



Determinants of livestock waste-to-energy adoption among smallholder farmers in East Java, Indonesia

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ABSTRACT

Background: Livestock waste holds significant potential as a renewable energy resource; however, waste management practices among smallholder farmers remain suboptimal. The adoption of waste-to-energy technology is limited, and the behavioral and socioeconomic determinants of this adoption gap are not yet fully understood. This study aims to identify livestock waste management practices, analyze differences in perceptions (energy-adopting and non-adopting farmers), and examine socioeconomic factors associated with biogas adoption. **Methods:** A quantitative cross-sectional survey was conducted in Sidoarjo Regency and Surabaya City, East Java Province, Indonesia. A total of 184 smallholder livestock farmers were selected through proportional random sampling. Data were analyzed using descriptive and comparative statistics, including Mann-Whitney U and Kruskal-Wallis tests to examine group differences in Theory of Planned Behavior (TPB) constructs. **Findings:** Non-energy practices dominate waste management, and the adoption of waste-to-energy technology remains limited. However, attitude scores, intentions, and behavioral control indicate a strong adoption potential. Mann-Whitney U test confirmed statistically significant differences for all four constructs: ATT ($U = 180.5$, $p = .006$), SN ($U = 251.0$, $p = .026$), PBC ($U = 138.5$, $p = .002$), and INT ($U = 242.5$, $p = .022$). Energy adopters consistently scored higher on all constructs, with the largest difference observed in PBC ($\Delta = +1.04$). Fermentation plays a transitional behavioral role toward energy use and is comparable in behavioral readiness to biogas adopters. **Conclusion:** A tiered policy approach based on the adoption ladder is recommended to accelerate renewable energy uptake. **Novelty/Originality of this article:** Although various step-based adoption models have been suggested in the literature, the present study operationalizes the Adoption Ladder based on the constructs of TPB. Fermentation farmers can be considered at a behavioral stage of transition toward adopting biogas, based on empirically comparable attitudinal and intentional profiles relative to biogas adopters. The findings show that attitudes, subjective norms, and behavioral control affect adoption intentions, and fermentation farmers are positioned within a pre-adoption behavioral stage that indicates readiness for transition to biogas adoption.

KEYWORDS: biogas; energy adoption; livestock waste; smallholder farmers; sustainable energy.

1. Introduction

The livestock sector has contributed to food security and economic development (Kitole, 2025). However, this comes at a cost: waste production, which usually comes from animal manure and feed residues. In developing countries, livestock waste is often poorly managed. This often results in environmental problems, such as water and air pollution.

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Feed is an important factor in the environmental footprint and affects human health and ecosystem damage (Fiorilla et al., 2024).

Livestock waste produces methane, which contributes to global warming, whereas livestock feed waste produces CO₂, N₂O, and CH₄ (Maharjan et al., 2021). Among livestock feeds, soybean meal has the highest impact on global warming, producing 1,240 kg CO₂ eq/t; corn follows with 670 kg CO₂ eq/t; and soybean oil is third (Fiorilla et al., 2024). This is a cause for concern because Falcon et al. (2022) predict a 50-60% surge in global food demand between 2019 and 2050. This projected increase will result in a rise in the demand for livestock and the subsequent generation of waste (Henchion et al., 2021), indicating an increase in animal food products from 1.4 billion tons to around 2.0 billion tons. The increasing demand for animal-based food intensifies livestock production and subsequently increases methane emissions (Aljehani et al., 2026).

Livestock waste impacts water, soil, air, and biodiversity, creating an environmental problem. However, livestock waste can be developed as a renewable energy source. Farmers' awareness of the potential to process cow manure into bioethanol and biogas remains limited (Arianti et al., 2024). Optimal waste management, starting from the collection, disposal, processing, and utilization of waste (Nair et al., 2026), is necessary to achieve sustainability. Although livestock waste is an important renewable energy resource for environmental sustainability, it is not well managed, particularly in developing countries. These countries generally consist of small farms with low waste production (Roubik & Mazancova, 2020). These structural conditions create challenges for smallholder farmers to scale waste-to-energy technologies.

Rising energy demands require environmentally friendly energy sources. One possible source of renewable energy that has not been used to its full potential is livestock waste. It can be processed through anaerobic digestion to produce biogas (Bist et al., 2024). Anaerobic digestion converts organic waste into methane-rich biogas that can be used as an alternative energy source. Using this resource can minimize environmental problems caused by livestock waste, such as reducing greenhouse gas emissions that contribute to global warming. Using livestock waste can also contribute to energy security and support sustainable development. Indonesia has great potential for developing bioenergy from livestock manure (Asih et al., 2025). This potential includes electricity generation and emission reduction through the conversion of livestock waste into biogas via methane fermentation processes (Bedru et al., 2026).

Livestock manure is generally considered a circular solution (Magnolo et al., 2024). It produces renewable biomethane energy, thereby reducing emissions. (Perera et al., 2024) compared the emissions of different livestock, finding that cattle farming produces the highest amount and intensity of emissions per kilogram of product compared to other animals. Furthermore, greater emissions are produced when livestock manure is stored in liquid systems, such as ponds. Several studies have reported the significant potential of sustainable energy use. According to Linh et al. (2026), livestock waste management can generate 7,300 m³ of biogas-based energy production. The potential for waste management to reach 2,267.72 m³ for energy development in Muna Regency, Indonesia, has been identified (Munadi et al., 2025). Central Java, East Java, NTT, and NTB in Indonesia have the greatest potential for using cattle manure waste.

