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Sustainability assessment of rural biogas systems using a rapid appraisal method in Klaten District, Indonesia

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Abstract. *Sabrina AD, Setyawan AD, Indrawan M. 2024. Sustainability assessment of rural biogas systems using a rapid appraisal method in Klaten District, Indonesia. Asian J Trop Biotechnol 21: 111-122.* Household-scale biogas systems are increasingly promoted as sustainable energy solutions for rural areas. However, their long-term viability depends on a range of ecological, economic, social, technological, and institutional factors that interact in complex ways. This study applied the Rap-Biogas method, a multidimensional scaling-based rapid appraisal approach, to assess the sustainability of a community-based biogas system in Mundu Village, Klaten District, Central Java, Indonesia. Data were collected through structured questionnaires, interviews, and secondary sources, covering 28 attributes across five dimensions. The overall sustainability index was 67.77%, indicating a fairly sustainable status. The ecological (81.78%), social (83.52%), and technological (77.95%) dimensions showed strong performance, driven by reductions in organic waste, high community participation, and user-friendly technology. In contrast, the economic (71.06%) and institutional (24.52%) dimensions revealed significant challenges, including limited business development, insufficient maintenance support, and the absence of long-term policy integration. Leverage analysis identified critical sensitive attributes within each dimension, providing clear targets for intervention. The study highlights the strengths and weaknesses of decentralized biogas systems. It emphasizes the need for improved institutional support, financial mechanisms, and policy alignment to enhance sustainability, with particular stress on the importance of financial mechanisms in this context. Rap-Biogas proved to be a practical and participatory tool for rapid sustainability diagnostics, and the findings offer valuable insights for replicating and scaling rural renewable energy programs in Indonesia and other developing regions.

Keywords: Biogas sustainability, community-based renewable energy, institutional support, Rap-Biogas, rural energy

INTRODUCTION

Energy plays a vital role in supporting human activities, ranging from lighting, cooking, and transportation to industrial operations. Over the years, global energy demand has surged due to population growth and industrial expansion (Muzayanah et al. 2022). Indonesia, as a developing country, faces significant challenges in meeting its energy needs while also ensuring sustainability. The heavy reliance on fossil fuels such as petroleum, coal, and natural gas has raised concerns about environmental degradation and energy security (Kahraman et al. 2024).

The consumption of fossil fuels is a major contributor to greenhouse gas emissions, which are accelerating global climate change. The combustion of these fuels releases carbon dioxide and methane, leading to air pollution and associated health risks (Wang and Azam, 2024). Moreover, fossil energy sources are finite; according to the Ministry of Energy and Mineral Resources (ESDM), Indonesia's oil reserves are projected to last only 9.5 years and its natural gas reserves for 19.9 years, if no new reserves are discovered (Ministry of Energy and Mineral Resources, 2021). These constraints underscore the urgent need to shift towards cleaner, renewable energy sources.

One promising alternative is biogas, which is produced through the anaerobic digestion of organic matter by microbial communities under oxygen-free conditions. This process is a key component of the carbon cycle and is facilitated by methane-producing bacteria (Sugiarto et al. 2013). Biogas not only serves as a renewable energy source but also reduces environmental pollution by converting organic waste into usable energy. Cow dung, a common agricultural waste product, is among the most effective substrates for biogas production (Batistuta et al. 2021).

The use of cow manure in biogas systems offers dual benefits: it mitigates environmental hazards and provides a low-cost energy source for rural households. Daily manure output can reach up to 12% of a cow's body weight, posing serious environmental threats if left untreated (van den Oever et al. 2021). In many rural areas, including those in Indonesia, improper disposal of livestock waste contaminates water bodies and degrades soil quality. Biogas technology, with its innovative approach, helps alleviate these issues by transforming waste into clean energy while also producing bio-slurry. This by-product can be utilized as an organic fertilizer (Listyawati et al. 2014).

Despite its potential, the adoption and long-term sustainability of biogas systems depend on various factors beyond just technological feasibility. Sustainability assessments must incorporate ecological, economic, social, technological, and institutional dimensions to capture the full complexity of implementation (Batistuta et al. 2021). The Rapfish method, initially developed for fisheries sustainability assessment, has been successfully adapted into Rap-Biogas for evaluating biogas systems through multidimensional scaling (Pitcher and Preikshot 2001; Fauzi and Anna 2002). This method enables rapid appraisal of sustainability status and helps identify key leverage points for improvement.

In recent years, biogas has gained popularity across Indonesia, including in remote and mountainous regions (Rianawati et al. 2021). The government has recognized the importance of renewable energy through policies, such as the National Energy Policy (PP No. 79/2014), which aims to achieve a 23% share of renewable energy in the national energy mix by 2025 and 31% by 2050. However, as of 2020, the actual share stood at only 11.31% (Setyono and Kiono 2021), indicating a significant gap between policy targets and on-the-ground implementation. This highlights the need for localized, community-driven renewable energy initiatives.

Mundu Village in Klaten District, Central Java, stands out as one of Indonesia's energy-independent villages, which has been utilizing livestock waste for biogas production since 2013 (Ningtyas et al., 2020). The village is located near the Pusur River Basin and has an economy that is largely based on agriculture and livestock. With a high cattle population, the village generates large amounts of manure that were previously disposed of improperly, leading to water contamination and health issues (Istikhomah and Riyadi 2021). The community's adoption of biogas technology represents a shift toward sustainable rural development.

Currently, Mundu Village operates 55 biogas units of varying capacities (6 m^3 to 20 m^3), reflecting both the scalability and practical application of biogas systems in rural Indonesia. However, questions remain regarding the long-term sustainability of these systems across different dimensions. While some previous studies have evaluated micro-scale biogas sustainability (Ristianingsih et al. 2018; Batistuta et al. 2021), there remains a lack of comprehensive, multidimensional assessments in Central Java, particularly using rapid, participatory methods.

This study attempts to address that gap by evaluating the sustainability status of the biogas system in Mundu Village using a rapid appraisal method based on the modified Rapfish framework. The assessment focuses on five key dimensions—ecological, economic, social, technological, and institutional—to identify the most sensitive attributes that influence sustainability. Using the Rap-Biogas approach, this research aims to provide evidence-based recommendations for policy and community-level action to strengthen biogas sustainability in rural Indonesia.

Ultimately, this study not only contributes to the growing body of literature on sustainable rural energy but also offers a methodological framework that can be replicated in other contexts. The findings are expected to support local and national policymakers in enhancing renewable energy programs, especially in agricultural communities. Through a robust and multidimensional analysis, the study highlights the potential of microbially mediated biogas systems to advance both environmental and socio-economic goals in developing regions.

