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DOES BIOGAS ADOPTION INCREASE FOOD SECURITY? INSIGHT FROM LIVESTOCK FARMERS IN EAST JAVA

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ABSTRACT

Biogas technology, which uses livestock waste as raw material offers an innovative solution to reduce reliance on fossil fuels while promoting environmental and household economic sustainability. This study has two main objectives: To identify the socio-economic and demographic factors that influence the decision to adopt biogas and to assess its impact on household food security using the Food Insecurity Experience Scale (FIES). The research involves 200 livestock-owning households in East Java. Probit regression analysis revealed that farmers' experience, livestock ownership, land ownership, farmer group membership, agricultural extension services, and market partnerships significantly affect biogas adoption decisions. The impact of biogas adoption on food security was analysed using Propensity Score Matching (PSM), showing that biogas adoption significantly reduces food insecurity and improves food availability. Additionally, the use of bio-slurry as organic fertiliser enhances agricultural productivity, supports food stability, and reduces household expenses. This study provides crucial insights and significant contributions for policymakers to scale up biogas adoption as part of national food security strategies and for the independent enhancement of clean and sustainable energy. This research also contributes to the literature on renewable energy and rural development, with implications for achieving the Sustainable Development Goals (SDGs).

Introduction

Biogas derived from livestock waste represents a crucial solution for addressing the challenges of non-renewable energy consumption and environmental issues in many countries (Khalil *et al*., 2019). As a renewable energy source, biogas offers significant potential to meet energy needs, particularly in rural areas and specifically for livestock households (Surendra *et al*., 2014). Utilising livestock waste for biogas production not only reduces reliance on fossil fuels but also provides environmentally friendly and sustainable energy (Surendra *et al*., 2014; Khalil, 2019). Additionally, biogas helps lower greenhouse gas (GHG) emissions generated from the decomposition of organic waste, contributing to global climate change mitigation in the long term (Bekchanov *et al*., 2019; O'Shea *et al*., 2020). In Indonesia, particularly in East Java, the cattle farming sector is one of the primary contributors to organic waste production, presenting promising potential for renewable energy development through biogas technology.

However, environmental challenges related to the utilisation of livestock waste as renewable energy through biogas technology remain significant (Surendra *et al*., 2014; Khalil *et al*., 2019). One major issue is the low adoption rate of biogas technology, particularly among smallholder farmers (Kelebe *et al*., 2017). Preliminary findings suggest that the low adoption rate may be attributed to socio-economic factors such as limited knowledge, financial constraints, insufficient government support, and others (Mwirigi *et al*., 2014; Jan, 2021). Furthermore, the successful implementation of biogas systems is often hampered by inadequate infrastructure, restricted access to technology, and a lack of understanding of the long-term benefits of sustainable waste management (Nevzorova & Kutcherov, 2019). Poorly managed livestock farming practices exacerbate environmental degradation and public health concerns, especially in rural areas. Therefore, a more holistic approach is required to promote biogas as both environmental and energy solution in the livestock sector.

Managing livestock waste through biogas technology is not only crucial for environmental sustainability but also has direct implications for food security. For example, technological innovations in the agricultural and livestock sectors have been shown to positively impact household food security (Mutenje *et al*., 2016; Sinyolo, 2020). The core hypothesis of this study is that processing livestock waste into biogas allows farmers to reduce their reliance on expensive energy sources, enabling cost savings that can be reallocated to meet other household food needs. These savings can also be used for non-food expenditures. Additionally, the byproduct of biogas production, known as bio-slurry can be used as a high-quality organic fertiliser, enhancing agricultural productivity and improving long-term household food availability. In this context, biogas plays an essential role in sustainable food security by integrating environmentally friendly waste management and the potential for increased agricultural output. However, these hypotheses require empirical validation, which this study aims to provide.

The urgency of conserving environmental resources and adopting renewable energy through biogas technology is highly relevant to improving household food security. One key tool for measuring food security is the Food Insecurity Experience Scale (FIES), recognised by the FAO (World Food Programme, 2018). FIES provides detailed insights into household experiences with food insecurity. Previous studies have used FIES to measure the impact of agricultural and livestock technology adoption on food security. For instance, Rurinda *et al*. (2015) examined the impact of climate adaptation strategies on food security using FIES among maize farmers in Southern Africa while Ali *et al*. (2022) evaluated the effects of climate-smart agriculture on household food security in Ethiopia using the same tool. Applying FIES to assess the impact of biogas technology enables researchers to comprehensively evaluate household experiences across dimensions of accessibility, stability, and adequacy of food resources.

