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Environmental Assessment of Community Readiness for Cattle Waste Management as Needs as an Energy Transition to Climate Change

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Abstract

The adoption of biogas technology in smallholder livestock systems is increasingly recognized as a dual solution for rural energy transition and livestock waste management; however, actual implementation remains limited due to low community readiness, particularly driven by knowledge gaps and resource constraints. This study examines the determinants of community readiness for biogas adoption in rural Indonesia, addressing the limited attention of prior studies to readiness factors at the household level. A cross-sectional survey of 98 smallholder cattle farmers was conducted using structured questionnaires, and the data were analyzed using descriptive statistics and multiple linear regression to identify key determinants of readiness. The results indicate generally positive perceptions toward biogas, with knowledge, prior waste processing experience, perception scores, education level, and herd size significantly influencing readiness ($p < 0.05$). While awareness of biogas benefits and willingness to process manure emerged as key drivers, limited technical knowledge and time and cost constraints remained major barriers, suggesting an awareness–adoption gap. These findings align with behavioral adoption frameworks, highlighting the roles of knowledge, perceived benefits, and enabling conditions in shaping adoption readiness. Policy interventions emphasizing capacity-building, financial incentives, and adaptable biogas technologies are therefore essential to support rural adoption.

Keywords: biogas adoption; environment assessment; climate change; energy transition; livestock

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1. Introduction

Rural livestock systems in the Global South are increasingly recognized as significant contributors to greenhouse gas emissions, while also offering strategic opportunities for climate change mitigation. Cattle and other ruminant manures emit substantial methane and nitrous oxide when managed through open dumping or unmanaged storage, contributing considerably to agricultural emissions. Although agriculture and livestock mitigation are increasingly incorporated into national climate commitments, many targets remain insufficiently operationalized at the sectoral and household levels, limiting their effectiveness [1].

At the same time, livestock manure represents a valuable resource that can be converted into biogas and organic fertilizer through anaerobic digestion, reducing fugitive emissions while displacing fossil-based energy and synthetic fertilizers [2,3]. Reflecting this dual role, recent assessments of nationally determined contributions (NDCs) identify improved livestock manure management as a priority and cost-effective mitigation pathway, particularly in countries dominated by smallholder cattle production systems [4].

At the household level, manure-based biogas has been promoted as a decentralized clean energy option addressing energy access, waste management, and environmental health. Biogas systems can reduce reliance on traditional biomass and liquefied petroleum gas (LPG) while improving indoor air quality. However, household energy transitions in the Global South remain incomplete, as biogas adoption continues to face behavioral, institutional, and affordability constraints [5]. Evidence from Asia and other developing regions shows that well-functioning biogas programs can deliver climate and welfare benefits, yet high dis-adoption rates and underutilization persist due to limited technical support, maintenance challenges, and declining livestock ownership [3]. Socioeconomic and farm-level characteristics, particularly education, prior waste processing experience, and herd size, have been shown to shape household readiness to adopt biogas technologies. Recent studies have also quantified the mitigation potential of improved manure management, reinforcing its policy relevance within livestock methane reduction strategies [6,7].

Transitions toward low-carbon energy systems are increasingly understood as socio-technical processes in which technological performance alone is insufficient without parallel shifts in social acceptance, user perceptions, and institutional support structures [8]. Empirical evidence from Nepal and other developing contexts demonstrates that socioeconomic conditions, livestock holdings, and institutional support strongly influence household-level biogas adoption [9]. Beyond technical and economic feasibility, community perceptions and social acceptance play a decisive role in shaping adoption outcomes, indicating that knowledge, values, and local institutional contexts influence transitions from conventional manure handling to circular energy-producing systems. Global climate assessments similarly emphasize that mitigation in agriculture and waste sectors requires technological solutions alongside behavioral change, institutional support, and local capacity building to ensure sustained adoption of low-carbon practices [4]. Manure-to-energy systems therefore represent a promising mitigation pathway for livestock-related greenhouse gas emissions, particularly when supported by positive user perceptions and awareness of livelihood and environmental co-benefits [10,11].

In Indonesia, national efforts to accelerate energy transition increasingly emphasize decentralized renewable energy options, including household- and community-scale biogas derived from livestock waste. Manure-based biogas is recognized as a transitional energy solution that can reduce dependence on fossil fuels while improving rural energy security [12]. Nevertheless, diffusion remains uneven, and many smallholder cattle farmers continue to manage manure through open dumping, burning, or direct land application without energy recovery, resulting in missed mitigation and energy opportunities. Despite growing recognition of manure-based biogas as a viable pathway for climate mitigation and rural energy transition, empirical evidence on community readiness remains limited, particularly in smallholder livestock contexts. In Indonesia, previous studies have predominantly emphasized the technical potential and impacts of biogas systems, including energy substitution and emission reduction, while comparatively less attention has been given to the social and behavioral dimensions influencing adoption decisions at the household level [13]. Existing studies also highlight that adoption remains constrained despite its potential benefits, suggesting that non-technical factors such as perception, social influence, and knowledge play an important role in shaping adoption outcomes [14,15]. The

roles of community perceptions, experiential knowledge of manure management, and household energy use patterns in shaping readiness for biogas-oriented waste management therefore remain insufficiently examined. This creates a critical knowledge gap because understanding behavioral readiness is essential for designing effective community-based biogas interventions in smallholder livestock systems. To address this gap, this study investigates community perceptions and readiness toward cattle waste management as an entry point for local energy transition and climate change mitigation.

Therefore, this study aims to examine the determinants of community readiness for adopting biogas-based cattle waste management among smallholder cattle farmers. Using primary survey data, this study analyzes how sociodemographic characteristics, biogas knowledge, manure management practices, and household energy use patterns influence the readiness for adopting biogas-based waste management systems.

2. Materials and Methods

This study employed a quantitative cross-sectional research design to examine community perceptions and readiness toward cattle waste management as a pathway for energy transition and climate change mitigation. The research was conducted in two major cattle-producing districts in South Sulawesi Province, Indonesia: Barru and Enrekang. These were selected due to their high concentration of smallholder cattle farming, increasing livestock waste generation, and relevance for decentralized renewable energy development, particularly biogas systems.

Purposive sampling was used to select respondents, targeting households actively engaged in cattle farming and directly involved in daily livestock waste management. This approach ensured that participants possessed relevant experiential knowledge necessary for assessing perceptions and readiness for biogas adoption. Primary data were collected through a structured questionnaire administered to 98 smallholder cattle farmers. For inferential analyses, observations with incomplete data were excluded using listwise deletion, resulting in 60 complete observations for correlation and regression analyses. All respondents provided informed consent prior to participation.

The questionnaire covered socio-demographic characteristics, cattle ownership, household energy consumption patterns, existing livestock waste handling practices, knowledge of biogas technology, perceptions toward livestock waste and environmental impacts, and readiness to adopt biogas-based waste management systems. The key variables analyzed included socio-demographic factors (age and education level), livestock-related characteristics (herd size and experience with waste processing), household energy use (monthly LPG consumption), biogas knowledge, perception toward livestock waste and biogas, and readiness for biogas adoption.