Waste management products can contribute 1.07 million MWh of electricity for biogas, which can mitigate climate change through bioenergy (Asih et al., 2025). The study's baseline scenario concluded that using biogas could reduce carbon emissions by 52% and save up to IDR 40.3 trillion in the state's energy subsidy budget (Kusmiyati et al., 2023). The process of turning waste into biogas creates a liquid called 'biogas slurry'. This slurry can be used as a fertilizer. This increases the income of farmers and improves their economic situation.

The Canary Islands have significant potential to produce renewable energy from waste given their continuous increase in waste production. Comprehensive waste use is estimated to generate up to 12.86 GWh of energy, equivalent to approximately 20% of the total energy consumption of the industrial sector. Furthermore, this strategy has the potential to reduce

greenhouse gas emissions by up to 5.88 Gg CO₂ equivalent, according to (Perez-remedios et al., 2024).

Processing livestock waste into renewable energy, such as biogas, is a promising management strategy for achieving energy security, environmental health, and supporting sustainable development. Furthermore, by reducing energy costs and producing organic fertilizer from digestate, this utilization can provide economic added value for farmers, creating dual benefits for the environment and rural community welfare. This discussion emphasizes the potential of livestock waste as a renewable energy source.

Even though livestock waste possesses tremendous potential as an alternative energy source, its management remains limited in practice. It is usually managed only through simple methods, such as composting. In some cases, many farmers improperly dispose of it, significantly contributing to environmental pollution.

Some of the waste in Karanganyar is not managed properly, with only two out of seven farms processing it into organic fertilizer (Arianti et al., 2024). The rest is either collected and disposed of in the local drainage system or taken by other parties to be used as fertilizer. Only 21.05% of the livestock waste is used as fertilizer, and a waste management system integrating pig farming and rice cultivation has been implemented to minimize waste and reduce environmental pollution (Linh et al., 2026). Pig farm waste is processed into fertilizer that can be used later to optimize rice cultivation.

Research on livestock waste-to-energy systems has primarily focused on technical aspects and environmental benefits, while the behavioural dimension of farmers has received less attention. (Linh et al., 2026) discussed the practice of recycling waste for use as agricultural fertilizer. Some studies have also explored environmental control technologies and resource efficiency approaches within livestock systems, although these remain largely separate from behavioral adoption analysis (Perera et al., 2024).

Shaibur et al., (2025) conducted research on using cow manure, focusing on assessing economic benefits and social acceptance. The sustainable development index in dairy cow management in Bangladesh is 0.73. The findings also suggest that livestock waste use can generate economic value while improving environmental performance. Sustainable livestock waste management can be achieved through the production of biogas and fertilizer.

Nevertheless, transitioning from waste management to energy use depends on more than just the availability of technology; it also depends on each individual's willingness to participate. Perceptions, behavioral intentions, and socioeconomic capacity of farmers are important determinants of adoption decisions. Understanding why farmers continue to rely on non-energy waste management practices is essential for accelerating the livestock industry's energy transition.

This study aims to identify popular livestock waste management technologies among farmers, analyze differences in their perceptions of adopting these technologies, and examine the relationship between waste management practices and behavioral intentions of farmers. Additionally, the study will analyze socioeconomic factors in the adoption of energy.

The gap between the high potential of livestock waste as a renewable energy source and its limited adoption, particularly among smallholder farmers, remains poorly understood from a behavioral perspective. This study is guided by the following research questions: (1) What livestock waste management practices are most prevalent among smallholder farmers in the study area? (2) Are there significant differences between energy-adopting and non-adopting farmers in attitude, subjective norm, perceived behavioral control, and intention? (3) What socioeconomic factors are associated with the adoption of livestock waste-to-energy technology?

Although the TAM and UTAUT are proven frameworks that have been extensively used in adoption research, they were developed with the ICT adoption situation in mind and neither of them incorporates social norms and PBC as individual constructs. TPB is chosen because its fundamental constructs of attitude, subjective norm, perceived behavioural control, and intention are directly correlated with the factors that determine the decision

process in the context of smallholder agriculture, where community influence and resource availability act as critical adoption determinants (Ajzen, 1991; Hagger & Hamilton, 2025). Therefore, the selection of a TPB is based on its conceptual fit with the behavioral and contextual factors shaping the adoption of technology among smallholder farmers.

Drawing upon the TPB theory, the current paper employs the notion of an “Adoption Ladder” to understand technology adoption as a continuous process. Although various step-based approaches for technology adoption have already been discussed within renewable energy studies (Caffaro et al., 2025; Mulugeta & Leta, 2022; Putra et al., 2019), the present study provides an empirical operationalization of the concept based on the results of the TPB construct analysis for smallholder livestock farmers in Indonesia. Rather than considering either adopters or non-adopters, this approach allows observation of intermediate steps in adoption when, for instance, fermentation may represent an intermediate stage characterized by behavioral profiles comparable to those of biogas adopters. The adoption ladder perspective demonstrates that technology adoption is a gradual process of increasing awareness, intention, and perceived control. It also highlights that behavioural preparedness depends not only on the psychological aspects of the individual but also on socioeconomic and contextual conditions. Additionally, this research contributes to the body of literature on community-based environmental governance and sustainability transition by highlighting the significance of stage-wise and contextual policy interventions for enhancing the adoption of livestock waste-to-energy technologies.