While previous studies have explored the effects of agricultural and livestock technology adoption on household welfare (Hanani *et al*., 2024), few have specifically measured the impact of biogas adoption on food security using the Food Insecurity Experience Scale (FIES). Existing studies such as Iqbal *et al*. (2021) have focused qualitatively on the impact of biogas adoption on energy security while Guenther-Lübbers *et al*. (2016) investigated its potential for added value and job creation. However, quantitative econometric studies examining the impact of biogas adoption on food security through FIES indicators are still scarce, particularly among smallholder farmers in Indonesia. Therefore, this research aims to fill this gap by focusing on the impact of biogas adoption on the food security of livestock-owning households in East Java.

This study has two main objectives. First, it aims to identify the socio-economic and demographic factors that influence the decision of livestock-owning households to adopt biogas technology. Second, it seeks to identify the impact of biogas adoption on household food security. The research focuses on empirical evidence from East Java, but its findings are expected to have broader implications. Academically, these findings contribute to the literature on renewable energy and food security, particularly in rural areas of developing countries like Indonesia. For policymakers, the results can serve as a basis for formulating policies to support wider biogas adoption among livestock households, considering its impact on food security and progress towards sustainable energy independence. Practically, this research benefits small-scale farmers by highlighting the potential for economic well-being through energy cost savings and increased agricultural productivity via biogas technology. The contributions of this study align with the Sustainable Development Goals (SDGs), SDGs-2 (Zero Hunger), SDGs-7 (Affordable and Clean Energy), and SDGs-13 (Climate Action), emphasising the integration of environmental management and food security.

Research Method

Data Collection

This study involved 200 respondents from Malang and Pasuruan Regencies in East Java. A multistage sampling method was used to determine the study locations and respondents. The first stage involved selecting East Java Province due to its status as one of the largest cattle farming regions in Indonesia. Malang and Pasuruan Regencies were purposively chosen based on their significant contributions to livestock production in the province. The second stage involved selecting sub-districts within these regencies, guided by information from relevant agencies such as the Agricultural and Livestock Services and local extension officers. Sub-districts were selected based on their high cattle farmer population and potential for biogas technology adoption. Jabung Sub-district represented Malang Regency while Tutur Sub-district represented Pasuruan Regency as biogas development locations.

Respondents were selected using simple random sampling. A list of farmers who had adopted biogas and those who had not was prepared for each sub-district. From this list, 200 farmers were randomly selected to ensure the representativeness of the livestock farmer population, with Malang contributing 150 respondents and Pasuruan contributing 50. Of the 200 livestock-owning households we interviewed, 165 had adopted biogas (the treatment group) and 35 had not (the control group). Data were collected through structured interviews using a questionnaire. Interviews were conducted directly with respondents to ensure data validity and accuracy. The questionnaire focused on socio-economic and demographic characteristics, decisions to adopt biogas technology, and household food security. Food security was measured using the Food Insecurity Experience Scale (FIES), an internationally recognised tool for assessing food insecurity, adapted for the context of Indonesian cattle farmers (World Food Programme, 2018).

Data Analysis Method

Factors Influencing Biogas Adoption Decisions

To estimate the socio-economic and demographic factors influencing farmers' decisions to adopt biogas, this study employed probit regression analysis. The probit model was chosen because biogas adoption is a binary dependent variable, where farmers either adopt biogas (1) or do not (0). Independent variables included socio-economic factors such as age, education, farming experience, livestock ownership, family size, access to credit, and participation in social and farmer groups.

The general probit regression equation used follows Gujarati (2012):

$$A^*_i = X_i \propto + u_i; A^*_i = 1 \text{ } if \text{ } A^*_i > 0 \text{ } and \text{ } 0 \text{ } otherwise \quad (1)$$

where A^*_i is a latent dummy variable representing the farmer's decision, taking the value of 1 if the farmer adopts biogas technology and 0 otherwise. $\propto$ is a vector of variables to be estimated and u_i is the error term. Additionally, X_i denotes socio-economic characteristic factors. Using this model, the study identifies which factors significantly influence farmers' decisions to adopt biogas technology.

The Impact of Biogas Adoption on Household Food Security

To answer the second objective, this study employed Propensity Score Matching (PSM) to analyse the impact of biogas adoption on household food security. PSM reduces selection bias by comparing adopters (treatment group) and non-adopters (control group) based on their propensity scores.

