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The Impact of Biogas Adoption on Household Food Security among Livestock Farmers

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ABSTRACT

Biogas technology has emerged as a strategic solution to address energy and environmental challenges in rural agricultural communities. However, its adoption rate and impact on household welfare particularly regarding food security remain relatively underexplored within the local Indonesian context. This study aims to: (1) identify the socio-economic and demographic factors influencing household decisions to adopt biogas technology, and (2) evaluate the impact of biogas adoption on household food security. The research was conducted using a cross-sectional survey design in Gendro Village, Tutur Subdistrict, Pasuruan Regency, Indonesia. A total of 129 livestock-farming households were purposively selected. Data were collected through structured questionnaires and analyzed using probit regression and two-sample t-tests. The findings indicate that farming experience ($p = 0.051$), livestock ownership ($p = 0.054$), membership in farmer groups ($p = 0.025$), and participation in extension programs ($p = 0.070$) significantly influence biogas adoption decisions. Furthermore, the t-test results show a statistically significant difference in food security between adopter and non-adopter households ($p = 0.000$). This study represents one of the first quantitative efforts in Indonesia to empirically examine the relationship between biogas technology adoption and household food security using the Food Insecurity Experience Scale (FIES). The results affirm that biogas technology contributes to energy savings and waste management and positively affects food security outcomes. Therefore, policy interventions should focus on expanding access to biogas technology through subsidy schemes, technical training, and integration with sustainable livestock development programs. Moreover, strengthening farmer group empowerment and community-based approaches is essential to promote wider and more equitable technology dissemination.

1. Introduction

In recent decades, the global discourse on clean and sustainable energy has intensified, highlighting the urgent need for integrated solutions that address environmental challenges and household-level vulnerabilities (Khalil et al., 2019). As one of the world's largest agrarian economies, Indonesia faces mounting pressure to meet its growing energy demand while ensuring food security among rural households (Surendra et al., 2014). Among the emerging solutions, biogas technology has gained attention as a promising renewable energy source, especially given Indonesia's large livestock sector. By converting livestock waste into energy and organic fertilizer, biogas offers dual benefits for farming households and aligns with Indonesia's national strategy for renewable energy development (O'Shea et al., 2020). Pasuruan Regency in East Java, Indonesia, characterized by a high concentration of smallholder dairy farmers and long-standing livestock activities, represents a strategic location for biogas development. However, despite the visible potential and pilot programs initiated by local cooperatives, the adoption of biogas technology remains relatively low and uneven across farming communities. Despite its visible potential and pilot initiatives facilitated by cooperatives such as KPSP Setia Kawan, biogas adoption remains relatively low and uneven. Structural barriers persist, including limited access to infrastructure, inadequate technical knowledge, and insufficient policy support. These factors hinder the wide-scale utilization of biogas, especially in rural areas where energy poverty and food insecurity remain pressing issues.

In addition to its environmental benefits, biogas adoption may offer important socio-economic advantages. Economically, it reduces dependence on fossil fuels, allowing households to redirect energy savings toward food and other necessities (Mutenje et al., 2016). Environmentally, it mitigates greenhouse gas emissions and encourages sustainable waste management. Socially, it improves the quality of life by providing clean and efficient energy. Importantly, clean energy access has also been linked to broader improvements in household welfare, particularly through better food purchasing power and health outcomes. Biogas adoption may positively influence household food security through at least two pathways. First, cost savings on energy expenditures may allow for increased spending on more diverse and nutritious food (Sinyolo, 2020). Second, reduced reliance on external fuels enhances energy resilience, indirectly improving the stability of food access. This study employs the Food Insecurity Experience Scale (FIES), a globally validated instrument developed by the FAO to assess household food insecurity based on experiential responses (FAO, 2017).

Despite this potential, empirical studies exploring the relationship between biogas adoption and food security in Indonesia remain scarce. Most existing research has focused on technical feasibility or environmental impact, with limited attention to household-level socio-economic outcomes (Luo et al., 2021; Nevzorova & Kutcherov, 2019). This study addresses that gap by employing primary household-level data and robust quantitative analysis to evaluate the impact of biogas adoption on food security. To the best of our knowledge, this is one of the first studies in the Indonesian context that explicitly links biogas technology and food security outcomes. The main objectives of this study are twofold. (1) to identify the socio-economic and demographic factors influencing household decisions to adopt biogas technology in Pasuruan Regency. (2) to assess whether biogas adoption significantly affects household food security outcomes, as measured by FIES. The underlying hypothesis is that biogas adoption reduces energy costs and enables households to reallocate resources toward food consumption and other necessities, thereby enhancing food security. This study contributes to both theoretical and practical domains. Theoretically, it enriches the literature on the intersection of clean energy adoption and household food security in rural agrarian settings. Practically, its findings offer policy-relevant insights for advancing inclusive and sustainable biogas programs, particularly in livestock-intensive regions of Indonesia. The study aligns with and supports the realization of Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action).

