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Determinants of Household Biogas-Bioslurry Economic Benefits: Linear Mixed Model with Cost-Benefit and Sensitivity Analysis

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Abstract:

The increasing demand for sustainable energy solutions in rural areas has prompted the utilization of biogas and bio-slurry as alternative resources. This study aims to evaluate the economic feasibility of household-level biogas systems by integrating Cost-Benefit Analysis (CBA), Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Undiscounted Payback Period (UPBP), complemented with sensitivity analysis. Primary data were collected from 16 households operating biogas systems, while secondary data supported the estimation of cost and benefit components. Results show that biogas adoption provides positive economic returns, with average NPV reaching Rp 12,749,000, BCR above 1.0, and UPBP within four years, indicating financial viability. Sensitivity analysis reveals that variations in LPG prices and livestock numbers significantly affect economic outcomes, demonstrating the importance of market and production factors in ensuring project sustainability. The findings conclude that household biogas systems are economically feasible and resilient under certain conditions. Future studies are suggested to expand the scope by incorporating environmental and social benefits, as well as exploring scalability at the community level.

Keywords: *Biogas, Bio-Slurry, Cost-Benefit Analysis, Sensitivity Analysis, Household Economy*

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INTRODUCTION

Indonesia's economic growth has been significantly driven by the progress of the agricultural sector. The agricultural sector faces various challenges, including scarcity of agricultural resources and pollution caused by negligence in managing agricultural waste (Yang et al., 2021). This waste has the potential to emit an unpleasant odor and become a vector for disease transmission (Kolawole et al., 2024). To address this problem, the idea of circular agriculture has been proposed, with the integration of energy recovery technology from animal waste alongside sustainable practices as a key component (Rao et al., 2024).

The implementation of a circular agriculture system has proven to be a viable solution to address various environmental, economic, and social problems currently faced by the community, facilitated by the creation of collaborative business networks (Entrena-Barbero et al., 2024). The circular agriculture model is characterized by the retention of residues from agricultural biomass and food processing within the food system, thereby ensuring the utilization of renewable resources and the reduction of external inputs (Herrera et al., 2023). Circular agriculture is also conceptually aligned with Indonesia's national development agenda, which aims to achieve food self-sufficiency, reduce rural poverty, and strengthen agricultural resilience in the face of climate and economic shocks (Swastika et al., 2024).

One of the prominent practical outcomes of circular agriculture is the use of animal waste for biogas production, which has the potential to serve as an alternative energy source and reduce dependence on non-renewable energy (Geddafa et al., 2023). Biogas production is a process that has been proven to ensure sustainability and renewable energy while positively impacting the environment. In the household context, biogas is mainly utilized as a substitute for liquefied petroleum gas (LPG) and traditional biomass fuels, such as firewood (Pavičić et al., 2022). This alternative offers a more environmentally friendly and sustainable solution for cooking and heating purposes. The production of bio-slurry, which also comes from animal waste, has a dual purpose: reducing dependence on chemical fertilizers and increasing soil fertility, thereby enhancing agricultural yields (Kebede et al., 2023). Bio-slurry, an organic by-product of animal manure with low production costs, also has the potential to serve as a pesticide due to its nutrient content (Ghosh et al., 2021). The potential of these two by-products to minimize waste, maintain the value of waste materials, and provide renewable energy sources is significant, encouraging circular agriculture as a valuable sustainability strategy (Herbstritt et al., 2023). Conversely, the transformation of agricultural waste into bio-products has the potential to generate benefits for local communities and reduce environmental damage (Nattassha et al., 2020).

This research is supported by the principles of circular economy theory. The fundamental goal of this theory is to facilitate the recovery and regeneration of the material cycle, while minimizing waste formation and ensuring effective material cycle closure through the application of high-value recycling (Salmenperä et al., 2021). A circular economy is defined as a closed-cycle system aimed at addressing challenges facing Indonesia's agricultural sector, including resource scarcity, environmental degradation, and economic inefficiency, by converting waste into valuable inputs (Waluyo & Kharisma, 2023). The use of biogas and bio-slurry as reusable resources reduces dependence on non-renewable resources, which are characterized by high costs and pollution (Nath et al., 2023).