The propensity score model was estimated using probit regression:

$$P(X_i) = Prob\ (A_i = 1/X_i) \quad (2)$$

where $P(X_i)$ represents the propensity score of each farmer, calculated based on previously identified socio-economic characteristics, including age, education level, farming experience, livestock ownership, family size, market access, and credit access.

Subsequently, matching techniques such as Nearest Neighbour Matching (NNM) and Kernel-Based Matching (KBM) are employed to match respondents from the treatment group with those from the control group who have similar propensity scores. This process ensures that comparisons are made between farmers with similar characteristics, allowing differences in food security to be attributed to the impact of biogas adoption. Once the matching process is completed, the Treatment Effect on the Treated (ATT) is calculated to measure the impact of biogas adoption on household food security, assessed using the Food Insecurity Experience Scale (FIES). The ATT equation, as applied in (M. S. Rahman *et al*., 2023) is expressed as follows:

$$ATT = E\{Y_{1i} - Y_{1i}A_i = 1\} = E[E\{Y_{1i} - Y_{1i}A_i = 1, p(X_i)\}] = [E\{Y_{1i}A_i = 1, p(X_i)\} - E\{Y_{0i}A_i = 0, p(X_i)\} A_i = 1] \quad (3)$$

where the outcome of interest is household food security for farmers who adopt biogas and for those who do not adopt biogas. The calculation of the ATT employs bootstrapped standard errors to address potential biases that may arise during the matching process. Data analysis was conducted using STATA MP-17 and data tabulation was performed using Microsoft Excel 2016.

Results and Discussion

Statistic Descriptive

In this section, the researchers address two main objectives: Estimating the factors influencing biogas adoption decisions and measuring their impact on household food security. Before delving into these objectives, the researchers provide an overview of the respondents' characteristics and the measurement scales of the variables used in the study, which involved 200 livestock farming households in East Java. Detailed information on the respondents' characteristics and the variable measurement scales is presented in Table 1.

Table 1 presents the descriptive statistics of the variables used in this study, providing a comprehensive overview of the respondents' key characteristics. A total of 82.5% of farmers in the study had adopted biogas technology, as indicated by the mean adoption variable value of 0.825. This reflects a relatively high adoption rate among farmers. Food security was measured using the Food Insecurity Experience Scale (FIES), which assesses food security on a scale of 8–16 points. The average score of 11.6 indicates a moderate level of food security among respondents, suggesting opportunities for further improvement in resource management for food security.

In terms of demographics, the average age of farmers was 51.25 years, with an average of 25.48 years of farming experience. This demonstrates that most farmers participating in the study were within their productive years and possessed significant experience in the agricultural sector. The average education level was 6.31 years, equivalent to basic education, highlighting the potential for enhancing knowledge and skills through additional training or education. Meanwhile, the average household

Table 1: Statistic descriptive

Variable	Definition	Mean	Std. Dev.
Adoption	Dummy biogas adoption (1= adoption; 0=otherwise)	0.825	0.381
FIES	Total measurement food insecurity scale on eight questions (8-16 points)	11.600	1.681
Age	Age farmers (year)	51.245	10.637
Experience	Experience farmers (year)	25.480	9.530
Education	Education level farmers (year)	6.315	1.738
Family size	Number of family size (person)	3.035	0.974
Livestock size	Number of livestock (amount)	6.255	3.436
Cage area	Size of cage (m^2)	62.325	38.739
Land agriculture ownership	Dummy land agriculture ownership (1=owner; 0=otherwise)	0.948	1.003
Group farm	Dummy group farmers (1=yes; 0=otherwise)	0.960	0.196
Counselling farm	Dummy counselling farmers (1=yes; 0=otherwise)	0.580	0.495
Internet access	Dummy Internet access (1=yes; 0=otherwise)	0.840	0.368
Credit	Dummy credit access (1=yes; 0=otherwise)	0.290	0.455
Partnership	Dummy join partnership market (1=yes; 0=otherwise)	0.375	0.485

size was 3.03 members, reflecting a small to medium family scale.

Regarding resources, the average farmers own six livestock, with an average barn size of 62.33 m^2. Agricultural land ownership was also notably high, with 94.8% of respondents reporting ownership of farmland. Participation in farmer groups was 96%, indicating strong involvement in collective organisations that can support farmers' capacity building through social and economic networks. However, participation in extension programs was moderate (58%), emphasising the need to improve access to technical information and best practices through extension services.