MATERIALS AND METHODS

Study area

The study was conducted in Mundu Village, Tulung District, Klaten District, Central Java, Indonesia (Figure 1). Geographically, the village is located approximately 15 kilometers northeast of Mount Merapi and situated within the upstream area of the Pusur River Basin. This location situates the village in a strategic yet environmentally sensitive zone, where land-use practices directly impact watershed health.

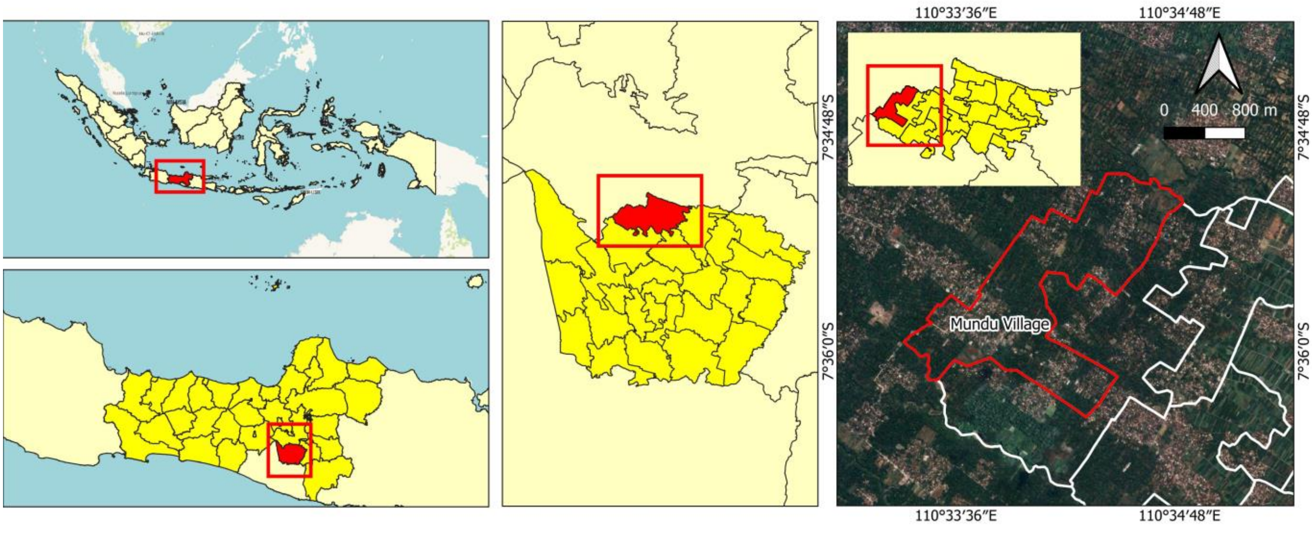


Figure 1. Map showing the research location in Mundu Village, Klaten District, Central Java, Indonesia

Mundu Village is characterized by a predominantly agrarian economy, with most residents engaged in farming and livestock breeding. The community maintains substantial numbers of cattle, which serve as both a primary source of livelihood and a contributor to organic waste accumulation. Traditional practices of livestock waste disposal have historically contributed to environmental degradation, particularly water pollution in nearby river systems.

The introduction of biogas technology in Mundu Village has provided a viable alternative to conventional waste management and fossil fuel dependence. Since 2013, the community has developed 55 household-scale biogas units of varying capacities, ranging from 6 m^3 to 20 m^3. These systems convert livestock manure into biogas for daily household energy needs while producing bio-slurry, a nutrient-rich fertilizer, as a valuable by-product. The biogas program has significantly enhanced local energy resilience and exemplifies the potential of community-based renewable energy systems in rural Indonesia.

Research design

This study employed a descriptive-quantitative research design using a multidimensional assessment approach. The design was selected for its importance in facilitating a comprehensive evaluation of various factors influencing the sustainability of rural biogas systems. The multidimensional framework allowed for an integrated analysis of ecological, economic, social, technological, and institutional factors, each of which contributes uniquely to the overall sustainability of the system.

The research was conducted over seven months, from December 2022 to July 2023, covering the entire research cycle, including planning, field data collection, stakeholder engagement, data analysis, and report writing. The fieldwork was centered in Mundu Village, where biogas users were observed, interviewed, and surveyed directly to obtain primary data.

The main objective of this research was to evaluate the sustainability of household-scale biogas systems operated by the rural community in Mundu Village. This evaluation aims to identify strengths, weaknesses, and sensitive attributes in each dimension that significantly affect the long-term viability of the biogas program. The results of this study were expected to support both local development planning and broader efforts to promote the adoption of renewable energy in Indonesia.

Sampling technique and respondents

The respondents in this study were selected using a purposive sampling technique. This method was considered appropriate because it allowed the selection of individuals who had direct experience with the biogas system and could provide relevant information based on practical use. The sampling focused on households that actively operated biogas digesters as part of their daily domestic energy needs.

A total of 55 households were selected as respondents from Mundu Village, each of which had been using biogas units with digester capacities ranging from 6 m^3 to 20 m^3. The respondents were chosen based on several inclusion criteria: they had to be permanent residents of the village, actively use the biogas unit for at least six months prior to the survey, and be involved in livestock activities, particularly cattle farming. This ensured that the data collected was representative of the actual user experiences and system performance.

Local administrative records and preliminary consultations with community leaders and village officials provided support for the selection process. Prior to administering the questionnaire, all selected respondents were briefed on the purpose of the study, and their informed consent was obtained. This approach not only strengthened the ethical foundation of the research but also increased the accuracy and relevance of the data gathered from the field.

Data collection

This study employed both primary and secondary data sources to ensure comprehensive and reliable results. Primary data were obtained through structured questionnaires and semi-structured interviews conducted directly with selected biogas users. The questionnaire was designed to explore five sustainability dimensions—ecological, economic, social, technological, and institutional—and included multiple attributes within each dimension based on validated indicators from previous studies (Ristianingsih et al. 2018; Batistuta et al. 2021).

Each questionnaire item was rated using a Likert-type scale, allowing respondents to express their perceptions of sustainability-related attributes. Prior to full deployment, the questionnaire was tested for clarity and reliability through a small pilot study involving non-sample respondents in a nearby village. Revisions were made accordingly to improve language, structure, and attribute relevance. Additionally, interviews were conducted to gain deeper insights into the contextual and behavioral aspects of biogas adoption and maintenance.