2. Methods

This study uses a quantitative approach with a cross-sectional survey design to analyze livestock waste management practices, the level of adoption of livestock waste utilization as an energy source, and the factors that distinguish energy-adopting and non-adopting farmers. A cross-sectional design was chosen because it effectively captures respondents' actual conditions, perceptions, and practices at a specific point in time (Fabricant, 2024; Harland & Heller, 2025; Ziauddin et al., 2023), particularly in the context of early-stage technology adoption. This approach is useful for examining the differences between non-energy-based waste management and energy utilization in the smallholder livestock sector without inferring long-term causal relationships, which typically require a higher level of adoption maturity and behavioral stability.

In this study, “smallholder farmers” refer to household-based livestock farmers who own a limited number of animals, manage operations primarily with family labor, and have limited access to capital, technology, and institutional support (Lowder et al., 2016). The sample size of 184 respondents was determined using proportional random sampling based on the registered population of smallholder livestock farmers in both study locations. The sample size was determined using the formula proposed by Yamane (1967), with a margin of error of 5% and a confidence level of 95%, yielding a minimum required sample of 178 respondents. The final sample of 184 was collected to account for potential non-response and ensure adequate representativeness across the study sites.

The TPB constructs were measured using survey items adapted from Ajzen (1991) and prior agricultural adoption studies. Attitude (ATT) was measured with 4 items (e.g., “Converting livestock waste into biogas is a good idea”), subjective norm (SN) with 3 items (e.g., “People important to me think I should use biogas technology”), perceived behavioral control (PBC) with 4 items (e.g., “I am capable of implementing waste-to-energy technology on my farm”), and intention (INT) with 3 items (e.g., “I intend to adopt biogas technology in the next 12 months”). Internal consistency reliability was confirmed for all constructs: ATT ($\alpha = 0.7234$), SN ($\alpha = 0.8401$), PBC ($\alpha = 0.8702$), INT ($\alpha = 0.7952$). All constructs exceeded the recommended reliability threshold of $\alpha = 0.70$ (Nunnally, 1978).

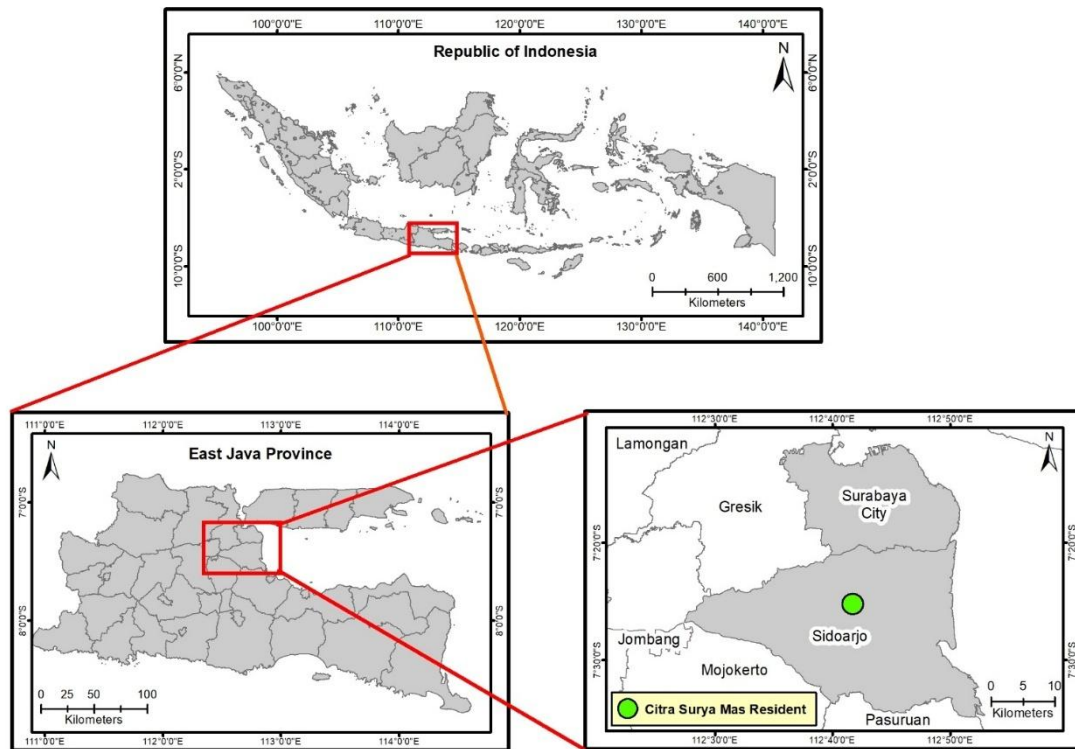


Fig. 1. Research location

The study was conducted in Sidoarjo Regency and Surabaya City in East Java Province, Indonesia. This region is a combination of peri-urban and rural areas, where smallholder livestock activities are common and substantial quantities of livestock waste are generated. However, it remains underutilized as a renewable energy resource (Susilo et al., 2025; Umilia & Saptarini, 2019). All survey instruments were administered by trained enumerators from January to March 2024. The study participants were small- to medium-scale smallholder farmers who raised cattle, goats, or sheep.