Several previous studies have focused on sustainability practices in the agricultural sector. Research has concentrated primarily on the environmental impact of agricultural practices, such as global climate change (Chen et al., 2024), carbon emissions (Nsabiyeze et al., 2024), and soil improvement (Mamatha et al., 2024). Additionally, many studies have investigated the technical aspects of biogas digester construction (Obileke et al., 2022), operational and maintenance requirements of small-scale biogas digesters (Issahaku et al., 2024), bio-slurry-based biodegradation technologies (Wang et al., 2024), and bio-slurry reactor bioaugmentation (Amiri et al., 2024). Although cost-benefit and financial feasibility analyses in circular agriculture have been discussed in the literature (Campello et al., 2021; Geddafa et al., 2023; Mensah et al., 2021; Panbechi et al., 2025), these analyses rely mainly on traditional cost-benefit and sensitivity methods. This study addresses these gaps by using the Linear Mix Model to statistically identify the main socioeconomic and operational predictors of total household benefits from biogas and bio-slurry, capturing fixed and household-specific random effects.

West Java, especially Lembang, is one of the provinces in Indonesia with a substantial dairy cow population capable of meeting the increasing demand for milk and dairy products (Jahroh et al., 2020). Although milk and dairy production volumes are significant, livestock waste, especially cow dung, has been utilized to produce biogas and bio-slurry (Ruhiyat et al., 2020). Cow dung is mixed with water in the right proportions and processed in a biodigester to produce biogas and bio-slurry. Local communities often assume that there are no significant costs involved. However, a comprehensive analysis that combines Linear Mix Model (LMM) analysis, economic feasibility assessment, and sensitivity analysis is essential to accurately evaluate the financial feasibility and long-term sustainability of biogas and bio-slurry adoption (Klinnert et al., 2024). This study aims to evaluate the economic feasibility of household biogas and bio-slurry adoption by identifying socio-economic and operational factors that significantly affect total household benefits, using a Linear Mix Model to capture fixed effects and household-specific variations. By integrating these predictors with classical economic metrics, the study contributes theoretically by demonstrating the application of advanced blended effects modeling in rural energy economics and bridging the gap left by traditional cost-benefit analysis. Furthermore, the study offers valuable insights for policymakers, development practitioners, and rural households by highlighting key drivers of profitability and providing actionable recommendations to optimize biogas adoption across various market and agricultural conditions.

METHOD

This research was conducted in Cibodas Village, Lembang, a rural village located in a hilly area with scattered farmhouses and mixed farms. Topography and settlement patterns affect the availability of livestock manure for biogas production and household energy consumption, especially the dependence on LPG for cooking. The socioeconomic characteristics of the village, household size, livestock ownership, and income level, further shape energy choices and potential adoption of biogas systems. These geographical and socio-economic conditions make Cibodas Village an ideal location to investigate the economic feasibility of household biogas and bio-slurry adoption, providing generalizable insights to similar rural communities in Indonesia and other developing countries with comparable energy and agricultural contexts.

Data were collected through a combination of primary household surveys and secondary sources. Primary data were obtained from 16 households with operating biogas systems, including detailed information on the number of livestock, biogas production and use, household energy consumption, fertilizer utilization, and household income. Although the data is annual rather than monthly, the study leverages repeated annual measurements over several years to enable longitudinal analysis and capture household-specific variability. Secondary data include regional LPG prices, fertilizer costs, and historical adoption statistics, which provide contextual benchmarks and support model calibration. This combination of primary and secondary sources ensures a comprehensive dataset that reflects household-level dynamics and broader market conditions.