Secondary data were collected from various sources, including village administrative records, technical reports, scientific publications, and government documents. These data supported the contextual understanding of the biogas program and provided benchmarks for evaluating sustainability indicators. Information such as the number and size of installed biogas units, demographic profiles, and government support programs was obtained from village documentation and official statistics.

The combination of structured surveys and supporting documents ensured that both quantitative and qualitative aspects of biogas sustainability were captured. This multi-source data collection approach enhanced the triangulation of findings and strengthened the validity of the subsequent sustainability analysis.

Sustainability assessment using Rap-Biogas

The sustainability assessment in this study employed the Rap-Biogas method, a modified version of the Rapid Appraisal for Fisheries (Rapfish) framework originally developed to evaluate marine resource sustainability (Pitcher and Preikshot 2001; Fauzi and Anna 2002). Rap-

Biogas applies the Multidimensional Scaling (MDS) technique to assess the sustainability of biogas systems across five core dimensions: ecological, economic, social, technological, and institutional. This method enables a rapid yet structured appraisal by converting qualitative judgments into quantitative indices.

Each dimension was composed of several attributes selected based on literature review, expert consultation, and field relevance. These attributes were then scored by field researchers and verified through respondent inputs, using a scale of 0 to 3 or 0 to 4, depending on attribute specificity. The scoring reflected the current status of each attribute in the village's biogas program. The data were then processed in Microsoft Excel to create input matrices, which were analyzed using Rapfish software to generate sustainability indices.

The index values generated for each dimension range from 0 to 100 and are interpreted according to four sustainability categories: unsustainable (0.00-25.00), less sustainable (25.01-50.00), fairly sustainable (51.01-75.00), and sustainable (75.01-100.00), as shown in Table 1. These thresholds were adopted from previous applications of Rapfish and modified appropriately for the biogas context (Batistuta et al. 2021).

In addition to calculating index values, leverage analysis was conducted to identify the most sensitive attributes influencing sustainability within each dimension. Sensitivity was determined based on the Root Mean Square (RMS) value, where attributes with RMS values above the median were considered key leverage points. These attributes represent critical areas for targeted intervention and improvement.

A Monte Carlo simulation was also performed to test the robustness and reliability of the MDS results. By running repeated simulations with randomized input variation, the analysis assessed the stability of the index values within a 95% confidence interval. The model was considered valid if the difference between MDS and Monte Carlo results was less than 5%, the stress value was below 0.25, and the coefficient of determination (R^2) was close to 1. These parameters ensured that the findings accurately reflected the real sustainability conditions in Mundu Village.

Statistical analysis

Several statistical procedures were applied to support the interpretation of sustainability index values. The primary tool was a leverage analysis, which aimed to identify the most sensitive attributes affecting sustainability in each dimension. The sensitivity of each attribute was calculated using the Root Mean Square (RMS) value, with attributes exceeding the median RMS value within a dimension classified as influential. These sensitive attributes indicate where management improvements or policy interventions would have the greatest impact.

Following the leverage analysis, a Monte Carlo simulation was performed to test the reliability and robustness of the Multidimensional Scaling (MDS) results. This simulation introduced controlled variability into the attribute scoring and assessed how much the final index values changed under repeated resampling. The validity of the model was confirmed if the difference between the Rap-Biogas index and the Monte Carlo index was less than 5%, which is the standard threshold for acceptable error in rapid appraisal studies (Kavanagh and Pitcher 2004).

In addition to numerical consistency, the goodness-of-fit of the model was assessed using two metrics: the stress value and the coefficient of determination (R^2). A stress value below 0.25 indicates that the model adequately represents the distance relationships between attributes in multidimensional space. Likewise, an R^2 value close to 1.00 suggests that the variance in the data is well explained by the MDS configuration (Fauzi and Anna 2002). These statistical indicators ensured that the Rap-Biogas method provided a robust and valid representation of biogas sustainability in the research context.

All computations were carried out using Rapfish software and Microsoft Excel 2019. The combination of MDS ordination, leverage analysis, and Monte Carlo simulation provided a comprehensive analytical framework to diagnose the sustainability performance of the biogas system in Mundu Village.

Table 1. Categories of sustainability status based on index values

Index Value (%)	Sustainability Category
0.00-25.00	Unsustainable
25.01-50.00	Less Sustainable
51.01-75.00	Fairly Sustainable
75.01-100.00	Sustainable

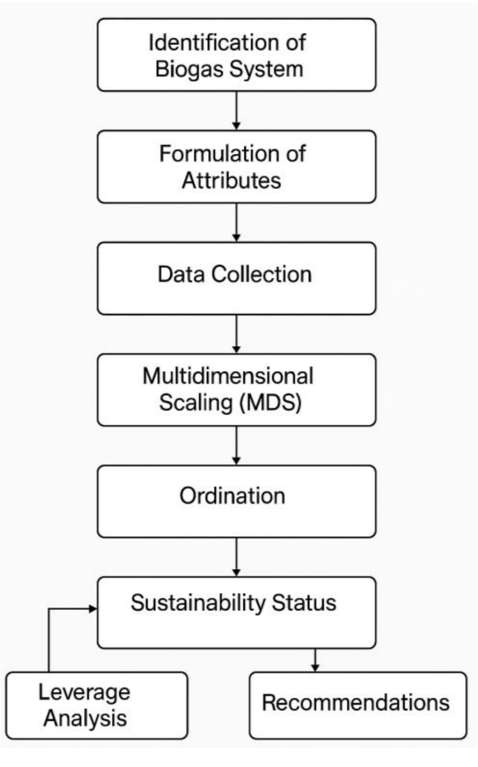


Figure 2. Analytical flow of sustainability assessment using Rap-Biogas

RESULTS AND DISCUSSION

Overall sustainability status of the biogas system

The overall sustainability index of the household-scale biogas system in Mundu Village was 67.77%, placing it in the fairly sustainable category. The ecological (81.78%), social (83.52%), and technological (77.95%) dimensions were classified as sustainable, while the economic dimension (71.06%) was considered fairly sustainable. The institutional dimension (24.52%) was categorized as unsustainable. These scores, along with the low-stress values (<0.20) and high R^2 (>0.90) for all dimensions, confirm the reliability of the multidimensional scaling results.

To ensure the validity of the results, a Monte Carlo simulation was conducted. The simulation yielded an overall sustainability index of 66.66%, compared to the original MDS score of 67.77%, resulting in a difference of 1.11%. This refers to the total score difference, not the average of per-dimension differences. Since this difference is below the 5% threshold, the model is considered statistically robust (Kavanagh and Pitcher 2004). Furthermore, all five sustainability dimensions demonstrated stress values below 0.25 and coefficients of determination (R^2) close to 1.00, confirming the goodness of fit of the model.