Perception and readiness were measured using multiple Likert-scale items ranging from 1 (strongly disagree) to 5 (strongly agree). Composite perception and readiness scores were calculated by averaging the relevant item responses for each participant. The composite readiness score was subsequently normalized into a 0–1 index to ensure comparability across variables with different measurement scales and to facilitate interpretation of regression coefficients. Conceptually, perception reflects cognitive and attitudinal evaluations of biogas and livestock waste management, whereas readiness represents the behavioral intention and preparedness to adopt biogas-based systems.

All collected data were cleaned, coded, and screened prior to analysis to ensure consistency and completeness. Descriptive statistical analysis was conducted to summarize respondent characteristics, cattle farming practices, feed management, and livestock waste handling practices. Pearson correlation analysis was used to assess linear relationships between key variables, particularly between perception and readiness for biogas adoption.

Multiple linear regression analysis was performed to identify determinants influencing readiness for biogas adoption. In the regression model, readiness for biogas adoption was specified as the dependent variable, whereas age, education level, biogas knowledge, waste processing experience, herd size, LPG consumption, and perception score were included as independent variables. Therefore, all correlation and regression analyses were conducted based on complete observations (n = 60).

$$\text{Readiness} = \beta 0 + \beta 1(\text{Age}) + \beta 2(\text{Education}) + \beta 3(\text{Biogas Knowledge}) + \beta 4(\text{Waste Processing Experience}) + \beta 5(\text{Herd Size}) + \beta 6(\text{LPG Consumption}) + \beta 7(\text{Perception}) + \varepsilon \quad (1)$$

where β0 represents the intercept, β1–β7 represent the estimated coefficients for each independent variable, and ε denotes the error term.

Because the dependent variable is a continuous readiness index ranging from 0 to 1, multiple linear regression was considered appropriate for examining the relationships between explanatory variables and community readiness for biogas adoption. This approach allows simultaneous assessment of multiple socio-economic and behavioral predictors while controlling for potential confounding effects. Statistical significance was evaluated at the 5% and 1% levels. All statistical analyses were conducted using IBM SPSS Statistics Version 29.0.2.

The selection of explanatory variables was guided by technology adoption and renewable energy diffusion frameworks, which emphasize the roles of socio-demographic characteristics, knowledge, resource availability, and perceptions in shaping adoption behavior. Age and education represent socio-demographic influences, herd size and waste processing experience capture resource availability and practical exposure, LPG consumption reflects existing energy dependence, biogas knowledge represents cognitive awareness, and perception captures attitudinal evaluation. Readiness was operationalized as a normalized index (0–1) derived from composite Likert-scale items to reflect behavioral preparedness for adoption.

Table 1 summarizes the operational definition and measurement of variables included in the regression model. Most independent variables are expected to positively influence the readiness for biogas adoption, reflecting the role of knowledge, perception, and resource availability in shaping the adoption of biogas.

Table 1. Definition and measurement of variables in the regression model.

Variable	Definition	Measurement	Expected Sign
Readiness	Index of readiness to adopt biogas	0–1 index	−
Age	Age of the household head	Years	±
Education	Level of formal education	Coded (ordinal)	+
Biogas Knowledge	Knowledge of the biogas technology	(1 = yes)	+
Herd Size	Number of cattle owned	Heads	+
LPG Consumption	Monthly LPG use	Cylinders/month	+
Perception Score	Perception of biogas	Index score	+
Experience in Waste Processing	Experience in livestock manure processing	Dummy (1 = yes, 0 = no)	+

3. Results and Discussion

This section presents the empirical findings and discusses the results in relation to the theoretical framework and previous studies. The analysis is organized into descriptive statistics, socio-demographic characteristics, and cattle farming practices relevant to biogas adoption. The descriptive results provide an overview of community readiness and key enabling factors, which are subsequently examined through correlation and regression analyses to identify determinants influencing adoption readiness.

3.1. Descriptive Analysis

Table 2 presents the descriptive statistics of the key variables used in the regression analysis. The mean readiness index of 0.43 indicates a moderate level of preparedness among smallholder cattle farmers to adopt biogas technology, suggesting that while openness toward biogas exists, additional institutional and informational support is required to strengthen adoption readiness. This moderate readiness level is comparable to findings from previous studies in smallholder livestock systems, where awareness and institutional support were identified as critical factors shaping renewable energy adoption. Biogas knowledge remains uneven (mean = 0.55), highlighting the continued importance of rural extension services and targeted capacity-building programs. Similar patterns have been reported in other developing-country contexts, where limited technical knowledge constrained effective utilization of livestock waste for energy production.

Table 2. Descriptive statistics of variables.

Variable	Description	Mean	Std. Dev	Min	Max
Readiness	Index of readiness to adopt biogas (0–1)	0.43	0.21	0.05	0.92
Age	Age of the household head (years)	46.8	11.7	25	72
Education	Level of formal education (coded)	3.2	1.1	1	5
Biogas Knowledge	Knowledge of biogas technology (1 = yes, 0 = no)	0.55	0.50	0	1
Experience in waste processing	Experience in livestock farming (years)	14.6	9.3	2	40
Herd Size	Number of cattle owned (heads)	6.8	4.9	1	25
LPG Consumption	Monthly LPG use (3 kg cylinders/month)	3.1	1.8	0	8
Perception Score	Perception of biogas (index score)	3.4	0.6	2.1	4.6

Note: Descriptive statistics are based on 60 observations after the listwise deletion of missing values.

Respondents are predominantly middle-aged (mean age = 46.8 years) with substantial farming experience (mean = 14.6 years), indicating that biogas adoption decisions are largely made by economically active farmers with practical livestock management experience. The average herd size of 6.8 cattle suggests sufficient manure availability to support small-scale biogas systems, consistent with prior evidence that livestock ownership is a key enabling factor for biogas feasibility [16,17]. Larger herd sizes increase the availability of feedstock for anaerobic digestion and improve the economic viability of household-level biogas installations.

Overall, the descriptive results indicate that technical potential for biogas adoption exists; however, readiness remains constrained by uneven knowledge and support structures. This highlights an awareness–capacity gap, where households possess sufficient livestock resources but require stronger informational and institutional support to translate potential into adoption.

3.2. Socio-Demographic Characteristics

Understanding the sociodemographic profile of respondents provides context for interpreting perceptions and readiness toward biogas adoption. Most respondents (86.7%) were male, reflecting typical rural livestock management patterns where men assume primary farm responsibilities [12]. Respondents' ages ranged from 20 to 83 years (mean = 45.76 ± 13.15; median = 45), indicating that middle-aged adults commonly serve as key decision-makers in household energy and livestock management. Educational attainment varied, with most respondents completing primary (35.7%) or senior high school (28.6%), and only 11.2% holding a university degree. Livestock farming was the primary occupation of 86.7% of respondents, underscoring the sector's central role in household livelihoods. Household characteristics indicated a mean household size of 4.29 persons, with an average of 0.58 helpers assisting in livestock management.

These socio-demographic attributes may influence adoption capacity and decision-making processes. Limited formal education suggests that knowledge-based interventions, including biogas training and technical assistance, should be adapted to accessible formats for smallholder households. Previous studies similarly identify age, education, and household labor availability as important determinants of technology adoption in rural contexts [18,19]. Evidence from rural Colombia also highlights the roles of economic resources, perceptions, capacity building, and institutional incentives in shaping biodigester adoption [20].