2. Methods

2.1. Study Area and Data Collection

This study was conducted in Tutur District, Pasuruan Regency, East Java, Indonesia. The location was purposively selected based on its high concentration of smallholder dairy farmers and its recognized potential for biogas development. According to BPS Jawa Timur (2022), Pasuruan Regency has one of the largest dairy cattle populations in the province. Furthermore, the selection was supported by recommendations from the KPSP Setia Kawan Cooperative, which has actively contributed to the region's livestock development and renewable energy initiatives, particularly biogas. The justification for choosing a cross-sectional survey design should be added, emphasizing its relevance for capturing adoption status and food security outcomes simultaneously. Additionally, clarify that purposive sampling—while guided by stakeholder input—may limit generalizability and carry potential selection bias.

Primary data were collected using a structured questionnaire administered through face-to-face interviews. The survey captured detailed household-level information on demographic characteristics, economic conditions, livestock assets, group participation, access to extension services and credit, internet usage, and food security status. The research targeted two groups: households that had adopted biogas technology (coded as 1) and those that had not (coded as 0). A total of 129 livestock-raising households were selected purposively from Gendro Village, Tutur District, based on information provided by local stakeholders. This sampling strategy allowed for the inclusion of diverse household profiles within a comparable socio-economic and geographical context. Trained enumerators from local universities were engaged to assist with data collection and minimize language barriers. All participants were informed of the study objectives and gave verbal informed consent prior to participation. The study followed ethical research practices applicable to non-clinical social research.

2.2. Sample Groups and Variable Coding

Households were divided into: a) Adopters: Those currently using biogas units (n = 101; coded 1); Non-adopters: Those not using biogas (n = 28; coded 0). Binary explanatory variables (dummy) were coded consistently: 1 = yes, 0 = no (e.g., group membership, access to credit, participation in counseling). Continuous variables included age, years of farming experience, education level, number of livestock, and household size. Add justification for using these two comparison groups (adopters and non-adopters) and consider noting whether any baseline differences between groups were assessed. Although inferential analysis follows, an initial mention of this would provide stronger methodological grounding.

2.3. Analytical Methods

A probit regression model was used to examine the first research objective—the determinants of biogas adoption. This model is appropriate for binary outcome variables, where the dependent variable indicates whether the household adopted biogas. The probit regression model is used, where the adoption decision's dependent variable is binary or dummy. Previous studies have widely used probit regression models for estimating similar decisions or objectives (Hanani AR et al., 2024; Rahman et al., 2021; Ullah et al., 2015). The probit regression econometric model in this study refers to Gujarati (2014) as follows:

$$P_i = \Pr(Y = 1|X) = \Pr(I_i^* \leq I_i) = \Pr(Z_i \leq BX) = F(BX) \quad (1)$$

The dummy dependent variable is a notation of the biogas adoption decision (Y = 1, yes; and Y = 0, no). An explanation of each socio-economic variable in equation model 1 is shown in Table 1. The significance level in the first research objective is α = 0.01, 0.05, and 0.1. So, the hypothesis for the first research objective is as follows:

H_0: Socio-economic factors do not significantly influence biogas adoption decisions.

H_1: Socio-economic factors significantly influence biogas adoption decisions.

Furthermore, to estimate the second research objective, namely the impact of biogas adoption on food security, we use a t-test analysis to determine the difference in the level of food security of farmer households that adopt biogas and households that do not. Previous researchers have carried out this model with similar research objectives (Firdaus et al., 2024; Nhan & Yutaka, 2019). The equation of this research t-test model is as follows.:

$$T_{test} = \frac{\bar{x} - \mu_0}{\hat{S}/\sqrt{n}} = \frac{\bar{x} - \mu_0}{\hat{S}/\sqrt{n-1}} \quad (2)$$

The significance levels used in the second research objective are α = 0.01, 0.05, and 0.1. Then the research hypothesis in the second objective is as follows:

H_0: There is no significant difference in household food security between adopters and non-adopters.