The kite diagram provides a visual representation of the sustainability index values across all five dimensions. The diagram indicates that the social, ecological, and technological dimensions are positioned furthest from the center point, suggesting a sustainable status in these areas. In contrast, the institutional dimension is positioned closest to the center, reflecting its unsustainable status and identifying it as a critical area for targeted intervention. These results provide a comprehensive baseline for understanding the multidimensional sustainability performance of biogas systems in rural Indonesia. The findings also underscore the need for enhanced institutional frameworks and effective stakeholder engagement to foster the long-term success of such initiatives.

The multidimensional sustainability performance of the household biogas system is illustrated in Figure 4, which reveals notable strengths in the ecological, social, and technological dimensions, but contrasts with a critically weak institutional component. The validity of the MDS model used in this assessment is supported by low-stress values and high R^2 across all dimensions (Table 2), indicating strong goodness-of-fit. It is important to note that the Difference (%) values in Table 2 refer to each dimension individually; the overall difference between MDS and Monte Carlo scores (1.11%) is derived from the total sustainability index (67.77% vs. 66.66%), not from averaging the per-dimension differences. Furthermore, the key leverage attributes that most influence sustainability outcomes—based on RMS values relative to each dimension's median—are summarized in Table 3. These leverage attributes are further visualized in Figure 4, which displays the comparative RMS values across all dimensions.

Ecological dimension

The ecological dimension of the biogas system in Mundu Village achieved a sustainability index of 81.78%, which falls into the sustainable category (Table 2). This result indicates that the biogas program has had a positive environmental impact, particularly in reducing organic waste and improving household sanitation. Compared to similar studies, such as Batistuta et al. (2021), which reported an ecological index of 56.35% in Cisondari Village, West Java, the ecological performance in Mundu Village is significantly higher.

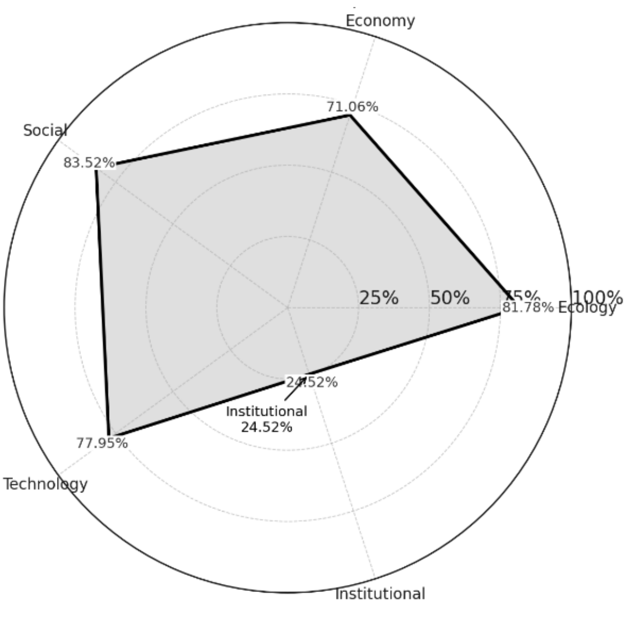


Figure 3. Kite diagram showing the sustainability index in five dimensions

Table 2. Summary of sustainability index, stress, and R^2 for each dimension

Dimension	Sustainability Index (%)	Monte Carlo (%)	Difference (%)	Stress Value	R^2	Sustainability Category
Ecology	81.78	79.77	2.01	0.17	0.93	Sustainable
Economy	71.06	69.86	1.20	0.18	0.95	Fairly Sustainable
Social	83.52	81.44	2.08	0.16	0.95	Sustainable
Technology	77.95	75.81	2.14	0.16	0.93	Sustainable
Institutional	24.52	26.41	1.89	0.14	0.97	Unsustainable
Overall	67.77	66.66	1.11	0.16	0.95	Fairly Sustainable

Note: The overall difference of 1.11% between MDS and Monte Carlo scores is calculated from the total sustainability index (67.77% vs. 66.66%), and not from the average of the five dimension-wise differences.