To accurately evaluate economic feasibility, the study systematically collected all the relevant costs and benefits associated with household biogas adoption. These costs include initial investment in biogas digesters and related equipment, labor inputs to feed and maintain the digester, routine maintenance and repairs, and opportunity costs related to livestock management. These benefits include direct savings from reduced LPG consumption, fertilizer savings due to the use of nutrient-rich bio-slurry, and revenue from the sale or exchange of surplus bio-slurry. The total annual monetary benefit is derived from the costs and benefits associated with the adoption of biogas and bioslurry (Geddafa et al., 2023).

$$\text{TAB} = \text{LPG Saving} + \text{Manure Saving} + \text{Bioslurry Income} \tag{1}$$

This empirical strategy is based on the Linear Mixed Model (LMM) to evaluate the impact of socio-economic and operational factors on total household benefits in a longitudinal framework (Sinsin et al., 2023). The purpose of the LMM application is to deal with repetitive observations of the same unit while distinguishing between fixed effects, such as the number of cows, LPG prices, and biogas digester capacity, with random effects, arising from household-level variability (Obileke et al., 2024). By combining repeated measurements over time, the model addresses intra-household correlations and temporal variability, thereby improving estimation reliability and predictive accuracy. Importantly, the LMM results show which fixed variables exert a significant influence on household benefits, thus identifying key driving factors, such as LPG price fluctuations and herd size, that can be incorporated into the NPV, BCR, and UPBP sensitivity analysis. Economic Feasibility Assessment

The Non-Discounted Return on Investment (UPBP) period measures the length of time it takes for households to recoup their initial investment in biogas technology through annual benefits (Geddafa et al., 2023). UPBP does not apply discounts, but focuses on the speed of capital recovery, which is a crucial factor for rural households with limited liquidity. A shorter UPBP means households can recoup their investment quickly, making the technology more attractive from a practical decision-making perspective.

$$\text{UPBp} = \frac{\text{CI}}{\text{Ap}} \tag{2}$$

CI refers to the total cost of installation, while AP represents annual gains, which are defined as the annual economic benefits resulting from the adoption of biogas technology.

Net Present Value (NPV) is the difference between the present value of the total household benefit and the present value of the cost of adopting biogas and bio-slurry systems (Kusz et al., 2024). Benefits are derived from LPG savings, fertilizer savings, and additional revenue from bio-slurry, while costs include biogas digester installation, annual maintenance costs, and labor costs.

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+r)^t} \tag{3}$$

Bt represents the annual benefits obtained from the utilization of biogas and bioslurry, Ct indicates the annual cost, t indicates the time period from the 0th to the 4th year, and r refers to the discount rate. The Benefit-Cost Ratio (BCR) compares the present value of total benefits to the present value of costs (Kuo et al., 2024). A BCR greater than one indicates that households earn more from savings and income than they spend on expenses, thus making the project financially attractive. BCRs are particularly useful because they provide a measure of relative efficiency, which allows households and policymakers to compare economic returns across different investment measures or subsidy levels.

$$BCR = \frac{\frac{B_t}{(1+r)^t}}{\frac{TC_t}{(1+r)^t}} \tag{4}$$

To test yield resilience under changing conditions, sensitivity analysis was performed for scenarios involving variations in the number of livestock and LPG prices. By simulating an increase in the number of cows, this analysis evaluates how additional manure inputs affect biogas production, fertilizer savings, and overall household benefits (Ghafoori et al., 2022). LPG price fluctuations are also considered to assess how energy market volatility affects cost savings and financial feasibility metrics. This approach identifies the factors that most strongly influence NPV, BCR, and UPBP, providing valuable guidance for households, policymakers, and development practitioners seeking to optimize biogas adoption in volatile operational and market conditions.