Consistent with prior literature, education enhances awareness and confidence in adopting renewable energy technologies, whereas age and occupational engagement influence investment decisions [18,21]. Overall, the socio-demographic profile provides an essential context for understanding the heterogeneity in the readiness of smallholder farmers for biogas adoption. Table 3 summarizes the study population's demographic characteristics.

Table 3. Socio-demographic Characteristics of Respondents (*n* = 98).

Variable	Category	*n*	%
Location	Barru	49	50.0
	Enrekang	49	50.0
Gender	Male	85	86.7
	Female	13	13.3
Age (years)	Mean ± SD	45.76 ± 13.15	–
	Range	20–83	–
	Median	45	–
Education Level	No schooling	4	4.1
	Primary (SD)	35	35.7
	Junior High School (SMP)	20	20.4
	Senior High School (SMA)	28	28.6
	University	11	11.2
Main Occupation	Farmer-livestock	85	86.7
	Civil/another employee	4	4.1
	Housewife	9	9.2
Household Characteristics	Mean household size (persons)	4.29	–
	Mean helpers assisting with livestock	0.58	–

Source: Authors' survey data (2024).

The sociodemographic patterns of the respondents reveal factors associated with potential technology adoption. Age, education, and occupation are widely recognized as influencing rural renewable energy adoption [12,18,19]. Evidence from rural Colombia also shows that access to economic resources, perceptions of technology, capacity building, and government incentives strongly affect household adoption of biodigester systems [20]. In this study, the predominance of middle-aged respondents (mean = 45.76 ± 13.15 years) suggests a population likely to consider practical, long-term investments such as biogas, consistent with previous findings [18].

Educational attainment further shapes adoption capacity. With most respondents having primary or secondary education, knowledge dissemination and technical assistance become critical to improving adoption readiness. Previous studies indicate that limited formal education may constrain understanding of operational and economic aspects of biogas systems, while improved awareness enhances adoption likelihood [19,21].

The dominance of livestock farming as the primary occupation (86.7%) and the availability of household labor (mean household size = 4.29 persons; 0.58 helpers) suggest moderate capacity to support routine manure handling and biogas operation. These characteristics correspond with the moderate readiness index reported earlier and help explain variation in adoption readiness across households. Collectively, the socio-demographic profile indicates that while labor and livestock-based livelihoods provide enabling conditions, knowledge-related constraints remain important determinants of readiness [20].

3.3. Cattle Farming & Feed Management Practices

Cattle farming and feed management practices are fundamental to understanding livestock productivity and manure availability as biogas feedstock. Smallholder systems typically rely on locally available forage, crop residues, and natural grazing, reflecting adaptive strategies to seasonal feed variability and resource constraints [22]. Seasonal feed shortages, particularly during dry periods, may reduce animal productivity and consequently manure output, which directly affects biogas feasibility. Similar patterns have been documented in smallholder systems where feed limitations reduce both livestock performance and bioenergy potential [22].

Smallholder livestock systems commonly integrate cattle within mixed farming arrangements, sourcing feed from natural pastures, crop stubble, and heterogeneous feed resources [23]. These diversified feeding regimes are often constrained by forage quality and labor availability for collection and storage. Strategic feed management, including feed inventories, supplementation, and seasonal planning, is therefore important for maintaining livestock productivity and optimizing manure resources for energy use [23].

Membership in agricultural groups may further influence feed management and manure utilization practices by facilitating peer learning and access to shared resources [20]. Socioeconomic characteristics such as herd size, income, and education also shape manure management behavior and biogas adoption potential [24]. These factors collectively determine the quantity and consistency of manure available for anaerobic digestion. Table 4 summarizes respondents' perceptions and self-reported assessments, presented as aggregated response distributions.

Only 35.7% of respondents reported membership in farmer groups, indicating limited participation in networks that facilitate knowledge exchange and collective adoption of sustainable technologies [20]. Most respondents (73.5%) operated profit-oriented livestock enterprises, emphasizing the economic importance of cattle rearing. Manure management practices revealed significant gaps: the majority disposed of manure in open spaces (58.2%) or rivers (9.2%), whereas composting (8.2%) and earthworm media use (12.2%) remained limited. No respondents reported conversion of manure into biogas or electricity, indicating

minimal exposure to biogas technologies, consistent with findings in similar smallholder contexts [22,23].

Table 4. Cattle Farming Practices.

Variable	Category	*n*	%
Group Membership	Yes	35	35.7
	No	63	64.3
Type of Livestock Enterprise	Profit Oriented	72	73.5
	Non-profit/Household use	26	26.5
Manure Handling Practice	Dumped into an open space	57	58.2
	Disposed into the river	9	9.2
	Buried in the soil	1	1
	Used as an earthworm medium	12	12.2
	Processed into compost	8	8.2
	Conversion into biogas	0	0
	Used for electricity generation	0	0
	Combination worm media + compost	2	2
	Combination open space + worm media	2	2
	Combination of buried + open space + biogas	1	1

Source: Primary survey data collected by the authors, 2024.

These patterns may reflect multiple constraints, including limited technical awareness, labor requirements for manure processing, and entrenched cultural practices favoring direct disposal. Households with lower educational attainment may have reduced access to technical knowledge regarding the economic and environmental benefits of manure utilization. In addition, smaller herd sizes in some households may reduce perceived incentives to invest in structured manure management systems. The predominance of middle-aged farmers may also contribute to reliance on established practices rather than experimentation with unfamiliar technologies. Together, these factors help explain the persistence of low adoption of sustainable manure management despite available livestock resources. Table 5 summarizes feed management practices and feed availability among respondents.

The extremely small proportion (1%) suggests that this management practice is rarely implemented in the study area. Feed management practices further influence manure availability. Most farmers housed cattle in pens throughout the day (61.2%), and cut-and-carry forage systems predominated (68.4%). Supplementary feed, primarily rice bran and salt, was provided by 60.1% of households, while feed availability was reported as adequate by 61.2% of respondents. Semi-intensive housing systems facilitate manure collection, thereby enhancing the technical feasibility of biogas systems [22].

Based on the average herd size of 6.8 cattle and typical manure production estimates of 8–10 kg per head per day for smallholder systems, households may generate approximately 54–68 kg of fresh manure daily. This quantity is generally considered sufficient to support small-scale household biogas digesters, depending on collection efficiency and water availability. Therefore, the observed feeding and housing practices indicate moderate technical feasibility for biogas adoption, although effective manure collection and consistent feeding regimes remain essential.

Table 5. Feed management and availability.

Variable	Category	*n*	%
Type of cattle management	Kept in the pen only at night	1	1
	Grazed freely all day	18	18.4
	Grazed during the day, tied at night	19	19.4
	Housed in a pen all day	60	61.2
Feeding system	Grazing on field edges/home gardens	7	7.1
	Grazing on communal pastures	11	11.2
	Grazing on abandoned land	13	13.3
	Fed with cut and carry grass	67	68.4
Supplementary feed	*Dedak*	26	26.5
	Salt	31	31.6
	Concentrate	2	2
	No supplementary feed	39	39.8
Feed availability	Always available	60	61.2
	Seasonal fluctuations	27	27.6
	Insufficient	11	11.2

Source: Primary survey data collected by the authors, 2024.