Table 3. Sustainability index and sensitive attributes for all dimensions

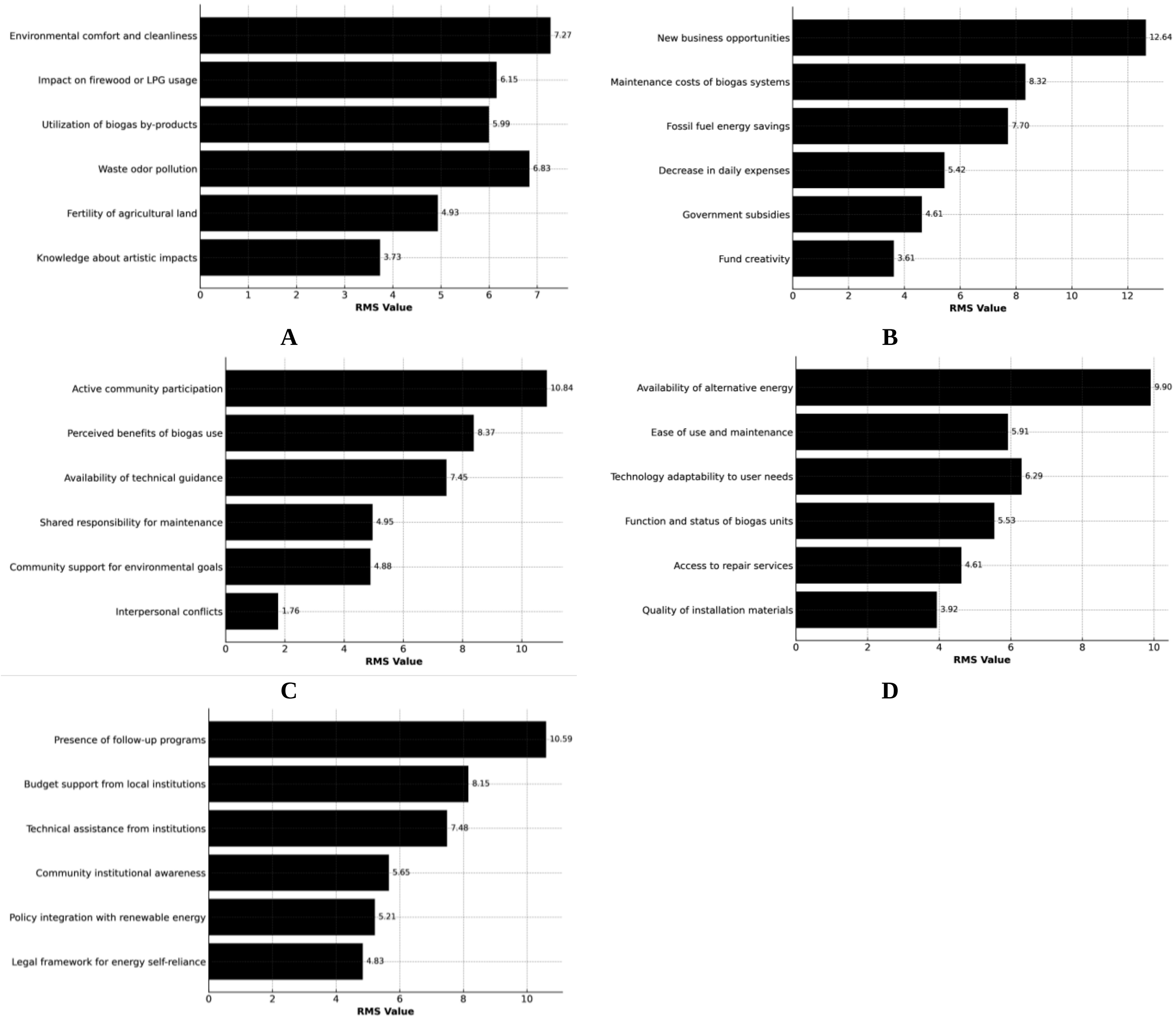
Attributes	Attribute	RMS value	Sensitivity category
Ecology	Environmental comfort and cleanliness	7.79	Sensitive
	Impact on firewood or LPG usage	7.51	Sensitive
	Utilization of biogas by-products	6.96	Sensitive
	Waste odor pollution	5.82	Less sensitive
	Fertility of agricultural land	4.93	Less sensitive
	Knowledge about waste impacts	3.75	Less sensitive
	Median RMS Value	6.39	–
Economy	New business opportunities	13.66	Sensitive
	Maintenance costs of biogas systems	8.00	Sensitive
	Fossil fuel energy savings	7.76	Sensitive
	Decrease in daily expenses	5.42	Less sensitive
	Government subsidies	4.37	Less sensitive
	Fund creativity	3.81	Less sensitive
	Median RMS Value	6.59	–
Social	Active community participation	10.53	Sensitive
	Perceived benefits of biogas use	10.19	Sensitive
	Availability of technical guidance	7.65	Sensitive
	Shared responsibility for maintenance	6.05	Less sensitive
	Community support for environmental goals	4.89	Less sensitive
	Interpersonal conflicts	4.26	Less sensitive
	Median RMS Value	6.85	–
Technology	Availability of alternative energy	8.90	Sensitive
	Ease of use and maintenance	8.01	Sensitive
	Technology adaptability to user needs	6.94	Sensitive
	Functional status of biogas units	5.52	Less sensitive
	Access to repair services	4.66	Less sensitive
	Quality of installation materials	3.92	Less sensitive
	Median RMS Value	6.23	–
Institutional	Presence of follow-up programs	10.20	Sensitive
	Budget support from local authorities	8.76	Sensitive
	Technical assistance from institutions	7.88	Sensitive
	Community institutional awareness	5.98	Less sensitive
	Policy integration with renewable energy	5.21	Less sensitive
	Legal framework for energy self-reliance	4.62	Less sensitive
	Median RMS Value	6.93	–
	Community institutional awareness	5.98	Less sensitive
	Policy integration with renewable energy	5.21	Less sensitive
	Legal framework for energy self-reliance	4.62	Less sensitive
	Median RMS Value	6.44	–

Leverage analysis was conducted to identify the most influential attributes contributing to the sustainability of the ecological dimension. The analysis revealed three sensitive attributes with Root Mean Square (RMS) values above the revised median threshold of 6.39: environmental comfort and cleanliness (7.79), impact on firewood or LPG usage (7.51), and utilization of biogas by-products (6.96). These attributes represent key leverage points that have the most substantial influence on the ecological outcomes of the biogas system (Table 3; Figure 4.A).

The results of this analysis suggest that reducing dependence on fossil fuel alternatives and improving household waste management are critical ecological benefits of the biogas program. Furthermore, the reuse of bio-slurry as organic fertilizer not only minimizes pollution but also supports agricultural productivity, providing a closed-loop resource cycle within the village. These findings reinforce the ecological value of the biogas system, especially in terms of reducing environmental pollution and improving rural household energy behavior. Continued efforts to enhance the use of biogas by-products and raise environmental awareness are expected to sustain or even improve ecological performance in the long term, offering a pathway toward long-term ecological sustainability.

Economic dimension

The economic dimension of the biogas system in Mundu Village obtained a sustainability index of 71.06%, categorizing it as fairly sustainable (Table 2). This score suggests that while the system has generated economic benefits for users, there are still opportunities to improve its financial viability and enhance its positive impacts on livelihoods. Compared to the study by Ristianingsih et al. (2018), which reported an index of 50.37% in Banyumas, the findings from Mundu Village indicate better performance but also highlight areas requiring further development.



A B

C D

E

Figure 4. Leverage analysis for all dimensions. A. Ecology, B. Economy, C. Social, D. Technology, E. Institution

Leverage analysis revealed three sensitive attributes within the economic dimension, each with RMS values exceeding the updated median of 6.59. The most influential was new business opportunities (13.66), followed by maintenance costs of biogas systems (8.00) and fossil fuel energy savings (7.76). These attributes directly affect household expenses and the broader financial attractiveness of biogas systems (Table 3; Figure 4.B).

The high sensitivity of the new business opportunities attribute reflects the current underutilization of bio-slurry and other by-products as economic commodities. While the community has begun using biogas for domestic purposes, the transformation of waste into marketable organic fertilizer remains limited. Meanwhile, the financial burden associated with maintaining biogas equipment—particularly the digester and stove—remains a concern for many users, which may impact system longevity and user satisfaction. The findings suggest that with proper institutional support and market linkage, the commercialization of bio-slurry and local entrepreneurship could significantly enhance the economic value of biogas systems. In the long term, reducing maintenance costs through improved technical training and equipment design may also contribute to greater economic sustainability.

Social dimension

The social dimension of the biogas system in Mundu Village achieved a sustainability index of 83.52%, placing it within the sustainable category (Table 2). This result indicates that community participation, perception, and knowledge regarding the biogas program are relatively high. The high social score aligns with the village's status as an energy self-sufficient community, supported by a shared awareness of environmental and energy issues.