Data were collected through a survey consisting of a three-part questionnaire. The first section contained questions about the socioeconomic characteristics of the farmers, including their age, level of education, farming experience, number of livestock, feed costs, distance from the administrative centers, and access to production resources. The second section measured perception and intention variables adapted from the TPB framework. These variables included attitude (ATT), subjective norm (SN), perceived behavioral control (PBC), and intention (INT) to process livestock waste into energy (Hagger & Hamilton, 2025). The third part consisted of open-ended questions related to livestock waste management practices, which were designed to capture variations in field practices without limiting respondents' answers to specific categories.

Perception variables were measured using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). The score for each TPB construct was calculated as the average of its constituent items. Open-ended responses regarding waste management practices were analyzed and coded manually using keyword-based content analysis to classify the data into four main categories: (1) utilization as fertilizer/compost, (2) fermentation-based processing, (3) energy-based utilization (biogas), and (4) conventional practices. Then, the energy adoption variable was constructed as a binary variable, with a value of 1 for biogas adopters and 0 for non-adopters.

Data were analyzed using descriptive and comparative methods. Descriptive analysis described the distribution of waste management practices and energy adoption rates, and comparative analysis compared the socio-economic characteristics and perception scores of the adopter and non-adopter groups. This type of analysis is most appropriate for the

context of technology adoption in the early stages when structural barriers, socioeconomic variability, and contextual factors are dominant (Agaton & Santos, 2025; Ferdoush et al., 2024; Khanal et al., 2024; Susilo et al., 2025). Descriptive analysis allows for an in-depth understanding of the local conditions and perceptions of farmers. Comparative analysis helps identify differences in adoption behavior and associated factors between adopter and non-adopter groups (Agaton & Santos, 2025; Gyimah et al., 2025; Khanal et al., 2024; Rahman et al., 2025). The limited number of biogas adopters reflects the early stage of technology diffusion in the study area and should not be interpreted as a sampling bias but rather as an empirical characteristic of the population.

3. Results and Discussion

3.1 Livestock waste management practices

Effective management of livestock waste is essential for sustainable farming practices because it reduces greenhouse gas emissions, particularly methane produced from the decomposition of organic waste. The adoption of livestock waste management technologies provides insight into farmers' readiness to utilize waste more productively while supporting environmental sustainability. Therefore, identifying the waste management practices used and the characteristics of the respondents' farming experience is necessary to provide an initial overview of technology adoption patterns among farmers. Table 1 presents the distribution of respondents based on the type of livestock waste management technology used and average farming experience.

Table 1. Livestock Waste Management Practices

| Waste management technology | Number of respondents | Average farming experience (Years) |
|-----------------------------|-----------------------|------------------------------------|
| Fertilizer/Compost | 144 | 23 |
| Simple Fermentation | 19 | 23 |
| Biogas/Energy | 6 | 25 |
| Landfilling/Conventional | 15 | 19 |

The findings indicate that fertilizer and compost production are the dominant livestock waste management practices among respondents, accounting for 144 of the 184 surveyed farmers. These practices are relatively easy to implement and contribute to nutrient recycling and improved soil quality. However, composting requires consistent temperature, moisture, and aeration management, which can be challenging for smallholder farmers (Modderman, 2020). In contrast, the use of waste as an energy source, particularly biogas, in fermentation-based practices remains limited. Only a small proportion of respondents have adopted biogas technology, whereas conventional practices, such as stockpiling or disposing of waste, remain common. These findings align with studies in other developing countries showing low levels of adoption of biogas in farming households despite its high technical potential (Marie et al., 2021).

An important finding is the relatively larger number of farmers using fermentation-based practices ($n = 19$) than those adopting biogas technology ($n = 6$). This suggests the existence of an intermediate stage between conventional waste management and energy-oriented utilization, supporting the notion that adoption may occur gradually rather than through an immediate transition to biogas technology.

The use of composting suggests that most livestock waste is already managed in a way that can greatly reduce emissions compared to unprocessed waste. Research indicates that composting livestock excrement decreases methane discharges by as much as 98.18% compared with fresh excrement (Pertiwinigrum et al., 2020), whereas composting goat excrement with the incorporation of decomposers can diminish emissions by approximately 45% (Puastuti et al., 2021). However, unlike livestock waste management through biogas technology, which captures methane and converts it into energy with

economic value, composting does not produce renewable energy that can be used directly. Therefore, while biogas can contribute substantially to emission reduction, it offers the additional benefit of energy production. These findings suggest that composting and biogas technologies may provide complementary environmental and economic benefits in livestock waste management.