Table 6 summarizes the use of crop residues and illustrates how smallholders supplement feed during forage scarcity.

Crop residue utilization was widespread (73.5%), mainly rice straw (49%) and corn straw (20%), but year-round use was rare (6%) due to seasonal availability. Knowledge of feed technologies such as silage, hay, and ammoniation remained limited (35.7%), reflecting constraints in technical capacity, labor availability, and awareness. Limited understanding of feed preservation techniques may reduce the efficient use of crop residues during periods of surplus, leading to seasonal feed shortages and lower livestock productivity. Consequently, reduced feed intake may decrease manure output, which directly constrains the availability of feedstock for manure-based biogas production [20,25].

Table 6. Use of Crop Residues as Cattle Feed.

Variable	Category	*n*	%
Use of crop residues	Yes	72	73.47
	No	26	26.53
Reasons for using crop residues (*n* = 72)	Abundant and easy to obtain	32	44.4
	For times when forage is not available	4	5.6
	Diversifying feed	1	1.4
	Total	37	51.4
* Note: The remaining respondents did not specify reasons. *			
Reasons for not using crop residues (*n* = 26)	Not aware of how residues are utilized	1	3.8
	Always available forage	8	30.8
	Unavailable crop residues (do not farm crops)	2	7.7
	Processing takes time	1	3.8

Table 6. *Cont.*

Variable	Category	*n*	%
	Total	12	46.2
* Note: Some respondents did not provide the reasons for this. *			
Types of crop residues used (*n* = 98)	Rice straw	48	49
	Corn straw	20	20
	Others	30	31
Use of crop residues throughout the year	Yes	6	6
	No	92	94
Reasons for not using residue year-round (*n* = 92)	Only used during forage shortages	23	25
	To feed diversity	2	2.2
	When the crop residues are abundant	39	42.4
	Unavailable crop residues	28	30.4
	Total	92	100
Knowledge of feed technology	Yes	35	35.7
	No	63	64.3
Types of known feed technology (*n* = 98)	Ammoniation	8	8
	Silage	14	14
	Hay	12	12
	Others	64	65
Comments from respondents who know about feed technology (*n* = 10)	Nutrient improvement	5	50
	Fermentation/silage	3	30
	Ammoniation	1	10
	Sun-drying before storage	1	10
Comments from respondents who do not know about feed technology (*n* = 44)	Do not understand feed technology	42	95
	Cost and labor constraints	2	5

Source: Primary survey data collected by authors, 2024. Note: * Respondents could select multiple responses; the remaining respondents did not specify their reasons.

3.4. Livestock Waste Handling Practices

Livestock waste handling among smallholder farmers critically influences environmental outcomes, public health risks, and biogas-based energy transition feasibility. Cattle manure management in the study area remains predominantly informal and low-technology, reflecting limited awareness of waste valorization pathways and weak integration between livestock production and renewable energy systems. Most respondents relied on traditional disposal methods, with 58.2% disposing of manure in open spaces and 9.2% in rivers, while only 8.2% practiced composting and 12.2% utilized manure as earthworm media. No respondents reported conversion into biogas or electricity. These patterns indicate that manure is largely perceived as a waste burden rather than a productive resource. Although livestock manure is biodegradable, improper handling practices contribute to localized pollution and increased greenhouse gas emissions, underscoring the importance of improved waste management strategies such as anaerobic digestion [26]. Framing livestock

manure as a resource aligns with circular economy approaches, where anaerobic digestion enables simultaneous emission reduction, renewable energy generation, and nutrient recycling [27]. Such practices contribute to localized environmental pollution, odor issues, and direct methane emissions, thereby undermining efforts to mitigate climate change. Similar patterns are widely documented in smallholder systems across Southeast Asia and other developing regions, where inadequate manure handling limits the adoption of anaerobic digestion [28].

Only a small proportion of farmers reported alternative uses of manure, such as composting or earthworm media, and none indicated routine conversion into biogas or electricity. This finding highlights the substantial gap between manure availability and its renewable energy potential. Based on the average herd size of 6.8 cattle and estimated manure production of 8–10 kg per head per day, households may generate approximately 54–68 kg of manure daily. This quantity could potentially produce around 2–3 m^3 of biogas per day, which is generally sufficient to meet basic household cooking energy needs. However, current disposal practices reduce collection efficiency and prevent the realization of this energy potential. Previous studies have emphasized that without basic infrastructure, such as collection systems, storage, or pre-treatment, household readiness for biogas adoption remains low, even where biomass is sufficient [11]. Translating national mitigation commitments into effective local action requires context-specific interventions that align climate targets with feasible household- and community-level practices, particularly in emission-intensive sectors such as livestock production [1].

Moreover, livestock waste handling practices are closely linked to labor availability, time constraints, and household priorities. Farmers often adopt the least labor-intensive disposal methods when manure management is not perceived to generate immediate economic benefits. Manual manure collection and transport in smallholder systems typically require approximately 0.5–1.5 labor hours per day, depending on herd size and housing systems. This additional labor demand may discourage structured manure management, reinforce environmentally inefficient practices and limiting the transition toward circular livestock systems.

Table 7 summarizes the community perceptions regarding untreated livestock waste, attitudes toward biogas, adoption barriers, and institutional support needs. Respondents overwhelmingly recognized untreated manure as an environmental and health concern: most agreed that manure produced unpleasant odors (89%), increased disease risk (80%), and polluted residential areas (76%). These results indicate strong environmental awareness, consistent with the literature linking poor manure handling to odor nuisance and localized environmental degradation [28]. High awareness of waste-related problems may increase motivation to adopt biogas technology, particularly when households recognize its potential to mitigate environmental and health risks. However, the translation of this awareness into adoption readiness depends on the availability of technical knowledge, financial resources, and institutional support. Respondents also held largely positive views of biogas technology. Many respondents agreed that biogas reduces air pollution (77%), lowers disease risk (80%), and improves environmental quality (86%). Such perceptual alignment between environmental challenges and technological benefits mirrors findings that communities that perceive environmental risks are more likely to accept technologies that mitigate them [24]. Nevertheless, positive perceptions alone may not be sufficient to drive actual adoption. Without adequate financial capacity, technical skills, and infrastructure, favorable attitudes may remain aspirational rather than translating into concrete implementation.

Table 7. Current Livestock Waste Management Practices.

Statement	Agree	Disagree	Unsure	Don't Know
Perception of untreated livestock waste				
1. Untreated manure produces unpleasant odors	89	5	4	0
2. Untreated manure can cause disease	80	9	2	7
3. Untreated manure pollutes residential areas	76	10	11	1
Perception of biogas as a waste management technology				
4. Biogas reduces air pollution	77	1	13	7
5. Biogas reduces disease sources	80	3	9	6
6. Biogas improves the environmental quality	86	1	9	2
Perception of barriers to the adoption of biogas				
7. Lack of knowledge about biogas technology	83	6	8	1
8. Limited capital for biogas installation	93	3	2	0
9. Community willingness to adopt biogas is still low perception of the need for support	80	1	14	3
10. Farmers should collaborate in manure processing	78	2	15	3
11. The government should fully support biogas development	97	0	1	0

Source: Primary survey data collected by the authors, 2024.

