorities. The internal and external factors identified were quantitatively developed in the SWOT analysis using a scoring system. The weight assessment reflects respondents perceptions of the influence each factor has on the current condition of the system [30]. Meanwhile, the rating illustrates the extent to which each factor contributes to the expected development of the system's sustainability [31]. The calculations of internal strategy factor analysis summary (IFAS) and external strategy factor analysis summary (EFAS) are presented in Tables 3 and 4.

Table 3. Internal strategy factor analysis summary (IFAS)

Code	Category	Factor description	Weight (a)	Rating (b)	Score (a x b)
S1	Strength	High public interest in biogas	0.13	4	0.52
S2		Biogas reduces environmental pollution	0.13	4	0.52
S3		Biogas becomes a solution to conflicts between tofu producers and the community	0.13	4	0.52
S4		Biogas can reduce household economic burden	0.12	4	0.48
S5		Biogas reduces the use of non-renewable energy	0.12	4	0.48
		Total (A)	0.63	20	2.52
W1	Weakness	The biogas flame produced is unstable and limited	0.06	3	0.18
W2		Community knowledge and skills are still low	0.08	3	0.24
W3		Biogas cannot be used for 24 hours continuously	0.07	2	0.14
W4		Inconsistent and unstable volume of tofu waste	0.08	2	0.16
W5		Decreased quality of biogas pipelines and installations	0.08	2	0.16
		Total (B)	0.37	12	0.90
		Total (A+B)	1	32	3.42

Table 4. External strategy factor analysis summary (EFAS)

Code	Category	Factor description	Weight (a)	Rating (b)	Score (a × b)
O1	Opportunity	Liquid tofu waste contains high levels of methane gas	0.14	4	0.56
O2		Government policies and subsidies for renewable energy	0.13	3	0.39
O3		Biogas as a solution to the scarcity of 3 kg LPG gas	0.13	3	0.39
O4		Innovation and replication of biogas in other areas	0.12	3	0.36
O5		Enhancing the village's image and achievements in environmental matters	0.12	3	0.36
		Total (A)	0.64	16	2.06
T1	Threat	Delayed biogas contributions/payments	0.09	2	0.18
T2		Neglected group meetings and functions	0.06	3	0.18
T3		Risk of technical failure in the biogas network and installation	0.09	2	0.16
T4		Safety risks and low public trust	0.06	2	0.12
T5		Competition with other energy sources	0.06	2	0.12
		Total (B)	0.36	11	0.79
		Total (A+B)	1	27	2.85

Based on calculation of IFAS and EFAS value, it was found that the strength factor (S) score is greater than the weakness factor (W) score, with values of 2.52 > 0.90, resulting in a positive IFAS score. Similarly, the external factor analysis (EFAS) also yielded a positive result, where the opportunity factor (O) score exceeds the threat factor (T) score, with values of 2.06 > 0.79. A positive score in both IFAS and EFAS indicates a favorable condition for implementing a management strategy focused on expansion to achieve optimal objectives [32]. Therefore, it can be concluded that the strategy mapping for the development of tofu wastewater biogas in Sambak Village falls within Quadrant I. The SWOT strategy matrix comprises: aggressive strategies (Quadrant I), diversification strategies (Quadrant II), turnaround strategies (Quadrant III), and defensive strategies (Quadrant IV) [33]. In the case of biogas development in Sambak Village, the identified strategic position is within Quadrant I—indicating an integration strategy that leverages strengths (S) to capitalize on opportunities (O). The SO strategy reflects a growth-oriented approach, utilizing internal strengths to fully exploit existing opportunities. This position is considered advantageous, as it indicates the simultaneous presence of both strengths and opportunities [34]. The strategic development coordinates (x,y) are visualized through the SWOT or grand strategy matrix, as illustrated in Figure 7.

Strategy formulation through integration (relationship) between factors is needed to determine the alternative strategies needed. Alternative strategies for developing liquid tofu waste biogas in Sambak Village are shown in matrix form in Tables 5 and 6. Each strategy item is associated with different factors and assigned varying scores. Decision-making is guided by the interrelation among these factors and the total score assigned to each strategy, which is essential for determining strategic priorities in the implementation process. The prioritized strategy plan is developed based on the interrelationships among factors, as presented in Table 7.

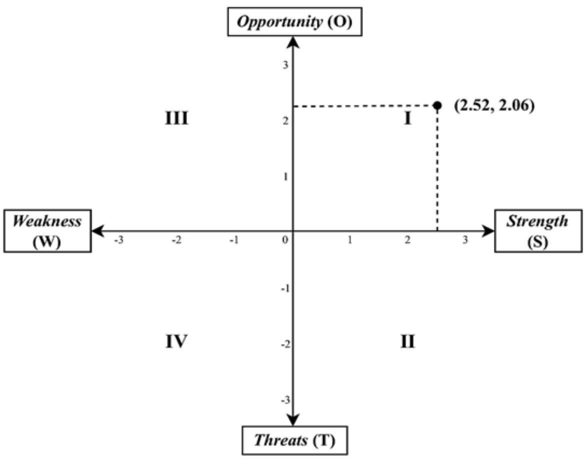

Figure 7. SWOT strategy relative position of biogas development

The top-ranked priority strategy is the upgrading and development of biogas installations and innovations in biogas injectors or storage tanks. Currently, 14 out of 15 tofu factories (93.33%) in Sambak Village have processed their waste into biogas, which is distributed to 68 users, representing 8.71% of the village's population. To ensure comprehensive waste processing, it is necessary to expand the network to include the remaining tofu factory. An increase in biogas supply is expected to reduce the incidence of combustion issues and boost the number of biogas users. Consequently, energy generated from tofu wastewater biogas can contribute significantly to the achievement of SDG 7: affordable and clean energy in Sambak Village. To broaden community access, Sambak Village has initiated an innovation to store biogas in tanks or injectors as a solution to the scarcity of 3 kg LPG gas tanks. This innovation also aims to overcome distribution challenges caused by topographic factors, such as elevation and the distance between households and digesters. Experimental use of the injector tanks demonstrated its ability to cook 10 eggs and boil one liter of water in a total of 40 minutes. However, as the technology is still in the prototype phase, further development is needed to optimize its application in terms of distribution, usage, and safety.