No major differences in farming experience were found between farmers who adopted energy technology and those who did not. This suggests that farming experience alone may not adequately explain differences in energy technology adoption among respondents. However, research shows that farming experience can influence the adoption of livestock technologies, indicating an inverse U-shaped relationship, whereby experience is useful in the early stages of adoption, but not later on (Ainembabazi & Mugisha, 2014). This implies that, while experience may initially help with adopting new technologies, it is not the only determining factor in the long run. Another study found that experienced farmers were more open to adopting biodigester technology (Bonokwane & Ololade, 2022). Nevertheless, experience is not the sole factor; other considerations, such as financial constraints, also influence adoption. Cost, infrastructure, market access, and labour management are also important factors that influence the adoption of appropriate farming technologies (Akinyemi et al., 2024; Mallinger et al., 2025).

3.2 Characteristics of respondents who adopt waste energy

In addition to general waste management practices, the extent to which livestock waste has been utilized as a renewable energy source by farmers must be reviewed. Table 2 presents the distribution of respondents based on the adoption of livestock waste utilization as an energy source.

Table 2. Livestock waste management practices

| Waste energy adoption | Men | Women | Total | Percentage (%) |
|-----------------------|-----|-------|-------|----------------|
| Non-Energy | 96 | 82 | 178 | 96.7 |
| Energy (Biogas) | 5 | 1 | 6 | 3.3 |
| Total | 101 | 83 | 184 | 100 |

Table 2 shows that male farmers represent a slightly larger proportion of respondents in both the energy adopter and non-adopter groups. This finding aligns with prior research indicating that men are more engaged in waste management and livestock technology activities (García-Agüero et al., 2024; Wang & Tao, 2020). Furthermore, the respondents' main occupations were analyzed to determine the extent to which farming contributed to energy adoption. The results are shown in Table 3.

Table 3. Characteristics of respondents who adopt waste energy

| Group | Gender | Entrepreneur | Farmer | Private Employee | Others | Total |
|-------|--------|--------------|--------|------------------|--------|-------|
| 0 | Men | 14 | 30 | 3 | 49 | 96 |
| 0 | Women | 0 | 28 | 1 | 41 | 70 |
| 1 | Men | 0 | 1 | 0 | 0 | 1 |
| 1 | Women | 12 | 4 | 0 | 1 | 17 |

Table 3 shows that the most dominant occupation in the majority group (non-energy) is in the 'Other' category, followed by 'Farmer'. This pattern is consistent between male and female respondents. In the small group that has adopted waste energy, the respondents are predominantly farmers. This pattern suggests that biogas adoption is more frequently observed among respondents whose primary livelihood is directly related to livestock production. However, farmers whose main occupation is outside of farming tend to be less

likely to adopt biogas systems due to the higher costs and lower perceived usefulness of the technology (Guntoro et al., 2024).

The “Other” category in main occupation refers to respondents engaged in non-agricultural activities as their primary livelihood, including trade/retail, civil service, construction work, and informal employment. Individuals who maintain livestock farming as a secondary or supplementary income source. One possible explanation is that farmers have more direct access to livestock waste, which is the primary feedstock for biogas production. This may reduce practical barriers to implementation and make waste-to-energy technologies more relevant to farming activities.

3.3 Differences in perception between energy adopters and non-adopters

A comparative analysis was conducted on the main constructs in the TPB to understand the differences in TPB-related perceptions and intentions between farmers who have adopted and those who have not adopted the use of livestock waste as energy. These constructs include attitude (ATT), subjective norm (SN), perceived behavioural control (PBC), and intention (INT). Table 4 below presents a comparison of the average scores for each construct between the adopter and non-adopter groups.

Table 4. Practices comparison of perceptions between livestock farmers who adopt waste energy and those who do not

| Waste energy adoption | ATT | SN | PBC | INT |
|------------------------|---------|--------|---------|--------|
| Non-Energy | 3.7 | 3.6 | 3.5 | 3.7 |
| Energy (Biogas) | 4.2 | 4.3 | 4.5 | 4.4 |
| Mann-Whitney U | 180.5 | 251.0 | 138.5 | 242.5 |
| p-value | 0.006** | 0.026* | 0.002** | 0.022* |
| Mean Diff (Δ) | +0.55 | +0.78 | +1.04 | +0.75 |

Note: ATT = Attitude; SN = Subjective Norm; PBC = Perceived Behavioral Control; INT = Intention. Scores are means on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). Statistical test: Mann-Whitney U (two-tailed). * $p < .05$. ** $p < .01$.

Table 4 shows consistent differences between farmers who and do not adopt waste energy in all TPB constructs. The average scores for ATT, SN, PBC, and INT were higher in the biogas adopter group than in the non-energy group. The most notable difference was seen in the PBC construct, indicating that adopters feel they have a greater ability and control to implement waste-to-energy technology.

These findings suggest that positive attitudes, supportive social norms, and stronger perceived behavioral control are associated with waste-to-en adoption and higher adoption intentions. The large difference in PBC highlights the importance of farmers' confidence in their ability to operate and manage the technology. These findings are consistent with previous studies showing that positive attitudes and high control perceptions are the main determinants of the intention to adopt agricultural and environmental technologies (Dey et al., 2025; Dong et al., 2022; Laksono et al., 2022; Nordin et al., 2023; Wang et al., 2024).