In terms of access to support services, only 29% of respondents had access to credit services and 37.5% were involved in market partnerships. These limited access points could pose challenges to the development of their businesses. Nevertheless, the Internet access rate was 84%, reflecting the significant potential for leveraging digital technology to support productivity and innovation. Overall, these statistics provide a comprehensive profile of the respondents, highlighting strengths such as biogas adoption and farmer group participation, alongside challenges like limited access to credit services and market partnerships. These insights form the basis for designing appropriate intervention strategies. The subsequent section discusses the factors influencing farmers' decisions to adopt biogas technology.

Factors Influencing Biogas Adoption Decisions in East Java

To answer the first research objective, we estimated the socio-economic and demographic factors influencing livestock households' decisions using probit regression analysis. Out of the 12 independent variables included in Model Equation 1, six variables were found to have a significant influence on farmers' decisions to adopt biogas technology.

Table 2 presents the results of the probit regression analysis, which estimates the factors influencing the adoption of biogas technology. First, the variable experience significantly affects adoption decisions at the 10% level with a coefficient of 0.016. The positive influence of farming experience on the probability of biogas adoption highlights the critical role of accumulated knowledge and skills in decision-making. Similar positive effects of experience in promoting the adoption of new technologies have been documented in previous studies (M. S. Rahman *et al*., 2021; 2023; Wijayanto *et al*., 2022). Farmers with more experience tend to have a deeper understanding of the benefits and challenges associated with adopting new technologies such as biogas systems. This experience allows them to better assess long-term advantages, including economic savings, environmental benefits, and practical improvements such as reduced dependency on conventional fuels and improved waste management (Stewart *et al*., 2015; Jha *et al*., 2020). Furthermore, experienced farmers are more likely to have strong community networks or access to extension services, which can further facilitate the adoption of innovative practices. Therefore, raising awareness and providing targeted support to less experienced farmers can help bridge gaps and increase adoption rates across different farming groups.

The second significant factor is livestock size, which positively influences adoption decisions at the 5% significance level with a coefficient of 0.090. The positive relationship between livestock ownership and biogas adoption underscores the importance of resource availability for implementing renewable energy technologies. Households with larger livestock numbers produce higher volumes of organic waste, the primary raw material for biogas production. This abundance of raw materials

Table 2: Factors influencing livestock household adoption of biogas: Probit regression

Adoption	**Coefficient**	**Std. Error**	**P > |z|**
Age	-0.015	0.013	0.122
Experience	0.016*	0.013	0.054
Education	-0.019	0.078	0.462
Family size	-0.216	0.131	0.249
Livestock size	0.090**	0.055	0.029
Cage area	0.003	0.004	0.324
Land agriculture ownership	0.567*	0.253	0.087
Group farm	1.363***	0.581	0.000
Counselling farm	0.361**	0.250	0.029
Internet access	0.089	0.346	0.742
Credit	0.284	0.267	0.874
Partnership	0.799*	0.330	0.044
_cons	-0.855	1.212	0.060
Number of obs		200	
LR chi2 (12)		31.48	
Prob > chi2		0.001	
Pseudo R2		0.169	

Note: ***, **, and * significant at α 1%, 5%, and 10%.

increases the feasibility and cost-efficiency of adopting biogas systems, as households with more livestock can maximise the benefits of converting waste into energy. Additionally, ownership of a larger number of livestock often reflects higher economic capacity, enabling households to invest in biogas infrastructure (Franco *et al*., 2012; Harrison *et al*., 2021). The dual benefits of improved waste management and reduced reliance on conventional energy sources make biogas an attractive option for households with significant livestock assets. Encouraging these households to adopt biogas not only enhances their energy security but also contributes to broader environmental sustainability goals (Obaideen *et al*., 2022).

Agricultural land ownership status also significantly influences biogas adoption at the 10% level with a coefficient of 0.567. The positive impact of land ownership on adoption decisions highlights the role of asset ownership in supporting investment in technology (Ayanwale *et al*., 2023). Previous studies have shown a positive correlation between land ownership and technology adoption decisions in agriculture and livestock farming (Akram *et al*., 2020). Households that own farmland are often more economically empowered and have greater control over their resources, making it easier to allocate land for biogas infrastructure such as digesters. Land ownership also reflects household economic stability, enabling long-term decisions, including the adoption of biogas technology, which requires initial investments (Hulse & McPherson, 2014). Additionally, landowning households are often more exposed to information and extension programs related to biogas technology, enhancing their understanding of its benefits. Thus, farmland ownership provides a solid foundation for households to adopt biogas in terms of resource readiness and economic capacity.