Leverage analysis identified three sensitive attributes with RMS values above the median of 6.85: active community participation (10.53), perceived benefits of biogas use (10.19), and availability of technical guidance (7.65). These elements are essential in maintaining public engagement and collective responsibility for biogas system operations (Table 2; Figure 4.C).

Despite the positive outlook, interviews revealed that not all community members had equal access to capacity-building programs. Some households expressed concern over the lack of routine maintenance training and the limited number of technicians available. Although these limitations have not yet significantly impacted community enthusiasm, they may pose future challenges if not addressed through inclusive outreach and educational initiatives. These findings highlight the importance of maintaining strong social cohesion and trust in the success of community-based biogas programs. Sustained engagement through education, open communication, and local leadership will be key to ensuring long-term social sustainability.

Technological dimension

The technological dimension of the Mundu Village biogas system obtained a sustainability index of 77.95%, placing it in the sustainable category (Table 2). This result reflects the community's capacity to operate and maintain biogas units with acceptable technical performance. Most households can utilize biogas for their daily cooking needs, and the majority of units remain functional with minimal technical disruption.

Leverage analysis identified three sensitive attributes that exceeded the recalculated median RMS value of 6.23: the availability of alternative energy (8.90), ease of use and maintenance (8.01), and technology adaptability to user needs (6.94). These factors determine user-friendliness, accessibility, and long-term feasibility of the biogas systems from a technical perspective (Table 3; Figure 4.D).

Despite generally positive findings, field observations and interviews revealed recurring issues related to digester clogging, gas pressure instability, and the limited availability of spare parts. Furthermore, while most users expressed satisfaction with the ease of use, a minority reported difficulties due to inadequate training or unclear installation guidelines. These challenges suggest a need for more structured and continuous technical support from relevant institutions. These results underscore the importance of enhancing the technical reliability and service infrastructure surrounding household-scale biogas systems. Technical sustainability will be strengthened through local technician training, standardized construction guidelines, and broader integration of user feedback in future system upgrades.

Institutional dimension

The institutional dimension received the lowest sustainability index among all five dimensions, scoring only 24.52%, which places it in the unsustainable category (Table 2). This score indicates significant deficiencies in organizational support, policy integration, and institutional responsiveness related to biogas program implementation. While community-level initiatives have shown promise, the absence of consistent external support remains a critical barrier to sustainability.

Leverage analysis revealed that three attributes exceeded the corrected median of 6.93, making them key leverage points for the institutional dimension: presence of follow-up programs (10.20), budget support from local authorities (8.76), and technical assistance from institutions (7.88). These aspects represent significant gaps that require urgent institutional strengthening (Table 3; Figure 4.E).

Interviews with community leaders and users revealed that, following the initial program launch in 2013, structured institutional involvement has declined. There has been a lack of periodic evaluation, funding allocation, and technical oversight. Furthermore, coordination between local government agencies, NGOs, and the village community remains limited, resulting in gaps in maintenance, upgrading, and capacity-building activities. These findings emphasize that the success of community-based biogas systems depends not only on technical or social factors but also on enabling institutional frameworks. Strengthening formal-informal linkages, ensuring routine support programs, and integrating biogas into local policy agendas will be vital to lifting the institutional dimension from its current unsustainable status.

Discussion

Interpretation of overall sustainability performance

The biogas system in Mundu Village achieved an overall sustainability index of 67.77%, which places it within the fairly sustainable category. This classification indicates that the system has performed well across several dimensions, particularly ecological, social, and technological, but still faces limitations in economic and especially institutional aspects. The result reflects a commendable level of community commitment and technological functionality, although the supporting governance structure remains weak. Such a profile is typical of community-based renewable energy projects initiated from the bottom up with minimal long-term institutional engagement.

When compared to similar studies in Indonesia, the performance of the Mundu Village biogas system is relatively strong. For example, Batistuta et al. (2021) reported an overall index of 56.75% in Cisondari Village, West Java while Ristianingsih et al. (2018) found even lower sustainability levels in Banyumas District, Central Java. These studies highlight the recurring challenges faced by rural biogas programs, particularly in sustaining economic viability and formal institutional support. The higher score observed in Mundu Village may be attributed to a combination of strong social participation and continuous household-level commitment to system maintenance and use.

From an international perspective, community-scale biogas programs in developing countries often demonstrate similar patterns: high ecological and social benefits, constrained economic returns, and limited policy integration (Amigun et al. 2008; Bond and Templeton

2011). These trends suggest that the case of Mundu Village is not isolated but rather representative of broader structural realities in decentralized renewable energy initiatives. The partial success of such programs emphasizes the need for integrative, multi-actor strategies that extend beyond infrastructure provision to include institutional capacity-building, post-installation monitoring, and value-chain development.

The implications of this finding are substantial for renewable energy development in rural contexts. While household-scale biogas has clear potential to reduce fossil fuel dependence, improve sanitation, and enhance local resource use, its long-term sustainability hinges on holistic program design. This includes reliable technical support, viable economic incentives, and consistent policy alignment at village and regional levels. Therefore, the "fairly sustainable" status achieved by Mundu Village should be viewed not only as a measure of current performance but also as a call to strengthen and replicate its successful aspects while addressing existing gaps through targeted interventions.

Ecological implications

The ecological dimension of the biogas system in Mundu Village was rated as sustainable, with an index of 81.78%, reflecting strong environmental benefits resulting from biogas adoption. One of the most immediate impacts observed was the reduction in organic waste accumulation and associated pollution. Livestock manure, which was previously discarded into waterways or left unmanaged, is now processed into biogas, significantly improving household sanitation and reducing odor pollution. This aligns with findings from Hnyine et al. (2016) and Rianawati et al. (2021), who emphasized the role of biogas in reducing environmental health risks in rural Indonesia.

A key ecological advantage of biogas systems is their ability to contribute to circular resource use. In Mundu Village, the use of bio-slurry—the semi-liquid residue of anaerobic digestion—as organic fertilizer has supported more sustainable agricultural practices. This substitution of chemical fertilizers reduces the risk of groundwater contamination and soil degradation, supporting long-term agroecological balance (Sugiarto et al. 2013). In addition, the use of biogas has led to a notable reduction in firewood consumption, helping to mitigate pressure on local forest resources and contributing to emissions reduction.

Compared to other regions, the ecological performance in Mundu Village is relatively high. In West Java, Batistuta et al. (2021) found ecological index values below 60%, primarily due to limited bio-slurry utilization and persistent issues with waste disposal. The success in Mundu appears to be supported by stronger awareness of environmental impacts and more consistent use of system by-products. This reinforces the importance of environmental education and demonstration in enhancing the ecological benefits of biogas adoption.