Mann-Whitney U tests were conducted to compare TPB construct scores between energy-adopting ($n = 6$) and non-adopting ($n = 178$) farmers. Statistically significant differences were found for all four constructs: ATT ($U = 180.5$, $p = 0.006$), SN ($U = 251.0$, $p = 0.026$), PBC ($U = 138.5$, $p = 0.002$), and INT ($U = 242.5$, $p = 0.022$). Energy adopters consistently scored higher on all constructs, with the largest difference observed in PBC ($\Delta = +1.04$), suggesting that PBC may represent an important distinguishing characteristic between adopters and non-adopters. These results are consistent with studies showing that positive attitudes and high control perceptions are the main determinants of agricultural technology adoption intention (Dey et al., 2025; Dong et al., 2022).

3.4 Fermentation as a transition stage towards energy

In addition to comparing energy adopters and non-adopters, this study further examines how variations in livestock waste management technologies are related to differences in farmers' TPB construct scores related to waste utilization. This analysis provides an overview of whether certain waste management practices can serve as a transition stage toward energy-based waste utilization. Table 5 presents a comparison of ATT, SN, PBC, and INT scores for various livestock waste management technologies.

Table 5. TPB construct scores by waste management technology group and kruskal-wallis test results

| Waste management technology | ATT | SN | PBC | INT | n | % |
|-----------------------------|------------|------------|------------|------------|------|------|
| Fertilizer/Compost | 3.7 | 3.5 | 3.4 | 3.7 | 144 | 78.3 |
| Simple Fermentation | 4.2 | 4.3 | 4.0 | 4.4 | 19 | 10.3 |
| Biogas/Energy | 4.2 | 4.3 | 4.5 | 4.4 | 6 | 3.3 |
| Landfilling/Conventional | 3.3 | 3.6 | 3.3 | 3.0 | 15 | 8.2 |
| Kruskal-Wallis H | 31.465 | 19.455 | 18.508 | 30.218 | df=3 | - |
| p-value | < 0.001*** | < 0.001*** | < 0.001*** | < 0.001*** | - | - |

Note: ATT = Attitude; SN = Subjective Norm; PBC = Perceived Behavioral Control; INT = Intention. Scores are means on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree).

Table 5 shows the variations in the attitudes and intentions of farmers based on the waste management technology used. Farmers who implement simple fermentation and biogas have relatively similar and higher attitude and intention scores than those who do not. These scores are compared with other management technologies. This indicates that both practices are associated with greater readiness to productively use waste. Conversely, conventional practices, such as landfilling, have the lowest attitude and intention scores, reflecting a low orientation toward waste use.

Interestingly, the ATT and INT scores, which are similar to the biogas scores, indicate that fermentation may represent a transitional stage toward adopting waste energy technology rather than just a non-energy practice. Farmers practicing simple fermentation reported similar ATT and INT scores to those observed among biogas adopters. These results align with the concept of the "Adoption Ladder" in renewable energy (Caffaro et al., 2025; Mulugeta & Leta, 2022), which posits that technology adoption is a gradual process rather than a single leap. Simple fermentation practices can be identified as a potential 'Intermediate Step' or a crucial transitional stage. The literature emphasizes that integrating effective waste management systems strongly predicts the feasibility of biogas adoption (Wang et al. (2021). Therefore, the high level of intent among the fermentation group suggests that they may be more receptive to adopting biogas technology than farmers relying on conventional waste management practices. In contrast, the conventional group may represent the earliest stage of the adoption ladder, as reflected by their lower ATT, SN, PBC, and INT scores.

Kruskal-Wallis tests revealed statistically significant differences across the four waste management technology groups for all TPB constructs: ATT ($H = 31.465$, $p < 0.001$), SN ($H = 19.455$, $p < 0.001$), PBC ($H = 18.508$, $p < 0.001$), and INT ($H = 30.218$, $p < 0.001$). Post-hoc Mann-Whitney U comparisons between the fermentation and biogas groups showed no significant differences in any construct (all $p > .05$), supporting the transitional positioning of fermentation as an intermediary stage in the Adoption Ladder.

Farmers in the fermentation stage can be conceptualized as a transitional group whose behavioral characteristics are more closely aligned with biogas adopters than with conventional waste management practices. Their relatively high ATT, SN, PBC, and INT scores suggest greater receptiveness to WT technologies and indicate their potential relevance as a target group for biogas promotion programs.

Given their similar attitudes and intentions, further analysis was conducted on the PBC and SN of the fermentation and biogas management groups (Table 6).

The typology of the adoption ladder based on structural features is as follows: (i) the traditional cluster (landfills) corresponds to the pre-contemplation level and has the lowest ATT and INT levels with no presence of environmentally responsible norms; (ii) the fertilizer/composting cluster denotes a basic level of participation and medium levels of attitudes and norms but lacks any energy orientation; (iii) the fermentation cluster signifies an empirically supported transition level, having social and attitudinal proximity to biogas adopters with a PBC difference of 0.54 points, which is worth exploring further but statistically insignificant ($p = 0.267$, $n = 6$); and (iv) the biogas cluster stands at the advanced level. Such a typology is consistent with stepwise adoption models described in the literature on renewable energy, as the intermediate behaviors have been found to come before technology adoption (Caffaro et al., 2025; Mulugeta & Leta, 2022). Table 6 presents the post hoc comparison between the fermentation and biogas groups across all four TPB constructs.