H_1: There is a significant difference in household food security between adopters and non-adopters.

This dual-method approach allows for both the identification of adoption drivers and the evaluation of welfare impacts, offering a comprehensive understanding of biogas technology's role in rural development.

2.4. Measurement of Food Security

Household food security was measured using the Food Insecurity Experience Scale (FIES), a standardized global indicator developed by the FAO (2017). FIES is based on eight experience-based questions assessing access to sufficient food over the past 12 months. Scores range from 0 (food secure) to 8 (severe food insecurity), with higher values indicating worse food security status. Although the FIES scale is standardized globally, it is unclear whether any local cultural adaptation or pilot validation was conducted. If not, this should be noted as a methodological limitation, especially given the subjective nature of experiential food insecurity measures.

FIES has been widely applied in national and cross-national household surveys and is recognized for capturing experiential dimensions of food insecurity (Jubayer et al., 2023; Manzilati et al., 2023). Its standardized structure and global comparability make it a valuable tool for assessing access to adequate food based on lived experiences. However, while FIES offers strong cross-cultural applicability, it is also sensitive to contextual interpretation, especially in settings where local cultural norms, dietary expectations, and social perceptions influence food insecurity. In this study, the FIES instrument was used directly in line with FAO guidelines without formal cultural adaptation or psychometric validation in the local context. This methodological choice presents a limitation, as experiential indicators—though globally validated—may require contextual calibration to reflect household realities in specific regions fully. Future research is encouraged to incorporate localized pre-testing or validation procedures to enhance FIES-based measurements' contextual reliability and cultural fit.

2.5. Data Processing

All data were initially tabulated and organized using Microsoft Excel 2016, facilitating preliminary data screening and consistency checks. This included basic data cleaning procedures such as identifying outliers, handling missing values, and verifying the logical consistency of responses. After ensuring data readiness, the dataset was imported into STATA-MP version 17.

3. Results and Discussion

3.1. Result

3.1.1. Descriptive Statistics

Table 1 summarizes the key socio-economic and demographic characteristics of the 129 surveyed livestock-farming households in Gendro Village. The average age of respondents was 50.21 years, and they had an average of 25.39 years of farming experience—indicating that the population largely consisted of mature and seasoned farmers. Despite their experience, formal education levels were relatively low, averaging 6.09 years, which may reflect limited access to formal schooling in rural settings. The average household size was 2.91 persons, suggesting that most households operated as small nuclear families.

Table 1 Descriptive statistics

Variable	Deskripsi	Mean	Std. dev.
adoption	Dummy biogas adoption (1= adoption; 0=otherwise)	0.78	0.41
age	Age of farmers (year)	50.21	9.68
experience	Experience farmers (year)	25.39	8.98
education	Education level of farmers (year)	6.09	1.30
familysize	Number of family size (person)	2.91	0.89
livestock size	Number of livestock (amount)	6.55	3.48
cage area	Size of Cage (m2)	66.96	37.11
land agriculture ownership	Dummy land agriculture ownership (1=owner; 0=otherwise)	0.28	0.45
group farm	Dummy group farmers (1=yes; 0=otherwise)	0.53	0.50
social group	Dummy Join Social Group (1=yes, 0=otherwise)	0.53	0.50
counseling participation	Dummy counselling farmers (1=yes; 0=otherwise)	0.58	0.49
internet access	Dummy internet access (1=yes; 0=otherwise)	0.74	0.44
credit access	Dummy credit access (1=yes; 0=otherwise)	0.45	0.50
Partnership	Dummy partnership market (1=yes; 0=otherwise)	0.17	0.38

Regarding productive assets, farmers owned an average of 6.55 livestock, and the average size of livestock pens was 66.96 m², pointing to small-scale operations across the sample. Notably, 78% of respondents had adopted biogas technology, reflecting a relatively high adoption rate likely influenced by regional cooperative-led initiatives. Meanwhile, 53% were active in farmer groups, and 58% had participated in extension services, underscoring the potential role of institutional support in influencing technology uptake. Access to the internet was fairly widespread (74%), which may facilitate information flow, while credit access remained moderate at 45%. Interestingly, despite institutional presence, participation in formal market partnerships was low at 18%, which could limit commercialization opportunities and the scalability of clean energy technologies like biogas.