Ecologically, biogas systems also serve broader climate mitigation goals by capturing methane emissions that would otherwise be released from decomposing manure. Methane is a potent greenhouse gas with a global warming potential of more than 25 times that of CO_2 over 100 years (IPCC 2021). Thus, the biogas program not only benefits local household environments but also contributes to Indonesia's national commitments to climate action under its Nationally Determined Contributions (NDCs). In this way, the ecological success of the system in Mundu Village illustrates how localized energy interventions can have both immediate and long-term environmental value.

Economic opportunities and constraints

The economic sustainability index of the biogas system in Mundu Village was 71.06%, placing it in the fairly sustainable category. This suggests that the system offers tangible financial benefits, particularly in reducing household energy costs. Most users reported a significant decline in expenditures on firewood and liquefied petroleum gas (LPG) after switching to biogas for cooking. These findings are consistent with those of Rachmawatie et al. (2022), who documented similar savings in household fuel costs among biogas users in Sleman, Yogyakarta.

Beyond direct savings, biogas systems also present economic opportunities through the utilization and marketing of bio-slurry. In theory, the conversion of organic waste into high-quality fertilizer could stimulate rural entrepreneurship, reduce input costs for farmers, and open access to organic agriculture markets. However, in Mundu Village, this potential remains largely unrealized. As noted in the leverage analysis, the attribute new business opportunities was highly sensitive, indicating that this economic function has not yet been optimized. Limited access to processing facilities, packaging, and marketing channels hampers the commercial viability of bio-slurry.

One of the persistent economic constraints is the cost of maintenance and repairs. Although the initial installation of biogas units was supported by government and NGO programs, users are ultimately responsible for the ongoing maintenance and operation of these units. Interviews revealed that the cost of replacing stove components, repairing digesters, or unclogging gas lines could pose a financial burden, especially for low-income households. These costs, when unexpected, may reduce user satisfaction and compromise the system's long-term operability. Similar concerns were raised by Ristianingsih et al. (2018), who found that financial resilience has a strong impact on system continuity.

Another challenge is the limited availability of financial support schemes for upgrading or expanding biogas units. Unlike urban renewable energy initiatives, rural biogas programs often lack formal financing instruments such as microcredit, subsidy matching, or community revolving funds. Without institutional backing, most users rely solely on personal funds, which restricts their ability to innovate or scale up. This situation is not unique to Indonesia; Amigun et al. (2008) reported comparable financing limitations in decentralized biogas programs across sub-Saharan Africa.

To unlock the full economic potential of biogas systems, future interventions must integrate livelihood strategies into system design. This includes linking biogas users with agricultural cooperatives, building capacity in bio-slurry value chains, and facilitating access to financial services. With such measures, biogas can transition from a subsistence technology into a catalyst for rural economic development.

Social engagement and community dynamics

The biogas system in Mundu Village demonstrated strong social sustainability, with an index of 83.52%, the highest among all five dimensions. This reflects a high degree of community awareness, acceptance, and involvement in managing biogas technology. Active participation by local residents—from system use to minor maintenance—has been critical in sustaining biogas operations since their installation in 2013. The strong performance in this dimension supports previous findings by Dhliwayo et al. (2020), who emphasized the importance of social capital in sustaining rural energy initiatives.

A key social strength is the perceived benefit of biogas adoption. Most users reported improvements in household health, convenience, and gender equity, particularly in reducing the domestic workload traditionally borne by women. The use of biogas has also enhanced household status within the community, contributing to a sense of shared progress. These findings align with studies by Bond and Templeton (2011), which highlight that social acceptance is often driven more by perceived non-monetary benefits than by financial incentives alone.

However, several challenges remain, as despite high community enthusiasm, technical knowledge and capacity are unevenly distributed. Some households lack sufficient understanding of system maintenance and troubleshooting, leading to a dependence on a small group of trained individuals. Moreover, interviews revealed that technical training sessions were conducted only during the early implementation phase and have not been followed by regular refresher programs. This situation risks creating a knowledge gap that may undermine system reliability in the future.

Another issue concerns the management of shared resources and responsibilities. Although the systems are installed on a per-household basis, community-wide coordination is still necessary—especially in managing spare parts, facilitating shared learning, and promoting collective troubleshooting. Inadequate facilitation in this area may lead to social tension or disengagement over time. Similar dynamics were observed by Ristianingsih et al. (2018), who noted that without continuous community facilitation, the sense of joint ownership and accountability tends to decline.

The case of Mundu Village illustrates how social cohesion, user trust, and community-driven motivation are foundational to the long-term sustainability of decentralized energy systems. To maintain these strengths, future programs should prioritize continuous education, local leadership development, and participatory monitoring mechanisms. Strengthening the social fabric around biogas usage can also serve as a buffer against weaknesses in other dimensions, particularly institutional support.

Technological adaptability and limitations

With a sustainability index of 77.95%, the technological dimension of the biogas system in Mundu Village is categorized as sustainable. This score reflects the generally high adaptability of the technology to local conditions and user needs. Most respondents reported that the system was relatively easy to operate, and the technology was sufficiently reliable for daily household energy requirements. These findings are consistent with Rianawati et al. (2021), who found that user-friendly design and low operational complexity are key drivers of biogas adoption in rural areas.

High performance in this dimension is closely related to the integration of the system into the daily routines of livestock-rearing households. Since cattle are a consistent source of feedstock, the input supply chain is secure, which enhances the reliability of gas production. Moreover, the technology is compatible with local cooking habits and does not require significant changes in infrastructure or behavior. This compatibility has enabled widespread and sustained use over more than a decade.

However, several technical limitations remain, particularly regarding system durability and maintenance logistics. Field observations revealed issues such as digester clogging, inconsistent gas pressure, and difficulties in obtaining replacement parts. These problems, although not frequent, can disrupt daily use and may discourage users without technical support. In some cases, users reported relying on informal solutions or temporary shutdowns of the system. Similar barriers were noted in studies by Amigun et al. (2008), especially in rural programs with limited technical backstopping.

Another constraint is the lack of standardized construction and repair protocols. Although the initial installations adhered to general biogas design principles, variations in construction quality, materials, and installer expertise resulted in inconsistent performance across households. This variability increases the burden on users to troubleshoot issues independently, often without formal guidance. In the absence of a structured maintenance system or trained local technicians, these weaknesses could gradually reduce system efficiency and user confidence.