Table 6. Post-Hoc comparison: Simple fermentation vs. biogas/energy group (All TPB Constructs)

| Waste management technology | ATT | SN | PBC | INT |
|-----------------------------|----------|----------|----------|----------|
| Simple fermentation | 4.2 | 4.3 | 4.0 | 4.4 |
| Biogas/energy | 4.2 | 4.3 | 4.5 | 4.4 |
| Mann-Whitney U | 51.0 | 56.0 | 39.5 | 55.0 |
| p-value | 0.718 ns | 0.974 ns | 0.267 ns | 0.920 ns |

Note: ATT = Attitude; SN = Subjective Norm; PBC = Perceived Behavioral Control; INT = Intention. Scores are means on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). Statistical test: Mann-Whitney U (two-tailed, post-hoc). ns = not significant ($p > .05$)

Based on Table 6, the post hoc Mann-Whitney U test showed no statistically significant difference in all TPB constructs between the simple fermentation and biogas groups (all $p > 0.05$). The most important finding here is that the PBC scores for both the fermentation group and the biogas adopters (4.0 and 4.5, respectively) are statistically similar ($p = 0.267$). These results suggest that farmers practicing simple fermentation exhibit behavioral characteristics similar to those of biogas adopters.

Although a descriptive difference of 0.50 in PBC was observed between the fermentation and biogas groups, this difference was not statistically significant ($p = 0.267$). Nevertheless, it may still provide useful exploratory insights. From an exploratory standpoint, this small numeric difference suggests that despite already possessing the requisite environmental attitude (ATT = 4.2) and social encouragement (SN = 4.3), fermentation farmers have some operational reluctance in regard to biogas equipment installation and maintenance compared with more experienced farmers (Shallo et al., 2020; Yun & Lee, 2015). Consequently, fermentation can be considered a good intermediary “behavioral incubator” along the stepwise adoption process (Caffaro et al., 2025; Mulugeta & Leta, 2022; Putra et al., 2019). Being in this intermediary position, farmers’ psychological condition makes them ready to adopt renewable energy sources, primarily requiring targeted technical assistance to fully adopt the technology (Ali et al., 2022; Ali et al., 2023; Rana et al., 2025).

3.5 Socio-economic characteristics and adoption of energy

Table 7 provides an overview of socio-economic profiles, such as livestock ownership and geographical location, which are commonly associated with farmers’ ability to adopt energy technologies. Energy adopters tend to operate farms with larger livestock and higher feed costs. These findings align with the literature indicating that larger-scale farms can more easily absorb the initial investment costs of energy technologies and benefit from economies of scale (Palma-Molina et al., 2023; Pan et al., 2021; Shimahata et al., 2020). For example, a study in China showed that large-scale dairy farms have higher adoption rates of livestock manure utilization technologies and better environmental performance (Liu et al., 2023). Energy adopters often face higher feed costs. This pattern may reflect the larger

scale of livestock operations among adopters, which generally requires greater feed inputs and operational expenditures. High initial investment costs, infrastructure requirements, and operational complexity (Atsbeha et al., 2020; Brown et al., 2020), which are often beyond the reach of smallholder farmers, remain the primary barriers to the adoption of waste-to-energy technologies (Mallinger et al., 2025; Welsh et al., 2019). The complexity and cost of implementing this technology can deter smaller farms, which may not have the same access to capital or technical expertise (Mallinger et al., 2025; Palma-Molina et al., 2023). The following, Table 7 provides an overview of socio-economic profiles, such as livestock ownership and geographical location, which are commonly associated with farmers' ability to adopt energy technologies.

Table 7. Socio-economic characteristics and energy adoption among farmers

| Waste energy adoption | Number of respondents | Average Number of livestock (heads) | Average cost of feed (Rp/day) | Average age of farmers (years) | Average distance from home to city/district (km) |
|-----------------------|-----------------------|-------------------------------------|-------------------------------|--------------------------------|--|
| Non-energy | 178 | 4 | 21659 | 53 | 24 |
| Energy (biogas) | 6 | 12 | 24167 | 51 | 34 |

Remarkably, the energy users in the current study lived farther away from the cities on average (34 km compared to 24 km). Although this is described purely as an exploratory observation, it cannot be presented as an established finding due to methodological constraints (Gebretsadik et al., 2025; Shallo et al., 2020; Skvortsov, 2023). The findings should be interpreted cautiously given the very small number of biogas adopters ($n = 6$) and the absence of statistical testing.