3.1.2. Estimated Result of Factors Influencing The Decision To Adopt Biogas

Various socio-economic and demographic factors can influence the decision to adopt biogas technology. Therefore, to determine the factors that influence the decision to adopt biogas, researchers present the estimation results of a probit regression model, where the dependent variable is a dummy. The results of this analysis are presented in Table 2.

Table 2 Estimated results of factors influencing the decision to adopt biogas; Probit

Adoption	**Coefficient**	**P>|z|**
Age	0.002	0.910
Experience	-0.033	0.051*
Education	0.047	0.682
Familysize	-0.020	0.905
Livestocks size	0.119	0.054*
Cage area	0.004	0.401
Land agriculture ownership	-0.361	0.258
Group farm	0.696	0.025**
Social group	0.040	0.888
Counseling participation	0.551	0.070*
Internet access	0.288	0.387
Credit access	-0.198	0.498
Neighborhood adoption	0.192	0.507
Partnership	0.089	0.830
_cons	-0.404	0.792
Pseudo R2	0.206	

Note : **,* Significan at α = 0.05 and 0.1
Primary Data Processed, 2024

3.1.3. Food Insecurity Experience Scale Measurement Result

Figure 1 illustrates the average Food Insecurity Experience Scale (FIES) score based on biogas adoption status. Non-adopters' average FIES score is notably higher (≈11.26) than that of adopters (≈9.25). Given that a higher FIES score indicates greater food insecurity, this result suggests that households adopting biogas technology tend to experience lower levels of food insecurity than their non-adopting counterparts.

This empirical evidence reinforces the hypothesis that biogas adoption contributes positively to household food security. The underlying mechanism may relate to reduced expenditures on conventional fuels, allowing households to reallocate savings toward more diverse and nutritious food. Additionally, access to clean and reliable energy may indirectly support better health outcomes, food preparation, and time use—especially for women—thus enhancing overall household welfare. These findings align with earlier studies (Mutenje et al., 2016; Sinyolo, 2020), highlighting the socio-economic benefits of clean energy adoption, particularly in rural agrarian contexts. However, given the cross-sectional nature of the data, the results should be interpreted as associations rather than definitive causal effects.

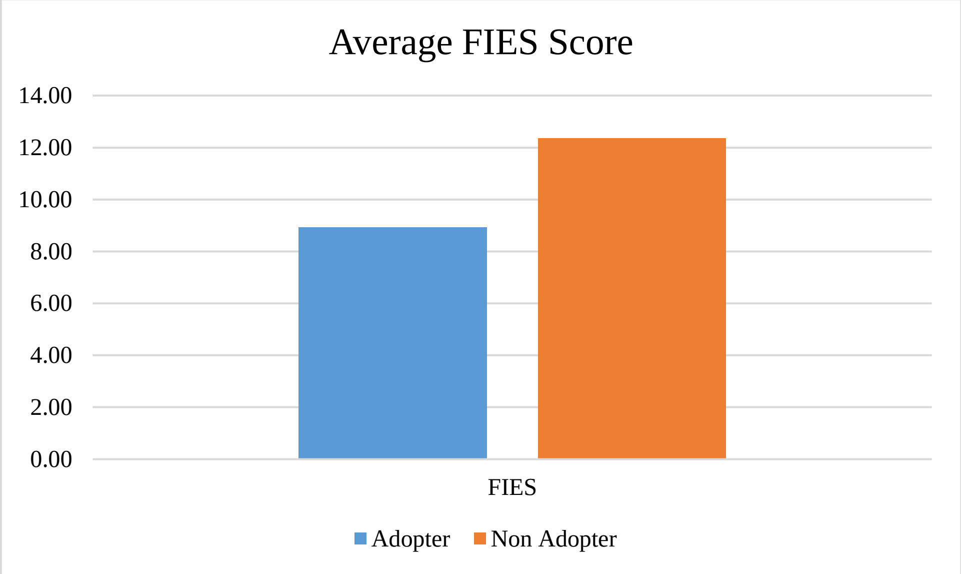

Figure 1 Estimated FIES Score Average by Adoption Categories

3.1.4. Estimated Result of Differences in Food Security Levels (FIES)

To answer the second objective of this study, which is to analyze the impact of biogas adoption on household food security, a two-sample t-test approach is used with food security variables measured using the Food Insecurity Experience Scale (FIES) indicator. The FIES score is used to represent the level of household food insecurity, where a higher FIES score indicates a lower food security condition. In this case, a t-test was conducted to compare the average FIES score between households that adopted biogas and those that did not. The results of this t-test analysis are presented in Table 3.