The Mundu Village experience highlights the importance of technical training, standardization, and post-installation services in sustaining biogas technologies. To maintain and scale up the program, regular capacity-building is essential for both users and local technicians. Additionally, the development of local service centers or village-level technician cooperatives could provide timely repairs and access to spare parts, thereby enhancing the overall quality of service. By enhancing the technological resilience of biogas systems, communities can ensure greater energy security and reduce dependency on external assistance.

Institutional challenges and policy gaps

The institutional dimension recorded the lowest sustainability index in this study—24.52%, classified as unsustainable. This finding reveals fundamental weaknesses in the governance, support structures, and policy integration of the biogas program in Mundu Village. While external partners supported the initial program implementation in 2013, there has been no consistent follow-up by formal institutions. The absence of routine monitoring, funding, and capacity-building initiatives has left the community to manage technical and managerial issues largely on its own.

Among the most sensitive attributes identified through leverage analysis were the absence of follow-up programs (RMS = 10.20), limited budgetary support from the local government (8.76), and a scarcity of technical assistance from formal institutions (7.88). These results highlight a significant institutional gap that could compromise the long-term viability of otherwise promising renewable energy projects. Without a structured support system, biogas users may struggle to address system failures, adapt to changing conditions, or scale up their operations. These findings mirror those of Ristianingsih et al. (2018), who found that institutional neglect was a key reason for stagnation in similar rural energy initiatives.

The lack of integration of biogas into local policy frameworks also contributes to weak institutional support. Interviews with local leaders revealed that biogas is not explicitly included in the village's Medium-Term Development Plan (RPJMDes) or prioritized in local environmental or energy agendas. As a result, there are no dedicated funds or institutional responsibilities assigned to sustaining the program. This administrative invisibility contributes to its marginalization and hampers opportunities for cross-sectoral collaboration.

The problem is not unique to Mundu Village. Across Indonesia, many community-scale renewable energy programs are launched with enthusiasm but falter due to insufficient policy alignment and administrative oversight (Fauzi and Anna 2002; Silaen et al. 2020). While technical feasibility and social acceptance are often high, institutional follow-through remains a weak link. The fragmentation of responsibilities between national, regional, and village-level agencies further complicates coordination and accountability.

Addressing these gaps requires a multi-tiered institutional strategy. At the village level, biogas governance must be formalized—for example, by incorporating it into annual work plans (RKPDes) and assigning responsibilities to village institutions such as BUMDes. At the district and provincial levels, local governments should allocate budget lines and technical resources to support the biogas program. Finally, partnerships with universities, NGOs, and private sector actors can provide ongoing innovation and supervision. By strengthening the institutional ecosystem, biogas programs can transition from pilot projects into resilient, policy-backed systems.

Methodological reflections and policy relevance

The application of the Rap-Biogas method, adapted from the Rapfish framework developed by Pitcher and Preikshot (2001), proved effective in rapidly assessing the multidimensional sustainability of household-scale biogas systems. Its strength lies in its ability to integrate qualitative perceptions and quantitative scores across ecological, economic, social, technological, and institutional dimensions (Fauzi and Anna 2002). This makes it particularly suitable for community-based renewable energy evaluations, especially in rural contexts where formal datasets are limited and participatory diagnosis is essential.

Another advantage of Rap-Biogas is its visual and communicative power. Tools such as kite diagrams, leverage analysis, and Monte Carlo simulations make the results more accessible to stakeholders at multiple levels (Kavanagh and Pitcher 2004). These visual outputs enhance engagement and facilitate participatory planning by enabling communities and decision-makers to easily interpret and respond to key sustainability findings. Furthermore, the use of Root Mean Square (RMS) in leverage diagnostics has been proven effective in identifying critical attributes in multidimensional scaling analyses (Batistuta et al. 2021).

The policy relevance of Mundu Village's findings is substantial. First, they demonstrate that community-driven biogas programs can yield sustainable outcomes even in the absence of continuous institutional oversight, as long as strong local participation and basic technical capacity are present (Bond and Templeton 2011). However, the institutional fragility exposed in this study points to the urgent need for formal policy integration and programmatic follow-up, as also emphasized in studies of biogas programs in India and sub-Saharan Africa (Amigun et al. 2008; Katuwal and Bohara 2009).

The study also highlights the importance of cross-sectoral coordination among the agriculture, energy, and rural development sectors. At the village level, integrating biogas into development planning tools such as RPJMDes and RKPDes could ensure dedicated resources and clearer accountability lines (Ristianingsih et al. 2018). Meanwhile, provincial and national stakeholders must provide supportive legal frameworks, technical training pathways, and financial mechanisms to sustain and replicate successful models, such as that of Mundu Village.

As a semi-quantitative method, it depends on the accuracy of attribute selection and consistency in scoring, which can introduce subjective bias (Pitcher and Preikshot 2001; Fauzi and Anna 2002). Furthermore, while effective at the system level, the approach may underrepresent intra-household differences or sociocultural variables influencing sustainability. Future research should consider combining Rap-Biogas with longitudinal ethnographic studies or economic modeling to generate more granular insights.

Despite these limitations, this study confirms that Rap-Biogas is a practical, participatory, and policy-relevant tool for evaluating sustainability in decentralized energy systems. The insights from Mundu Village may serve as a reference for rural communities, development agencies, and governments aiming to implement effective, resilient, and inclusive renewable energy strategies.

In conclusion. this study assessed the sustainability of a household-scale biogas system in Mundu Village, Klaten District, using the Rap-Biogas method across five dimensions: ecological, economic, social, technological, and institutional. The system scored an overall index of 67.77%, placing it in the fairly sustainable category. Strong ecological, social, and technological performance reflected benefits such as reduced waste, active community involvement, and ease of use. However, economic potential through bio-slurry utilization was underdeveloped, and institutional aspects were critically weak, particularly due to the absence of structured follow-up programs, policy integration, and local government support. These institutional limitations pose serious risks to long-term sustainability. Interventions should include regular monitoring, technician training, and integration of biogas governance into village development plans to strengthen the system's viability. Improving market access and financial support for bio-slurry products would also improve economic outcomes. Despite these challenges, the system shows that community-based biogas can be a viable model for rural renewable energy when supported by strong social participation, appropriate technology, and environmental compatibility. Addressing institutional and economic gaps is a key factor. This case provides valuable lessons for scaling sustainable biogas programs in other rural areas of Indonesia and similar contexts in developing countries. Policymakers should consider integrating household biogas systems into village-level energy planning instruments (e.g., RPJMDes) to ensure long-term institutional support and resource allocation.

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