Furthermore, distance from the city is likely to correlate with other variables. Notably, energy users own significantly more livestock (12 compared to 4 animals), implying that the availability of resources may play a greater role in adoption than geographical remoteness. As an exploratory observation, this trend aligns with research indicating that households distant from traditional energy sources (e.g., firewood, LPG) are more likely to opt for alternative energy because of urgent needs (Chekol et al., 2022; Shallo et al., 2020). However, future studies using larger samples and multivariate approaches are needed to determine whether distance independently contributes to adoption decisions. Beyond land factors, the average livestock ownership of 12 heads among adopters, compared to four heads among non-adopters, is consistent with the importance of resource availability in the adoption of livestock technologies (Ngcobo et al., 2022). Previous studies have confirmed that the availability of resources, such as livestock ownership and larger land area, is positively correlated with increased opportunities for the adoption of biogas technology. Larger livestock operations may provide farmers with greater financial flexibility to absorb the investment costs associated with renewable energy technologies. For small farmers, risk aversion is a major barrier to adopting new technologies. Conversely, farmers who are more willing to experiment with new technologies may be more likely to adopt renewable energy solutions. Furthermore, larger business scales allow farmers to absorb initial investment costs and achieve technical efficiency. Empirical findings show that renewable energy adopters on large-scale farms can achieve up to 10% higher technical efficiencies than non-adopters, making biogas investment a strategic step for long-term business sustainability (Wang et al., 2023).

These findings emphasize the crucial role of institutional support and policy interventions in ensuring equitable access to renewable energy technologies among smallholder farmers. Access to these technologies is shaped not only by individual economic and technical factors but also by the broader institutional environment that influences the availability, affordability, and awareness of these technologies.

In addition, the findings from the TPB analysis suggest that social norms may play an important role in shaping adoption intentions. Previous studies have also highlighted the contribution of peer networks and institutional support in facilitating technology adoption. Within farming communities, information exchange and trust in peers and local institutions often play a key role in shaping perceptions and encouraging the adoption of new technologies. Overall, this demonstrates that technology adoption is not merely a technical or economic process, but a socio-institutional process that is deeply embedded in local contexts, where social, institutional, and environmental factors influence decision-making.

The Adoption Ladder paradigm is employed in this study, where TPB factors are used to demonstrate that the adoption process of biogas involves incremental behavioral steps rather than a single discrete adoption decision. This paradigm, combined with TPB variables, shows that farmers' attitudes, subjective norms, and perceived behavioral control are associated with their behavioral positioning across these stages, where fermentation farmers are found to be statistically similar to biogas adopters in ATT, SN, PBC, and INT. These findings suggest that targeted policy and institutional interventions are necessary to support farmers across different stages of technology adoption. In particular, farmers who can be described as "mental incubators" function as informal change agents in the diffusion of agricultural technologies, contributing to broader shifts in community perceptions toward waste-to-energy adoption.

4. Conclusions

The findings of this study indicate that livestock waste management among smallholder farmers is predominantly characterized by non-energy practices, such as composting and using livestock waste as fertilizer. The adoption of waste-to-energy technologies remains minimal. However, the higher scores that energy adopters received in the areas of attitude, intention, and behavioral control indicate substantial potential for expanding the use of energy from livestock waste. This study has several limitations. First, the cross-sectional design captures a static snapshot of adoption behavior and cannot establish causal relationships or temporal trends. Second, the study is limited to two adjacent locations in East Java, which may restrict the generalizability to other regions of Indonesia with different agro-ecological and socioeconomic contexts. Third, the small number of biogas adopters ($n = 6$) restricts the statistical power of group comparisons. Future research should employ longitudinal designs to track adoption transitions over time, expand sampling to multiple provinces with diverse farm scales, and include larger samples of biogas adopters to enable more robust inferential analyses. Of particular methodological note, the cross-sectional design is inherently unable to capture the temporal dynamics of adoption behavior—specifically, it cannot determine whether farmers currently in the fermentation stage will transition to biogas adoption or what triggers that transition over time. Therefore, longitudinal follow-up studies are a critical direction for future research.

A key finding is that fermentation acts as a transitional stage toward energy use with a behavioral readiness level similar to that of biogas adopters. The remaining structural challenges to transitioning to biogas include limitations in investment, infrastructure, and institutional support. Based on the findings of this Adoption Ladder, a uniform policy approach may be less effective than stage-specific interventions. A tiered policy approach is required. First, for the conventional group, interventions should focus on awareness campaigns that change perceptions of waste from a "problem" to a "resource," for example, by providing simple composting training. Second, for the transition (fermentation) group, which has high intentions but may still face practical implementation challenges despite relatively high PBC scores, interventions should focus on technical facilitation rather than socialization. The fermentation group may represent a promising target for biogas promotion programs and technical assistance initiatives given their behavioral similarity to biogas adopters. Shifting from conventional disposal practices to energy-based processing can reduce methane emissions from livestock manure, a major source of greenhouse gases in the livestock sector.

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Author Contribution

Conceptualization, E.F. and F.M.; Methodology, F.M.; Software, F.M.; Validation, E.F., F.M. and R.S.; Formal Analysis, F.M.; Investigation, F.M. and R.S.; Resources, R.S.; Data Curation, F.M.; Writing – Original Draft Preparation, F.M.; Writing – Review & Editing, E.F.; Visualization, F.M.; Supervision, E.F.; Project Administration, R.S.; and Funding Acquisition, E.F. All authors have read and agreed to the published version of the manuscript.

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Ethical Review Board Statement

Ethical review and approval were waived for this study because it involved anonymous survey responses regarding agricultural practices, posed minimal risk to participants, and no sensitive personal or health data were collected.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

Not available.

Conflicts of Interest

The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Declaration of Generative AI Use

During the preparation of this work, the author(s) used Grammarly to assist in improving the grammar, clarity, and academic tone of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and took full responsibility for the publication's content.

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