Table 3 Estimation results of differences in food security levels (FIES); T-test

Group	Obs	Mean	Std. err.
1 (Adoption)	101	8.921	0.084
0 (No adoption)	28	12.357	0.225
Combined	129	9.667	0.149
Diff		-3.436	0.199
Pr (|T| > |t|)		0.000***	

Note : *** Significan at $\alpha = 0.01$

Primary Data Processed, 2024

3.2. Discussion

3.2.1. Determinants of Biogas Adoption

The probit regression results in Table 2 reveal several statistically significant factors influencing biogas adoption. Farming experience exhibited a significant negative relationship with biogas adoption. This finding implies that farmers with longer years of experience may be less inclined to adopt new technologies such as biogas. One plausible explanation is that more experienced farmers tend to rely on traditional practices that have been personally validated over time. Such individuals may also perceive biogas as unfamiliar, complex, or risky compared to conventional energy sources like firewood or LPG. This pattern aligns with prior empirical evidence suggesting that older or more experienced farmers resist innovation due to habitual behavior, skepticism toward change, or lower exposure to contemporary training (Agbenyo et al., 2022; Li et al., 2021). In the context of Pasuruan, it is also likely that younger farmers, particularly those with access to the internet and training, are more responsive to energy-based innovations.

Livestock ownership had a positive and statistically significant effect on adoption, emphasizing the critical role of input availability—namely animal manure—for biogas system viability. Households that own more livestock generate a greater volume of organic waste, making the operation of biogas digesters both technically feasible and economically worthwhile. These findings are consistent with prior studies highlighting the importance of resource endowment—especially biomass availability—as a precondition for successful adoption of bioenergy technologies (Franco et al., 2012).

Membership in farmer groups was found to increase the likelihood of adoption significantly. This supports the hypothesis that social capital is key in facilitating technology diffusion. Being part of a farmer group provides access to shared information, peer learning, demonstration activities, and trust-based discussions that can reduce uncertainty surrounding new technologies. Social interaction within groups can also create normative pressure to adopt, particularly when influential members endorse the technology. This finding aligns with previous literature emphasizing the importance of horizontal knowledge transfer and the role of networks in agricultural innovation adoption (Awotide et al., 2016; Ngwira et al., 2014).

Participation in extension services had a positive and significant association with biogas adoption. Extension programs are a formal mechanism for transferring technical knowledge, raising awareness of benefits and maintenance procedures, and linking farmers with institutional support (e.g., subsidies or installation assistance). In the study area, extension activities often involve direct interaction with cooperative representatives (e.g., KPSP Setia Kawan) and government officials, which can reduce the perceived complexity of biogas systems and build farmer confidence. The significance of this variable reinforces the role of targeted outreach and capacity building in overcoming adoption barriers, particularly among smallholder farmers who may lack initial exposure to clean energy solutions (dos Santos et al., 2020; Willy & Ngare, 2021).

Other variables such as age, education, land ownership, and internet access did not show significant effects, indicating that biogas adoption is more strongly influenced by practical resource availability and institutional engagement than individual-level demographic factors. These findings are consistent with similar studies in Ethiopia and Bangladesh (Mengistu et al., 2016; Ahmad & Wu, 2022), but differ from regions where subsidies or national programs are the primary drivers. In Pasuruan, adoption is more organically driven through local cooperatives, suggesting the critical role of community-based institutions in renewable energy diffusion.

3.2.2. Impact of Biogas Adoption on Household Food Security

The two-sample t-test results, as presented in Table 3, reveal a statistically significant difference in household food security outcomes between biogas adopters and non-adopters. Households that had adopted biogas technology reported a lower average FIES score (8.92) compared to their non-adopting counterparts (12.36), with a p-value of less than 0.01. Since FIES scores are inversely related to food security—where a higher score reflects greater food insecurity—these findings suggest that biogas adoption is positively associated with improved household food security status. This association can be explained by several interlinked pathways through which biogas adoption impacts household resource allocation, health, and daily living conditions. First, biogas significantly reduces reliance on conventional fuels such as liquefied petroleum gas (LPG) or firewood, often comprising a substantial share of household expenditure in rural areas. By substituting purchased energy with self-generated biogas, households can redirect their limited cash resources toward essential needs, particularly food. Prior studies (Arthur et al., 2011; M. M. Rahman et al., 2014) have noted that biogas systems reduce recurring energy costs, enhancing household purchasing power.