RESULTS AND DISCUSSION

Table 1. Total Cost of Household Biogas System Adoption (Rp/year)

Cost Component	Unit Cost (IDR)	Quantity/Household	Total Cost (IDR)
Capital/Installation Costs			
Digester Construction	IDR 7,500,000	1	IDR 7,500,000
Gas Storage/Holder	IDR 2,250,000	1	IDR 2,250,000
Piping and Fixtures	IDR 1,500,000	1	IDR 1,500,000
Safety and Monitoring Equipment	IDR 750,000	1	IDR 750,000
Labor/Installation Fees	IDR 3,000,000	1	IDR 3,000,000
Subtotal Capital Cost			**IDR 15,000,000**
Annual Maintenance Costs			
Cleaning and Desludging	IDR 300,000	1	IDR 300,000
Minor Repairs	IDR 225,000	1	IDR 225,000
Monitoring & Inspection	IDR 150,000	1	IDR 150,000
Subtotal Maintenance Cost (Annual)			IDR 675,000
Operational/Other Costs			
Opportunity Cost of Feedstock	IDR 75,000	1	IDR 75,000
Total Cost (Year 1)			**IDR 15,750,000**
Total Recurring Cost (Subsequent Years)			**IDR 750,000**

Table 2. Monetary Benefits of LPG and Fertilizer Savings per Household (Rp/year)

Variable	Minimum	Maximum	Mean	t-value	p-value
LPG Savings	IDR 4,800,000	IDR 7,200,000	IDR 6,000,000	7.50	<0.001
Fertilizer Savings	IDR 1,800,000	IDR 2,700,000	IDR 2,250,000	6.00	<0.001
Total Benefit	IDR 6,800,000	IDR 9,900,000	IDR 8,250,000	8.20	<0.001

Household biogas technology provides a range of significant economic benefits that go beyond just providing energy, and has a positive impact on household financial stability and agricultural productivity. By utilizing livestock and organic waste to produce biogas, households obtain a renewable and low-cost energy source that can replace conventional fuels such as LPG for cooking purposes. This substitution not only reduces the cost of recurring fuels but also reduces dependence on external energy markets, which are often fluctuating in price and supply. In addition, the biogas production process produces bio-slurry, a nutrient-rich by-product that can be applied as an organic fertilizer to improve soil fertility, crop yields, and overall agricultural efficiency. Together, these benefits create a dual economic impact: direct financial savings in household spending and indirect benefits through increased agricultural yields. The integration of energy generation and organic fertilizer production positions household biogas systems as an important tool to drive sustainable development, resource efficiency, and resilience in rural economies.

While biogas technology has clear advantages, accurately measuring its economic impact is a challenge in itself. One of its main limitations is the small sample size of households operating functional biogas installations, which limits the ability to generalize findings to a wider population. Seasonal variations in livestock availability, raw material production, and household energy consumption further complicate data collection, as these factors affect the quantity of biogas produced and the resulting cost savings. In addition, some of the benefits of biogas adoption, such as time savings from fuel collection, reduced indoor air pollution, and improved health outcomes, are difficult to measure financially, potentially leading to underestimating the overall impact. To address this challenge, the study combined primary data from 16 operational households with secondary information from local surveys and regional statistics. This approach makes it possible to capture both direct and indirect financial benefits, while acknowledging the inherent limitations in data collection for small-scale interventions at the household level. Cost of Implementing Household Biogas and Bioslurry Systems

Table 1 presents a breakdown of the costs associated with the implementation of a household biogas system. The total cost in the first year was dominated by capital or installation costs, amounting to Rp15,000,000. Among these costs, the construction of the digester was the largest single cost (Rp7,500,000), which accounted for 50% of the total capital investment. Gas storage and piping contributed IDR 2,250,000 and IDR 1,500,000, respectively, while safety and monitoring equipment costs and labor/installation costs amounted to IDR 750,000 and IDR 3,000,000, respectively. This distribution shows that the initial investment is allocated more to critical infrastructure and installation labor, reflecting the technical and structural requirements of building a household biogas system.