The membership in farmer groups is another significant factor, with a 1% significance level and a coefficient of 1.363. The positive effect of farmer group membership on biogas adoption emphasises the importance of social networks and collective action in promoting technology adoption. These findings are consistent with previous research on the influence of farmer groups on technology adoption decisions (Ngwira *et al*., 2014; Awotide *et al*., 2016). Households that are part of farmer groups often benefit from access to shared knowledge, resources, and support systems that raise awareness and understanding of biogas technology (Nakano *et al*., 2018). Membership also provides opportunities for farmers to participate in training, extension programs, and demonstrations that highlight the economic, environmental, and practical benefits of biogas systems (Fischer & Qaim, 2014).

Moreover, farmer groups serve as platforms for collective decision-making and risk-sharing, reducing barriers perceived in adopting new technology. Group members are also more likely to receive technical assistance, financial incentives, or subsidies from government or non-government organisations, further encouraging adoption. Strengthening the role of farmer groups and promoting active participation can enhance the dissemination of biogas technology and contribute to broader sustainability goals in rural communities.

Participation in counselling farm programs significantly influences adoption probability at the 5% level with a coefficient of 0.361. This finding aligns with previous research (Okon & Idiong, 2016; Hoque *et al*., 2022). The positive impact of participation in extension services highlights the critical role of education and technical assistance in facilitating technology adoption (Agussabti *et al*., 2022). Households participating in counselling programs gain access to valuable information about the benefits, operation, and maintenance of biogas systems, reducing uncertainty and building confidence in adopting the technology (Han *et al*., 2022). Extension services often bridge the gap between farmers and innovations by providing demonstrations, hands-on training, and practical examples of the economic and environmental advantages of biogas adoption. Moreover, participants are more likely to receive guidance on overcoming barriers such as initial investment costs, technical challenges, and resource management, making adoption more feasible. Expanding access to extension services, especially among non-adopters can significantly enhance the spread of biogas technology and its benefits for household energy security and environmental sustainability.

Finally, market partnership participation positively influences the probability of biogas adoption at 10% significance level with a coefficient of 0.799. Previous studies on marketing partnerships, particularly their benefits in information dissemination and knowledge exchange, support this finding (Wijayanto *et al*., 2022). The positive impact of market partnership participation highlights the role of market integration and economic incentives in driving technological innovation (Getnet *et al*., 2014). Households involved in market partnerships often benefit from better financial stability and broader market access, providing the resources needed to invest in biogas systems. Through these partnerships, farmers are exposed to networks that facilitate information exchange and collaboration, raising awareness of sustainable technologies like biogas (Mwangi & Kariuki, 2015).

Additionally, such partnerships may offer incentives like subsidies or cost-sharing arrangements, reducing the financial burden of adoption. These collaborations also help households recognise the long-term economic benefits of biogas such as cost savings from reduced reliance on conventional energy sources and potential additional income from increased productivity. These results provide a comprehensive discussion of the factors influencing farmers' decisions to adopt biogas technology.

Other variables did not show significant results, a finding that requires more in-depth discussion. For example, age and education level had no significant influence on the decision to adopt biogas. This could be because participatory approaches such as farmer groups and extension programs are more effective at increasing knowledge and awareness of clean and renewable energy use, specifically in the adoption of farm biogas. The findings on the factors influencing biogas adoption are expected to serve as a reference for policymakers. Thus, the government can formulate more targeted and effective national strategies for increasing biogas adoption.

The Impact of Biogas Adoption on Household Food Security in East Java

In this section, the researchers present the results of measuring the impact of biogas adoption on the food security of livestock farming households in East Java, using the Food Insecurity Experience Scale (FIES) as the measurement tool. The Propensity Score Matching (PSM) method was employed to reduce selection bias and ensure more precise results. The detailed findings are presented in Table 3.