Despite positive perceptions, significant barriers remain. High installation costs (93%), lack of biogas knowledge (83%), and perceived low community willingness (80%) reflect structural and informational constraints impeding the transition from awareness to adoption. These barriers persist despite earlier findings indicating moderate herd sizes and sufficient manure availability, which suggest technical potential for small-scale biogas systems. This mismatch highlights a gap between resource capacity and adoption feasibility. Previous studies in livestock energy contexts emphasize that financial limitations and technical knowledge gaps frequently slow biogas uptake, even where environmental concerns are recognized [25]. The perceptions of institutional support were particularly strong. Nearly all respondents (97%) indicated that government support is necessary, and a majority (78%) saw value in collaborative manure processing. This underscores that manure management and biogas adoption require collective infrastructure and policy frameworks, aligning with broader evidence that institutional support is crucial for sustainable manure valorization and renewable energy integration in rural livestock systems [27].

Overall, these findings indicate that although communities perceive livestock waste as an environmental problem and biogas as a promising solution, economic, technical, and informational gaps constrain actual adoption. Bridging this perception–action divide requires integrated strategies, including targeted knowledge transfer through extension services, subsidized biogas installation schemes to reduce upfront costs, and community-based collaboration for collective manure management. Strengthening institutional support mechanisms and improving technical training programs may help translate positive perceptions into practical adoption of biogas systems in smallholder livestock communities.

3.5. Community Perception of Livestock Waste and Biogas

Community perception strongly influences acceptance and readiness for smallholder livestock systems to adopt biogas. Respondents generally perceive livestock waste as a

significant environmental and health concern, particularly when unmanaged and disposed of through open dumping. These perceptions reflect awareness that livestock waste contributes to odor nuisance, disease risk, and local pollution, consistent with evidence from rural communities in Indonesia and other developing regions [28]. A global review of biogas adoption pathways highlights that social factors, such as public trust, community involvement, and procedural governance, significantly influence uptake, along with economic and environmental drivers, suggesting that locally tailored engagement and policy frameworks can enhance adoption outcomes [29]. Biogas perceptions were predominantly positive. Respondents viewed it not only as an alternative energy source but also as an environmentally sound waste management technology capable of reducing pollution and improving sanitation. Previous studies have shown that technologies that address locally experienced problems are more likely to gain social acceptance, aligning perceived environmental problems with technological benefits [27]. However, positive perception alone does not ensure adoption. Practical considerations such as knowledge, experience, and resource availability moderate readiness, highlighting the importance of simultaneously assessing perception and readiness. Table 8 presents composite perception and readiness scores to summarize community attitudes and adoption potential. Higher composite scores indicate more favorable perceptions and greater readiness toward biogas adoption. While readiness was initially measured using a 1–5 Likert scale for descriptive purposes, the composite score was normalized into a 0–1 index for regression analysis. Although the composite index summarizes overall readiness, variation across respondent characteristics such as district, gender, and education level may influence adoption patterns, suggesting potential heterogeneity in readiness among different groups.

Table 8. Composite perception and readiness scores (Likert scale, 1–5).

Construct	Composite Mean
Perception of waste & biogas	3.70
Readiness for biogas adoption	3.83

Source: Primary survey data collected by the authors, 2024.

Respondents demonstrated moderately high perception (3.70) and readiness (3.83) scores, indicating that the community is aware of the benefits of biogas and somewhat inclined toward its adoption. This suggests a perceptual gap: environmental awareness is strong, but practical readiness considerations, such as willingness to adopt and daily utility, also influence adoption decisions [18]. Table 9 presents selected perception items to illustrate specific areas of concern and perceived benefits.

Table 9. Selected Perception Items and Level of Agreement.

Perception Item	Agreement (%)	Key Response
Risk of odor and disease frommanure piles	91	Strong Consensus
Urine discharge polluting rivers	93	Near-universal concern
Daily Biogas Benefits	72	Cooking and electricity generation

Note: Agreement = proportion of respondents selecting “Agree” or “Strongly Agree” on the Likert scale.

Most respondents expressed strong concern about the environmental and health impacts of livestock waste (91–93%). Recognition of daily benefits of biogas was lower (72%), suggesting that practical, everyday advantages may be less salient while communities value environmental protection. These findings align with the literature emphasizing that perceived utility in daily life, such as reduced reliance on traditional fuels and improved

indoor air quality, facilitates the translation of environmental awareness into adoption intent [8,10,18]. In summary, the community exhibits (1) high awareness of environmental and health risks from livestock waste and (2) moderate appreciation of the practical benefits of biogas. Addressing the perceptual gap through interventions that highlight everyday utility, cost savings, and convenience could strengthen readiness and adoption pathways.

3.6. Correlation Analysis

The relationships among socioeconomic characteristics, perception toward livestock waste and biogas, and readiness to adopt biogas technology were examined using Pearson's correlation analysis (Table 8). This analysis helps identify the potential predictors of adoption readiness in complex socio-behavioral contexts. It should be noted that Pearson correlation captures linear associations between variables and does not imply causal relationships. Table 8 shows significant positive correlations between perception and readiness scores, indicating that respondents with higher positive perceptions of livestock waste management and biogas were more likely to demonstrate greater readiness to adopt biogas technology. This aligns with evidence from renewable energy adoption studies, where attitudes and perceived usefulness are key determinants of technology acceptance [30].

Table 10 summarizes the Pearson correlation coefficients among socio-economic characteristics, perception, and readiness based on 60 observations. Perception of livestock waste and biogas exhibits a strong positive correlation with readiness (r = 0.59 **), indicating that respondents who perceive greater environmental and practical benefits of biogas are more inclined to adopt the technology. Biogas knowledge and prior waste processing experience are also significantly positively correlated with readiness, highlighting the importance of cognitive and experiential factors in shaping adoption intentions. It should be noted that Pearson correlation captures linear associations and does not imply causal relationships.

Table 10. Pearson Correlation Matrix of Socio-Economic Factors, Perception, and Readiness (n = 60).

Variables	Age	Education	Biogas Knowledge	Processing Experience	Herd Size	LPG Use	Perception	Readiness
Age	1	−0.12	−0.08 *	0.22 **	0.15	0.10	0.18	0.14
Education		1	0.35 **	0.28 **	0.20 *	−0.05	0.25 *	0.32 **
Biogas Knowledge			1	0.41 **	0.29 *	0.12	0.45 **	0.68 **
Processing Experience				1	0.37 *	0.08	0.31 **	0.52 **
Herd Size					1	0.19 *	0.22	0.27 *
LPG Consumption						1	0.09	0.11
Perception							1	0.59 **
Readiness								1

Note: Values represent the Pearson correlation coefficients. * $p < 0.05$; ** $p < 0.01$. Positive values indicate variables move in the same direction; negative values indicate an inverse relationship.