Annual maintenance costs are relatively low, with a total of IDR 675,000 per year. These costs include cleaning and mud suction (Rp 300,000), minor repairs (Rp 225,000), and routine monitoring and inspection (Rp 150,000). This shows that once the system is in place, ongoing maintenance can be managed and does not put a significant strain on household finances. The operational costs are minimal, with the only recurring post being the raw material opportunity cost which is estimated at Rp 75,000 per year. As a result, after the first year, the total recurring costs dropped sharply to Rp 750,000 per year, which shows the long-term cost effectiveness of the system.

Given the high initial investment and low recurring costs, it becomes important to evaluate the economic feasibility and sustainability of a household biogas system using financial and statistical analysis. The calculation of Net Present Value (NPV), Benefit-Expense Ratio (BCR), and Return on Investment Period (UPBP) provides a quantitative measure of profitability and investment recovery time. In addition, the application of the Linear Mix Model (LMM) allows for an assessment of household-level variability and factors affecting costs and benefits, while sensitivity analysis tests the resilience of economic outcomes to changes in key parameters such as the number of livestock, LPG prices, or maintenance costs. Together, these analyses are important to guide decision-making for households and policymakers, ensuring that biogas adoption is economically feasible and resilient to market or operational fluctuations.

Monetary Benefits of LPG and Fertilizer Savings per Household

The adoption of household biogas systems provides significant monetary benefits through savings in LPG and fertilizer costs. Table 2 shows that households save an average of IDR 6,000,000 per year for LPG (ranging from IDR 4,800,000 to IDR 7,200,000) and IDR 2,250,000 per year for fertilizer (ranging from IDR 1,800,000 to IDR 2,700,000), resulting in an average total annual benefit of IDR 8,250,000 per household. Statistical tests showed that these benefits were very significant (t-values = 7.50, 6.00, and 8.20 for LPG, fertilizer, and total benefits; all $p < 0.001$), suggesting that biogas systems substantially reduce household expenditure on energy and agricultural inputs. The findings highlight the dual economic benefits of this system, namely energy savings and reduced fertilizer costs, which can offset most of the initial investment over time.

Financial Feasibility of Household Biogas and Bioslurry Systems

Table 3. Financial Feasibility of Household Biogas System (Rp/year)

Scenario	UPBP (years)	NPV (IDR)	BCR
Without Subsidy	2.1	IDR 8,024,000	1.37
With Subsidy (30%)	1.47	IDR 12,749,000	1.88

The financial evaluation of household biogas and bioslurry systems shows strong economic potential for households, both in subsidized and non-subsidized scenarios. The non-discounted return on capital (UPBP) period was relatively short, with households able to return their initial investment in about 2.1 years without subsidies and only 1.47 years with a 30% subsidy, which was estimated based on interviews with participant households. Net present value (NPV), calculated using a 10% discount rate, has a positive value in both scenarios, namely IDR 8,024,000 without subsidies and IDR 12,749,000 with subsidies, indicating that the total benefits discounted during the system's operational life exceed the associated costs. The benefit-cost ratio (BCR) of 1.37 without subsidies and 1.88 with subsidies further strengthens the profitability of the system, suggesting that each unit of cost results in a much higher economic return. Even without financial backing, the system remains profitable, while subsidies based on household insights increase the speed of return on capital and overall financial gains, making adoption more feasible and attractive.

In addition to these financial metrics, this analysis highlights broader economic implications at the household level. Substantial monetary benefits, especially from reduced spending on LPG and chemical fertilizers, provide consistent annual savings, improve household cash flow and economic resilience. These recurring savings also reduce dependence on external energy and agricultural inputs, which contributes to long-term sustainability and self-sufficiency. Low recurring operating and maintenance costs, amounting to just $750,000 per year, mean that after the initial investment, households continue to enjoy net benefits with minimal financial burden, which is especially important for low- and middle-income households considering biogas adoption.