Table 5. SWOT factors

Group	Category	Factors strategies
Internal	Strength (S)	1. High public interest in biogas 2. Biogas reduces environmental pollution 3. Biogas becomes a solution to conflicts between tofu producers and the community 4. Biogas can reduce household economic burden 5. Biogas reduces the use of non-renewable energy
	Weakness (W)	1. The biogas flame produced is unstable and limited 2. Community knowledge and skills are still low 3. Biogas cannot be used for 24 hours continuously 4. Inconsistent and unstable volume of tofu waste 5. Decreased quality of biogas pipelines and installations
External	Opportunities (O)	1. Liquid tofu waste contains high levels of methane gas 2. Government policies and subsidies for renewable energy 3. Biogas as a solution to LPG scarcity 4. Innovation and replication in other areas 5. Enhancing village image and environmental achievements
	Threats (T)	1. Delayed biogas contributions/payments 2. Neglected group meetings and functions 3. Risk of technical failure in the biogas network and installation 4. Safety risks and low public trust 5. Competition with other energy sources

Table 6. SWOT matrix

External factor	Internal factor	
	Strength (S)	Weakness (W)
Opportunities (O)	S-O: 1. Development of biogas installations and innovation in injectors or storage tanks ($S_{1,2,3,4,5}$ $O_{2,3,4}$) 2. Build partnerships through branding as an eco-friendly village ($S_{1,2,5}$ $O_{4,5}$)	W-O: 1. Routine maintenance of networks and installations with full stakeholder support ($W_{1,2,3,5}$ $O_{2,3}$) 2. Improvement of biogas flame quality and stability ($W_{1,3,4}$ $O_{1,3,4}$) 3. Training and mentoring on biogas for the community ($W_{2,5}$ $O_{2,4,5}$)
Threats (T)	S-T: 1. Establishing more sustainable biogas policies ($S_{1,2,3,4}$ $T_{1,2,4}$) 2. Improvement and standardization of biogas installations ($S_{2,5}$ $T_{3,4,5}$) 3. Increasing public participation and trust through recognition and rewards ($S_{1,2}$ $T_{1,4}$)	W-T: 1. Reorganizing the biogas management group ($W_{1,2,3,4,5}$ $T_{1,2,3,4}$) 2. Diversification of biogas-based energy sources ($w_{1,3,5}$ $T_{1,4,5}$)

Table 7. Alternative strategy

No.	Alternative strategy	TAS
1.	Development of biogas installations and innovation in injectors or storage tanks	3.66
2.	Making biogas policies more sustainable	2.52
3.	Build partnerships through branding as an eco-friendly village	2.24
4.	Improvement of biogas flame quality and stability	1.79
5.	Reorganizing the biogas management group	1.52
6.	Training and mentoring on biogas for the community	1.51
7.	Routine maintenance of networks and installations with full stakeholder support	1.50
8.	Improvement and standardization of biogas installations	1.40
9.	Increasing public participation and trust through recognition and rewards	1.34
10.	Diversification of biogas-based energy sources	1.08

The second strategy involves implementing a more sustainable biogas policy. Digitalization of fee collection and complaint handling can be achieved through a dedicated platform accessible to both users and biogas administrators. The application can be continuously developed by incorporating various features such as user registration, guidance modules, alerts, remote monitoring using IoT sensors, and others. Biogas management can be strengthened through structured programs, including regular meetings, monitoring, maintenance, evaluation, and the continuous development of sustainable biogas systems.

The third strategy focuses on building networks and partnerships through eco-village branding. These partnerships may involve research, infrastructure development, management, public outreach, and educational tourism related to tofu wastewater biogas. The development strategy for tofu wastewater-based biogas in Sambak Village encompasses several integrated approaches aimed at enhancing both the quality and stability of biogas flame. This includes gas purification using various absorbents such as activated carbon, zeolite, quicklime, and natural desulfurizers, which have been proven effective in increasing methane concentration while significantly reducing CO_2 and H_2S content [35]. Substrate supply stability is maintained through the expansion of storage tank capacity and co-digestion with livestock manure. Technical standardization, guided by SNI 7826:2012 on fixed-dome digester materials, serves as a benchmark for ensuring biogas system quality and safety.

4. CONCLUSION

The overall sustainability status of tofu wastewater biogas in Sambak Village is considered moderately sustainable, with a score of 74.15. The ecological (82.70), economic (77.01), and social (88.99) dimensions fall within the sustainable category. This is primarily due to biogas serving as a resolution to conflicts between the local community and tofu producers, by improving environmental quality while also providing an affordable source of clean energy. The technological dimension is deemed quite sustainable (74.41), as the amount of biogas produced has yet to fully meet the energy demands of the entire community. Meanwhile, the institutional dimension is classified as less sustainable (47.63), due to the lack of structured or well-planned management of biogas operations through local groups. The top priority strategy for further development is the expansion of biogas installations and innovation in injectors or storage tanks, intended to bridge the gap between existing technology and the community's increasing interest in biogas utilization. Recommendations derived from this study suggest that the development of tofu wastewater-based biogas in Sambak Village should be accompanied by continuous guidance, monitoring, and evaluation. Community empowerment through active participation (sense of belonging) is essential to support the long-term sustainability of the biogas program.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author, [HHAM], on request.

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