Second, biogas contributes to a cleaner cooking environment by eliminating smoke and harmful emissions commonly associated with traditional fuels. This has direct health benefits, particularly for women and children most exposed to indoor air pollution (Iqbal et al., 2021). Improved health conditions can reduce out-of-pocket medical expenses and improve physical capacity for income-generating or caregiving activities, indirectly contributing to better food access and utilization. Cleaner cooking spaces also support improved hygiene during food preparation, a critical but often overlooked aspect of food security. Third, access to a more stable and controllable energy source allows households to prepare meals more frequently and flexibly, which is particularly important in households with irregular work schedules or school-age children (M. S. Rahman, Majumder, et al., 2021). This can contribute to more regular meal consumption patterns and greater dietary diversity, both essential dimensions of food security. In the study area, qualitative feedback from farmers revealed that biogas users experienced fewer interruptions in cooking routines and were better able to prepare hot meals even during energy shortages or price spikes of LPG.

These findings align with global evidence linking clean energy access to multidimensional improvements in household welfare, including food security (Sinyolo, 2020; Yadav et al., 2023). In the specific context of Pasuruan Regency, integrating biogas within smallholder dairy farming systems enhances environmental sustainability, livelihood resilience, and nutritional well-being. Nevertheless, while the observed differences are statistically and practically significant, caution must be exercised in interpreting them as causal effects due to the non-experimental, cross-sectional nature of the study. Potential selection bias—whereby households more likely to adopt biogas may also differ in unobserved characteristics (e.g., motivation, awareness, access to networks)—could influence the results. Future studies are encouraged to use quasi-experimental methods such as Propensity Score Matching or Instrumental Variable techniques to isolate better the causal impact of biogas adoption on food security.

3.2.3. Policy and Development Implications

The empirical evidence suggests that biogas technology is a multi-functional intervention, enhancing energy access, environmental sustainability, and food security. In light of Indonesia's commitment to renewable energy and rural development, several policy implications emerge: 1) strengthening community-based cooperatives can accelerate adoption through social learning, shared investment, and peer influence; 2) bundling biogas programs with livestock and food security schemes—especially those under the Ministry of Agriculture and Ministry of Energy—can maximize cross-sectoral impact; 3) Incorporating biogas into village development plans (RPJMDes) may encourage local governments to allocate village funds (Dana Desa) for clean energy infrastructure; 4) tailored extension programs that combine technical training with food security education may improve adoption and household outcomes.

3.2.4. Limitations and Directions for Future Research

Despite its contributions, this study has several limitations. The use of cross-sectional data limits causal inference. Future research should consider panel data or quasi-experimental methods such as Propensity Score Matching (PSM) or Difference-in-Differences (DiD) better to isolate the causal impacts of biogas on welfare indicators. Additionally, further studies could explore gender-disaggregated impacts of biogas adoption on household dynamics; long-term economic returns of biogas investments; environmental benefits through carbon reduction metrics, and fertilizer substitution.

4. Conclusion

This study investigated the socio-economic factors influencing biogas adoption and its impact on household food security among livestock farmers in Pasuruan Regency, East Java. The empirical findings demonstrate that farming experience, livestock ownership, group membership, and participation in extension services significantly affect the likelihood of adopting biogas technology. These results highlight the importance of both resource availability and institutional engagement in facilitating renewable energy adoption in rural settings. Moreover, adopting biogas was found to have a positive and statistically significant impact on household food security, as measured by the Food Insecurity Experience Scale (FIES). Households using biogas reported improved food security outcomes due to reduced energy expenditures, cleaner cooking environments, and more consistent access to cooking fuel. These findings support the argument that biogas technology can serve as an integrative solution, simultaneously addressing energy poverty, environmental sustainability, and household welfare.

From a policy perspective, this study offers several key recommendations promote cooperative-based biogas programs, leveraging social capital and collective decision-making to enhance adoption; integrate biogas promotion into national food security and livestock development strategies, particularly in dairy-producing regions; expand extension and technical support services tailored to smallholder farmers, with emphasis on energy efficiency and household nutrition; provide financial incentives and flexible credit schemes to reduce initial investment barriers, especially for low-income farming households. By positioning biogas as a technical innovation and a rural development tool, this study underscores the potential for clean energy to transform livelihoods and strengthen food system resilience in agrarian economies like Indonesia.

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