Furthermore, the results of the study suggest that policy interventions, such as targeted subsidies identified through household interviews, can accelerate adoption and amplify economic benefits. By lowering the initial cost of capital, subsidies reduce financial barriers, encourage wider participation, and increase the overall profitability of the system. Households benefit not only from immediate financial savings, but also long-term economic and environmental benefits, including cleaner energy use, reduced greenhouse gas emissions, and increased soil fertility thanks to the use of organic fertilizers. These combined benefits underscore the dual role of household biogas systems as an economically sound investment as well as a sustainable resource management solution.

Linear Mixed Model (LMM)

Table 4. Estimation of Linear Mix Model of Factors Affecting the Monetary Benefits of Biogas and Household Bioslurry

Variables	Factor/Level	Estimate	Significance (p-value)	Interpretation
Education	Level 1	2.42 x 10-7	<0.001	Households with primary education slightly higher TOT_BENEFIT than reference (level 2)
	Level 2	0	-	Reference category
Biogas Capacity	1	5.19 x 10-7	<0.001	Small capacity increases TOT_BENEFIT relative to reference (level 4)
	2	8.13 x 10-7	<0.001	Medium capacity yields largest positive effect
	3	5.35 x 10-7	<0.001	Larger capacity increases TOT_BENEFIT, but less than medium
	4 (ref)	0	-	Reference category
Subsidy	0	-1.99 x 10-7	<0.001	Households without subsidy have lower TOT_BENEFIT than those with subsidy
	1 (ref)	0	-	Reference Category
Economic Variables	LPG Price	2.76 x 10-9	<0.001	Higher LPG price slightly increases TOT_BENEFIT due to greater LPG savings
	Number of Cows	-6.82 x 10-7	<0.001	More cows slightly reduce TOT_BENEFIT, likely due to higher feedstock costs

Variables	Factor/Level	Estimate	Significance (p-value)	Interpretation
Savings & Revenue	LPG Savings	1.00	<0.001	Directly increases TOT_BENEFIT; primary contributor
	Fertilizer Savings	1.00	<0.001	Directly increases TOT_BENEFIT
	Bio-slurry Revenue	1.00	<0.001	Directly increases TOT_BENEFIT; reflects income from bio-slurry

The results of the LMM show that many factors affect the total monetary benefit, but not all factors are equally uncertain or vary in practice. Among the economic and household variables, LPG prices and cow counts were selected for sensitivity analysis because they are both most likely to fluctuate and have a direct impact on household net benefits. LPG prices can vary over time due to market dynamics, subsidies, or regional supply differences, which directly alter the monetary savings of switching to biogas. Similarly, the number of cows determines the amount of raw materials available for the biogas system, which affects biogas production and bio-slurry output potential; Therefore, small changes in the number of livestock can significantly alter household benefits. Other variables in the LMM, such as education level, subsidy status, or biogas capacity, were fixed for each household during the study period and did not vary over time, making them less suitable for sensitivity testing.

Focusing the sensitivity analysis on these two key variables allowed the study to assess how realistic fluctuations in the household environment affected system profitability, the period of return on capital, and the benefit-cost ratio. This targeted approach ensures that the analysis captures the practical risks and uncertainties facing households, while keeping the evaluation managed and relevant. Combined with the LMM results, this approach provides a robust understanding of how financial outcomes respond to crucial economic and operational changes, helping policymakers and households anticipate and plan for variability in system performance.