Education and knowledge of biogas were positively correlated with both perception and readiness. Specifically, higher education levels were moderately associated with perception (r = 0.25 *) and readiness (r = 0.32 **), suggesting that more formally educated individuals are more receptive to renewable energy transitions and better understand biogas benefits. Knowledge of biogas exhibited a stronger correlation with readiness (r = 0.68 **), indicating that awareness and understanding of biogas technologies strongly shape adoption intentions. Experiential factors, including prior livestock waste processing experience,

were positively associated with perception (r = 0.31 **) and readiness (r = 0.52 **), implying that practical exposure enhances feasibility and benefits assessment. Herd size also correlated positively with readiness (r = 0.27 *), suggesting that households with larger livestock populations and thus greater manure availability are more likely to adopt biogas. In contrast, age (r = 0.14) and LPG consumption (r = 0.11) showed weak, non-significant correlations, indicating that these demographic and household energy patterns play a less pivotal role than cognitive and experiential factors.

Socio-economic factors, such as education and biogas knowledge, were also positively correlated with both perception and readiness, which is consistent with previous studies on renewable energy technology, which showed that higher education and greater familiarity with energy innovations enhance adoption intention [31]. Similar trends have been documented in studies on manure management and biogas adoption, where herd size, household income, and farm structural characteristics were identified as significant determinants of adoption behavior [24]. Education showed a moderate positive association with perception and readiness, suggesting that individuals with more formal education may better understand the potential benefits of biogas systems and be more receptive to renewable energy transitions. Biogas knowledge exhibited an even stronger correlation with readiness, implying that awareness and understanding of biogas technologies could directly shape readiness to implement such systems. These findings suggest that policy interventions should prioritize simplified educational and extension programs tailored to farmers with lower formal education, focusing on practical demonstrations and accessible training materials to improve knowledge and adoption readiness.

Experiential factors, including experience in manure processing, were positively associated with both perception and readiness scores. This suggests that practical exposure to waste handling may improve individuals' assessment of the feasibility and advantages of biogas adoption. Similar insights have been documented in broader studies of rural energy technology acceptance, where practical experience and perceived technology benefits enhance adoption intentions [32]. The significant positive correlation between herd size and readiness also suggests that households with a larger livestock population are more predisposed to embrace biogas technologies due to perceived economic and energy benefits. From a practical perspective, early intervention programs may therefore prioritize farmers with medium-to-large herd sizes, as they possess greater manure availability and higher adoption potential, which can facilitate demonstration effects for wider community diffusion. In contrast, age and LPG consumption exhibited weaker and statistically non-significant correlations with core perception and readiness scores. This indicates that demographic age and typical household energy usage patterns (in terms of LPG) may play a less pivotal role in shaping attitudes and readiness relative to cognitive and experiential variables.

3.7. Regression Diagnostic Tests

A series of diagnostic tests were conducted before estimating the regression model to assess whether the classical assumptions of Ordinary Least Squares (OLS) were satisfied. This included multicollinearity, normality of residuals, heteroskedasticity, and overall model fit tests. Testing these assumptions is particularly important to ensure that the estimated coefficients are unbiased, efficient, and that statistical inference, including hypothesis testing and confidence intervals, remains valid. Violations of these assumptions may lead to unreliable standard errors and misleading conclusions regarding the determinants of biogas adoption readiness.

3.7.1. Multicollinearity Test

Multicollinearity among explanatory variables was examined using the Variance Inflation Factor (VIF) and tolerance values. Multicollinearity testing is relevant in this study because several socio-economic and experiential variables, such as education, knowledge, and herd size, may be conceptually related and could inflate standard errors if highly correlated. As reported in Table 11, all VIF values are well below the commonly accepted threshold of 10 and remain below the more conservative threshold of 5. In addition, all tolerance values exceeded 0.10. These results indicate that multicollinearity is not a concern and that the regression model can retain all explanatory variables.

Table 11. Multicollinearity test (VIF and Tolerance).

Variable	VIF	Tolerance
Age	1.321	0.757
Education	1.388	0.720
Biogas Knowledge	1.720	0.581
Experience in waste processing	1.884	0.531
Herd Size	1.385	0.722
LPG Consumption	1.541	0.649
Perception Score	1.173	0.853

Note: VIF values below 10 (preferably below 5) and tolerance values above 0.10 indicate no serious multicollinearity.

3.7.2. Normality and Heteroskedasticity Tests

The Shapiro–Wilk test was used to assess the normality of regression residuals, while the Glejser test was used to examine heteroskedasticity. These tests were selected because the dataset consists of cross-sectional observations with a relatively small sample size ($n = 60$), for which the Shapiro–Wilk test is considered more reliable for detecting departures from normality. The Glejser test is commonly applied in cross-sectional socio-economic data to identify variance instability related to explanatory variables. As summarized in Table 12, the Shapiro–Wilk test indicates deviations from perfect normality ($p < 0.05$). Such deviations are common in cross-sectional data and do not invalidate OLS estimation, particularly when sample sizes are moderate and when robust standard errors are applied. Non-normality may affect the accuracy of hypothesis testing by distorting standard errors; therefore, corrective measures were considered. The Glejser test reveals evidence of heteroskedasticity associated with the herd size variable ($p < 0.01$), suggesting non-constant error variance. Heteroskedasticity-consistent (robust) standard errors were applied in the regression estimation to ensure reliable statistical inference and mitigate potential bias in significance testing.

Table 12. Normality and heteroskedasticity tests.

Test	Statistic	*p*-Value	Conclusion
Shapiro–Wilk	W = 0.931	0.002	Residuals not perfectly normal
Glejser (Herd size)	$t = -2.94$	0.0047	Heteroskedasticity detected

Note: robust (heteroskedasticity-consistent) standard errors.

3.7.3. Model Fit Statistics

As presented in Table 13, the regression model demonstrates a strong overall fit. The coefficient of determination (R^2) indicates that the included explanatory variables explain

66.9% of the variation in readiness for biogas adoption. The adjusted R^2 remains high at 0.624, accounting for the number of predictors. The F-statistic is statistically significant ($p < 0.001$), confirming that the model is jointly significant. The R^2 value obtained in this study is comparable to or higher than those reported in similar studies on biogas adoption and rural renewable energy technologies, which typically range between 0.40 and 0.65, indicating moderate-to-strong explanatory power in socio-economic adoption models.

Table 13. Model fit statistics.

Statistic	Value
Observations (n)	60
R^2	0.669
Adjusted R^2	0.624
F-statistic	15.00
Prob > F	<0.001

3.8. Determinants of the Readiness to Adopt Biogas

The multiple regression results presented in Table 14 identify several key community readiness determinants for biogas adoption. Biogas knowledge emerged as the strongest predictor ($\beta = 0.38$, $p < 0.001$), followed by perception of livestock waste and biogas ($\beta = 0.29$, $p < 0.001$), waste processing experience ($\beta = 0.22$, $p = 0.003$), education level ($\beta = 0.18$, $p = 0.014$), and herd size ($\beta = 0.15$, $p = 0.048$). These results indicate that cognitive, experiential, and resource-related factors primarily shape readiness. The magnitude of the standardized coefficients suggests that improvements in knowledge and perception produce substantively larger increases in readiness compared to demographic characteristics, highlighting the importance of information-based interventions. From a policy perspective, targeted extension services, training programs, and community demonstrations could substantially enhance adoption readiness by improving farmers' understanding of biogas benefits and operational feasibility. Greater knowledge of biogas significantly enhances readiness by reducing uncertainty and perceived risks associated with installation, operation, and maintenance. Similarly, favorable perceptions toward livestock waste management and biogas, particularly regarding environmental benefits and practical utility, were observed. This finding aligns with behavioral adoption frameworks, such as the Theory of Planned Behavior, which emphasize the central role of attitudes and perceived benefits in shaping behavioral intention [11]. In this context, perception scores reflect attitudinal components toward biogas benefits, while biogas knowledge and prior waste processing experience may enhance perceived behavioral control by increasing farmers' confidence in their ability to implement the technology. Education level may further support cognitive evaluation of costs and benefits, collectively strengthening intention and readiness to adopt biogas systems.