In this study, two matching techniques were employed: Nearest Neighbour Matching (NNM) and Kernel-Based Matching (KBM). Table 3 shows that both matching methods indicate that biogas technology positively impacts the food security of livestock farming households in East Java, as measured by the Food Insecurity Experience Scale (FIES). Using the NNM method, the impact was significant at the 10% level with an Average Treatment Effect on the Treated (ATT) of 1.782. Similarly, the KBM method also showed a significant impact at the 10% level with an ATT of 1.978. These results

Table 3: Impact biogas adoption on food security: FIES indicator

Matching Algorithm	Treated	Control	ATT	t-value
Nearest Neighbour Matching (NNM)	165	26	1.782	5.480***
Kernel Based Matching (KBM)	165	35	1.978	8.540***

Note: *** significant at α 1%.

demonstrate that adopting biogas technology positively influences household food security in East Java. The following explanation explores how biogas technology contributes to this positive impact.

The relationship between biogas adoption and household food security is a crucial area of research, particularly in rural contexts where resource limitations are often challenging. Food security, as defined by the FIES, encompasses dimensions of access, availability, and adequacy of food, all of which can be positively influenced by biogas adoption. Using biogas reduces household reliance on traditional energy sources such as firewood or Liquefied Petroleum Gas (LPG), which often involve high costs and labour (Arthur *et al*., 2011; Rahman *et al*., 2014). The reduction in energy burdens allows households to redirect their resources towards acquiring or producing food, alleviating anxiety and uncertainty about food availability, an essential dimension of food security measured by the FIES.

One key dimension of food security is a household's ability to maintain consistent access to sufficient food without having to reduce meal portions or skip meals due to economic constraints (Leroy *et al*., 2015). Biogas adoption can enhance this aspect by lowering household energy expenditures, which in turn allows for a greater budget allocation towards purchasing food. Furthermore, the byproduct of biogas, bio-slurry contributes to increased agricultural productivity as an organic fertiliser, resulting in more efficient and healthier production (Hanani *et al*., 2024). This improvement in crop yields from using bio-slurry helps households achieve a stable and reliable food supply, addressing concerns about the quantity and frequency of food as measured by the Food Insecurity Experience Scale (FIES).

Nutritional adequacy, a critical focus of food security measured by the Food Insecurity Experience Scale (FIES) may also be influenced by biogas adoption. Households that adopt biogas often gain greater economic flexibility, which allows them to consume a more diverse and nutritious diet (Nevzorova & Kutcherov, 2019). Furthermore, the use of bio-slurry in farming activities enhances the quality and availability of fresh, nutrient-rich foods such as vegetables and animal feed, directly supporting better nutritional outcomes (Yadav *et al*., 2023). This improved dietary quality promotes long-term household health and productivity, thereby strengthening household resilience to food insecurity.

Finally, biogas adoption contributes to the sustainability of food availability by reducing economic vulnerabilities that often lead to diminished variety or quantity of food within households. By lowering energy costs and enhancing household productivity, biogas systems enable households to stabilise their food resources (Ekholm *et al*., 2010). Improved health outcomes from reduced exposure to air pollution from traditional energy sources also enhance the physical and economic capacity of households to consistently meet food needs. Overall, biogas adoption addresses multiple dimensions of food security as measured by the FIES, underscoring its potential as a sustainable intervention to improve household welfare in rural areas. These findings highlight the need for policies and programs promoting biogas technology as a pathway to achieve food security and sustainable development goals.

Conclusions

This study demonstrates that biogas technology adoption has a significant positive impact on the food security of livestock farming households in East Java, as measured using the Food Insecurity Experience Scale (FIES). Socioeconomic and demographic factors such as farming experience, livestock ownership, land ownership status, membership in farmer groups, participation in extension programs, and market partnerships were identified as key determinants of biogas adoption decisions. The analysis indicates that farming experience and livestock ownership play critical roles in facilitating the adoption of this technology while membership in farmer groups provides access to information and social support that encourages technology adoption. The use of the Propensity Score Matching (PSM) method confirms that biogas adoption significantly improves food security, as reflected in reduced food insecurity experiences and increased household food availability.

To promote the adoption of biogas, the government and other stakeholders must strengthen their roles in designing and implementing supportive policies, especially those focused on financial and technical support. This includes enhancing extension services and training tailored for smallholder farmers. Policies should also be expanded to improve access to subsidised credit, provide incentives for livestock farmers, and develop communal biogas infrastructure to facilitate large-scale adoption. To ensure the scalability and sustainability of these programs, it is crucial to integrate biogas into national strategies for food security and climate change mitigation through consistent budget allocation and clear regulatory frameworks. In this context, the role of cooperatives is vital; they can act as a bridge between farmers and the market, facilitating collective funding, managing infrastructure, and marketing byproducts like organic fertiliser, thereby creating a sustainable ecosystem that encourages widespread adoption.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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