Sensitivity Analysis

Table 5. Sensitivity Analysis

Scenario	NPV (IDR)	BCR	UPBP (Years)	Description
Base Case-With Subsidy	IDR 20,850,000	1.52	2.2	Initial investment reduced by subsidy; system generates strong positive returns
Base Case-Without Subsidy	IDR 5,850,000	1.10	3.5	Without subsidy, project remains viable but with lower profitability and longer payback
LPG Price +20% (With Subsidy)	IDR 27,450,000	1.75	1.9	Higher LPG price increases savings, strengthening financial viability
LPG Price -20% (With subsidy)	IDR 14,250,000	1.30	2.7	Lower LPG price reduces savings, but the system still provides positive returns
Number of Cows +2 (With Subsidy)	IDR 18,900,000	1.40	2.4	Additional cows increase feedstock but higher feed cost slightly reduces net benefit
Number of Cows -2 (With Subsidy)	IDR 22,800,000	1.60	2.1	Fewer cows reduce feed requirements, slightly improving net returns under household conditions

The sensitivity analysis highlights how changes in key economic and household conditions affect the financial viability of household biogas systems. In the case of the basic with subsidies, this system shows strong feasibility, with an NPV of IDR 20,850,000, a BCR of 1.52, and a payback period of more than two years. This shows that when households receive external support to offset the initial costs, the adoption of biogas technology is very attractive and financially sustainable. In contrast, the basic case without subsidies shows a much lower NPV, which is IDR 5,850,000 and a longer return on capital, which is 3.5 years, although this system remains relatively feasible with a BCR above 1. This comparison underscores the important role of subsidies in accelerating adoption and ensuring economic attractiveness.

Changes in LPG prices also have a significant impact on system outcomes. The 20% increase in LPG prices increased household savings, increased NPV to IDR 27,450,000 and shortened the payback period to less than two years. On the other hand, the 20% decrease in LPG prices weakened yields, lowered NPV to Rp 14,250,000 and extended the payback period to 2.7 years. Even in these less favorable conditions, the system still produces a positive NPV and a BCR greater than 1, indicating that the investment remains strong against a moderate decline in energy prices. This confirms that biogas adoption is particularly valuable in areas with high or fluctuating fossil fuel prices.

The effect of changes in the number of cows shows a more nuanced picture. The addition of two cows slightly reduced the overall NPV to Rp 18,900,000, which likely reflects higher opportunity costs of raw materials despite increased gas production. On the other hand, reducing the number of cattle by two increases the NPV to Rp 22,800,000 and slightly shortens the payback period. These findings may initially seem counterintuitive, but they reflect a trade-off at the household level: Fewer cows reduce resource load and allows for more efficient operation of the system. These results are in line with the LMM analysis, which also shows a negative coefficient for the number of livestock, which suggests that once it reaches a certain point, more cows do not necessarily result in a higher net benefit.

Overall, sensitivity analysis shows that household biogas systems remain financially viable in a variety of plausible scenarios, with subsidies and LPG price dynamics having the strongest influence on investment returns. These results reinforce the importance of policy interventions such as subsidies to lower initial costs and maintain household adoption. At the same time, these results highlight the need to consider local conditions, particularly livestock management, when promoting biogas technology. This comprehensive assessment, which combines the findings of NPV, BCR, UPBP, and LMM, ensures that financial projections reflect economic variability and household-level realities.

CONCLUSION

The study assessed the financial feasibility of household biogas systems by analyzing costs, monetary benefits, and return determinants, finding that while initial capital investment is substantial, maintenance and operational costs are low. Households benefit from significant savings on LPG and fertilizers, supplemented by income from bio-slurry, resulting in a positive net present value (NPV), favorable benefit-cost ratio (BCR), and a relatively short payback period, particularly with subsidies. Sensitivity analysis indicated that despite changes in LPG prices and livestock numbers, adoption remains financially attractive though profitability varies. Longitudinal research evaluated system durability and the effects of maintenance and household practices, while also considering environmental and social benefits such as carbon emission reductions, health improvements, and gender-related advantages for a comprehensive assessment. Advanced econometric methods like panel regression or structural equation modeling were used to explore the complex interplay of economic, technical, and social factors influencing adoption. Future research should involve larger, more diverse samples across different regions to better capture variability in costs, subsidy access, and energy price dynamics, enhancing the understanding of widespread adoption and impact.

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