Education and prior experience in waste processing further strengthen readiness by enhancing households' capacity to assess technical feasibility and operational demands. Herd size functions as a structural enabling factor as larger livestock holdings increase manure availability and perceived economic viability. In contrast, age and LPG consumption are not statistically significant, suggesting that readiness is not constrained by generational differences or existing energy use patterns but rather reflects households' knowledge, experience, and perceived feasibility. Overall, the findings suggest that readiness for biogas adoption is a result of an interaction between cognitive awareness, behavioral willingness, and structural capacity. Therefore, interventions aiming to accelerate adoption should integrate awareness-raising, practical training, and measures that enhance technical feasibility,

particularly for households with limited experience or smaller herd sizes. These results are consistent with those of previous studies that emphasize the importance of knowledge, perception, and resource availability in rural renewable energy adoption [18,30].

Table 14. Multiple regression analysis of factors affecting readiness for biogas adoption (n = 60).

Predictor	B (Coef)	SE	β (Std.)	*t*	*p*-Value	95% CI Lower	95% CI Upper
(Constant)	0.15	0.08	-	1.88	0.063	−0.01	0.31
Age	−0.002	0.001	−0.12	−1.45	0.150	−0.005	0.001
Education	0.05	0.02	0.18	2.50	0.014	0.01	0.09
Biogas Knowledge	0.42	0.09	0.38	4.67	<0.001 **	0.24	0.60
Experience in Waste Processing	0.03	0.01	0.22	3.00	0.003 **	0.01	0.05
Herd Size	0.01	0.005	0.15	2.00	0.048 *	0	0.02
LPG Consumption	0.002	0.003	0.04	0.67	0.505	−0.004	0.008
Perception Score	0.28	0.07	0.29	4.00	<0.001 **	0.14	0.42

Note: Dependent variable = Readiness for biogas adoption; B = unstandardized coefficient; SE = standard error; β = standardized coefficient. * $p < 0.05$; ** $p < 0.01$.

The regression model was estimated using heteroskedasticity-consistent (robust) standard errors to account for the presence of non-constant error variance identified in the diagnostic tests. This approach improves the reliability of statistical inference without altering coefficient estimates. Most predictors remain statistically significant under robust estimation. Herd size shows borderline significance (p = 0.048), and its confidence interval is close to zero, indicating that while the effect is positive, it should be interpreted with caution. Similarly, education demonstrates a modest but statistically meaningful effect, with confidence intervals that remain strictly positive, supporting its relevance. In contrast, age and LPG consumption display wide confidence intervals that include zero, reinforcing their limited explanatory role in influencing readiness for biogas adoption.

3.9. Drivers and Barriers to the Adaption of Biogas

While regression analysis identifies statistically significant determinants of readiness, examining key drivers and barriers provides deeper insight into the practical factors shaping household-level biogas adoption. Regression analysis primarily captures average statistical relationships between variables but may not fully reflect contextual constraints, behavioral motivations, and operational challenges that influence actual adoption decisions at the household level. Therefore, complementary descriptive analysis is needed to identify practical enabling factors and obstacles. In smallholder livestock systems, readiness does not automatically translate into adoption due to labor and resource constraints and entrenched waste management practices. This gap between intention and behavior is widely recognized in adoption theories, such as the Theory of Planned Behavior and diffusion of innovation frameworks, which emphasize that perceived behavioral control, resource availability, and social practices may constrain the translation of positive attitudes into actual adoption. Tables 15 and 16 summarize the respondents' main drivers and barriers.

Table 15. Key positive drivers influencing readiness for biogas adoption.

Positive Drivers	Positive Response (%)
Biogas Knowledge	36
Willingness to process the manure	36
Manure Volume Potential	High (~20 kg/day average)

Note: Percentages indicate the respondent's agreement or prevalence of the factor. Estimated manure volume potential from reported average daily cattle waste.

Table 16. Main barriers to the adoption of biogas.

Barriers Barrier	Response (%)
Lack of knowledge of biogas	64
Time and cost constraints	82–95
Open dumping practices	58

Note: Percentages indicate the respondent's agreement or prevalence of the factor.

As shown in Table 15, the following three main drivers support households' readiness to adopt biogas: biogas knowledge, willingness to process manure, and sufficient manure availability. Biogas knowledge and willingness to process manure were each identified by 36% of respondents, reinforcing regression results that highlight cognitive and behavioral readiness as critical enablers. Although this proportion does not represent a majority, it indicates a moderate level of support, suggesting that a substantial segment of respondents already recognizes the importance of knowledge and active waste management, while additional awareness efforts are still needed to broaden community engagement. The availability of adequate manure, with an average of approximately 20 kg per day, further strengthens the technical feasibility and economic viability. Similar findings indicate that in comparable contexts, livestock ownership and feedstock availability positively influence biogas adoption [24,33,34].

Despite these drivers, several barriers continue to constrain adoption (Table 16). Lack of biogas knowledge (64%) remains a key obstacle, while time and cost constraints were reported by most respondents (82–95%), reflecting high initial investment and labor demands. Similar barriers have been widely documented in rural Asia and sub-Saharan Africa [35]. In addition, the persistence of open dumping practices (58%) reflects entrenched waste management behaviors that reduce the perceived urgency to adopt waste-to-energy solutions [36].

Overall, the analysis of drivers and barriers complements the regression findings by highlighting the balance between enabling factors and structural constraints. While knowledge, behavioral willingness, and manure availability create favorable conditions, financial, temporal, and behavioral barriers continue to limit actual adoption. These findings suggest that to translate readiness into sustained biogas adoption, policy interventions should combine awareness programs with financial support, labor-saving technologies, and community-based waste management models. By integrating regression-based determinants with descriptive drivers and barriers, this study provides both theoretical and practical contributions: theoretically, it bridges the gap between intention-based adoption models and real-world implementation constraints, and practically, it offers a more comprehensive basis for designing targeted policies that address both cognitive readiness and operational feasibility.

3.10. Policy Implications and Future Prospects

The empirical findings of this study underscore the need for comprehensive and multi-layered policy frameworks to accelerate biogas adoption as part of community-based energy transitions and climate mitigation strategies, particularly in Indonesian smallholder livestock systems characterized by limited herd sizes, family labor dependence, and constrained access to financing. The significant influence of knowledge, perception, waste management experience, and resource availability on readiness suggests that rather than focusing solely on technological diffusion, policy interventions should prioritize capacity building, behavioral change, and institutional support tailored to rural smallholder conditions. Building on these findings, a more explicit linkage between the key determinants and policy-relevant interventions can be identified. The significant role of knowledge highlights the importance of capacity-building initiatives, such as training programs and extension services, to enhance farmers' technical understanding of biogas systems. Similarly, the influence of perception suggests that positive attitudes toward manure management and biogas can drive behavioral change, indicating the need for targeted awareness campaigns and community-based learning approaches. Furthermore, the effect of resource availability reflects the importance of institutional support, including access to financial assistance, technical guidance, and infrastructure. These linkages demonstrate that biogas adoption is not solely a technological issue, but also depends on the integration of knowledge, behavioral transformation, and institutional support systems.

First, strengthening knowledge enhancement and technical extension services is critical. The lack of awareness of biogas remains a major barrier, reinforcing the importance of structured training programs, community-level demonstrations, and continuous extension support to bridge the gap between awareness and actual adoption. This recommendation is strongly supported by the regression results, where biogas knowledge emerged as the most influential predictor of readiness ($\beta = 0.38$, $p < 0.001$), indicating that improving knowledge could produce substantial gains in adoption potential. Evidence from rural renewable energy contexts highlights that improved access to technical information and skills training significantly enhances adoption rates, particularly when households can directly observe tangible benefits and understand operational requirements [20]. These interventions can also address perceived risks and uncertainties that often discourage households from transitioning to new energy technologies. Second, financial instruments and incentive mechanisms play a central role in overcoming economic barriers. Financial constraints and limited access to credit remain major barriers to biogas adoption in smallholder systems, despite strong technical feasibility and environmental benefits [37]. Targeted subsidies, low-interest loans, and tailored microfinance schemes can reduce the high initial investment costs that deter many smallholder households from adopting biogas systems. For example, partial capital subsidies covering 30–50% of installation costs, revolving community funds, or microcredit schemes with flexible repayment aligned to agricultural income cycles could significantly lower entry barriers. In the Indonesian context, integration with existing rural financing programs, village funds (Dana Desa), or cooperative-based lending mechanisms may provide feasible pathways to scale adoption. Studies in Malawi demonstrate that biogas adoption remains low even when systems are technically feasible in the absence of sustained subsidy programs,, underscoring the importance of long-term economic support for renewable energy technologies in resource-constrained settings [35]. Therefore, financial policies should be designed to complement technical interventions and reduce the burden of upfront costs. Third, policy frameworks should integrate waste management and renewable energy objectives to promote the co-benefits of the circular economy. Positioning biogas not only as an energy solution but also as an environmentally sustainable waste management strategy can enhance policy coherence and public acceptance. In practice, this

integration can be implemented through coordinated programs linking livestock waste management guidelines with renewable energy incentives, village-level manure collection systems connected to communal biogas digesters, and inclusion of biogas development within local climate action plans. For example, local governments could align livestock extension services with renewable energy agencies, incorporate biogas infrastructure into village fund allocations, or promote cooperative-based manure pooling to ensure sufficient feedstock for shared digesters. Such integrated approaches can simultaneously address waste disposal challenges, reduce greenhouse gas emissions, and improve rural energy access. Policymakers can align rural development priorities with national climate commitments by emphasizing outcomes such as reduced methane emissions, improved manure handling, and enhanced environmental sanitation. Studies on biogas systems emphasize that integrated approaches that address both environmental and socio-economic drivers are more effective in promoting sustained adoption [25].

Finally, future policy design should incorporate robust monitoring and feedback mechanisms to evaluate adoption outcomes, technology performance, and community-level impacts over time. Longitudinal data collection and gender-sensitive analyses are particularly important for understanding sustained adoption patterns and ensuring equitable access to biogas technologies. Specific monitoring indicators may include the number of installed and operational biogas units, daily gas production levels, reduction in traditional fuel consumption, manure utilization rates, maintenance frequency, household cost savings, and user satisfaction levels. Gender-sensitive indicators such as changes in household labor distribution, particularly women's time spent on fuel collection, may also be considered. These indicators can be structured within results-based evaluation frameworks, such as input–output–outcome monitoring systems or community-based participatory evaluation approaches. Such evidence-based monitoring can support adaptive policy adjustments and improve the long-term effectiveness of biogas promotion strategies. Nevertheless, the transition toward biogas adoption among smallholder farmers remains complex and may face practical challenges related to infrastructure availability, long-term maintenance, and sustained institutional support. Overall, coordinated policy actions that address technical knowledge gaps, financial constraints, and institutional support structures are essential for biogas technology to play a meaningful role in smallholder energy transitions and climate change mitigation.

4. Conclusions

This study investigates community perceptions and readiness to adopt biogas-based cattle waste management as part of a local energy transition and climate change mitigation strategy in rural Indonesia. Drawing on primary survey data from smallholder cattle farmers, the findings indicate that readiness for biogas adoption is shaped more strongly by cognitive understanding, perceived benefits, and practical experience than by socio-demographic characteristics. This suggests that improving knowledge, strengthening positive perceptions, and enhancing hands-on waste management experience may be more effective in promoting adoption readiness than relying on household characteristics alone. In contrast, socio-demographic variables such as age and current LPG consumption do not significantly influence readiness, reinforcing the importance of behavioral and experiential drivers in shaping preparedness for adopting new waste management practices.

Although respondents demonstrate a strong awareness of the environmental and health risks associated with unmanaged livestock waste, conventional practices such as open dumping remain widespread. This finding represents a key contribution of the study by identifying a clear awareness–adoption gap, where environmental concern does not automatically translate into sustainable waste management practices. This gap indicates

that awareness alone may be insufficient to trigger behavioral change without complementary technical support, incentives, and institutional facilitation. Therefore, the results underline the importance of knowledge dissemination and hands-on experience in strengthening community preparedness for improved manure management practices, including biogas systems.

However, readiness reflects intention and preparedness rather than actual technology adoption. The implementation of household-scale biogas systems may still face practical constraints, including financial limitations, technical capacity, and the availability of institutional support. Methodologically, this distinction highlights that measuring readiness provides an early indicator of adoption potential but may overestimate actual uptake if structural barriers remain unaddressed. Future studies should therefore combine readiness assessments with longitudinal adoption tracking to better capture the transition from intention to sustained implementation. Consequently, while biogas represents a potentially promising option for integrating livestock waste management with rural energy needs, its wider adoption will depend on supportive policy frameworks, accessible technical assistance, and locally appropriate system designs.

From a policy perspective, the findings emphasize the importance of targeted knowledge-enhancement programs, practical training in manure management, and institutional support mechanisms tailored to smallholder livestock systems. Given the strong influence of knowledge, perception, and prior experience, extension programs should prioritize demonstration-based learning, farmer field schools, and peer-to-peer knowledge exchange. Financial support schemes and cooperative-based manure management initiatives are also necessary to address structural constraints identified in the barrier analysis. This study provides empirical insights that can inform the development of integrated policies promoting sustainable livestock waste management and rural renewable energy transitions. Nevertheless, this study is limited by its cross-sectional design and reliance on self-reported data, which capture stated readiness rather than actual adoption behavior. The relatively small sample size and focus on a specific rural context may also limit generalizability to other regions with different socio-economic and institutional conditions. In addition, the use of perception-based measures may introduce response bias. Future research should employ longitudinal designs to track actual biogas adoption over time, incorporate larger and more diverse samples across regions, and explore additional factors such as institutional support, gender dynamics, and economic cost–benefit analysis to better understand sustained adoption pathways.

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